SPECIAL PUBLICATION 31

Proceedings of the 1985 Conference on Coal Mine Subsidence in the Rocky Mountain Region

Edited by Jeffrey L. Hynes

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PROCEEDINGS OF THE 1985 CONFERENCE ON COAL MINE SUBSIDENCE IN THE ROCKY MOUNTAIN REGION

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Jeffrey L. Hynes, editor

Colorado Geological Survey
Department of Natural Resources
Denver, Colorado
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FOREWARD

The need for increased awareness of, and sensitivity to, the phenomenon of mine subsidence has been identified as part of the overall plan by the Office of Surface Mining to minimize the adverse impacts of past mining.

The value of improved understanding and communication in and among both the technical and administrative organizations dealing with the problem cannot be overstated.

The impacts are especially significant in the Rocky Mountain West where population growth and rapid community expansion have increased development pressure on significant areas of subsidence-prone ground. The consequences of unrecognized and poorly managed subsidence hazards are much more serious in the emerging urban and suburban environment than they were in the past where they occurred primarily in agricultural lands.

Where coal mine subsidence was once a low-impact issue dealt with by ranchers and miners, it has now become a land use consideration requiring the attention and expertise of a multi-disciplinary team consisting of geologists, engineers, architects and planners.

This conference was convened in the spirit of sharing the experience and knowledge of the many professionals working on the various aspects of the mine subsidence problem and to improve the understanding and cross-specialty communication and cooperation among the attendees.

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COAL MINE SUBSIDENCE, PAST, PRESENT, AND FUTURE, IN THE ROCKY MOUNTAINS

John B. Ivey
Amuedo and Ivey, Inc.

ABSTRACT

The emphasis will be on Colorado in this paper. However, much of what is said generally and philosophically applies to the other Rocky Mountain states.

Subsidence is primarily a man-made hazard that has adversely affected many types of man-made works. The potential for additional subsidence effects to be manifested exists particularly in areas where inactive mines are found.

Underground coal mining, that began in the late 19th and early 20th centuries, was done on a far less sophisticated basis than is done today. The types of records which are useful to subsidence analysis generally were not kept. Concern with subsidence and the potential for it was essentially nil until after World War II.

Today's regulations require that the potential for subsidence be taken into account prior to and during mining. Pressure to develop undermined land which formerly was considered remote is considerable. Subsidence investigations today are a problem, the parameters of which are generally defined as the solution is developed. Although not the best procedure, this appears to be the most feasible one.

The future of subsidence-related projects is reasonably predictable. Where data is questionable, we must refine our techniques of examination and analysis. Where mining is controlled by current regulations, a greater level of confidence should develop in solving the subsidence problem.

INTRODUCTION

This paper is pertinent mainly to Colorado, although much of what is said philosophically will pertain to coal mining in any of the Rocky Mountain states.

Other papers in this symposium volume will elaborate on some of the things that are only briefly touched on here. Hence, these remarks can be considered essentially an introduction. Much of what is presented here is drawn from personal experience, and in no way is it meant to preempt the substance of any of the papers that will follow.

The Rocky Mountain states contain large deposits of coal, many of which are yet to be mined. Coal mining is part of the resource-development heritage that all of these states possess to varying degrees. Many problems arise in mining coal at the surface and in the subsurface. Detailed recitations of these problems have filled books and have been the subject of many technical articles. The problems of the western coal industry relate to exploration, quality, development, environment, transportation, marketing, and other facets of a large infrastructure. The present concern is subsidence, a pervasive, and frequently frustrating, environmental problem where underground mining has taken place. This problem has assumed increasingly greater proportions in the last two decades because of a concerted development of the surface in areas where underground mining has occurred.

Many of the subsidence investigations today are done as a result of mining which took place before many of us were even born. In a real sense we have inherited many of the problems for which solutions are sought today. Shakespeare recognized the vagaries of human nature when he wrote,

> "Some are born great, some achieve greatness, and others have greatness thrust upon them."

We as scientists and engineers might paraphrase the bard and say, "that we have had subsidence thrust upon us." Those working in subsidence investigations often may be justified in feeling that something great has been sent their way, in the sense of problems that are presented to us for solution.

A consideration of the past provides some insights on how it affects what we are doing today. Some of this work is being shared, and eventually most of it will be. As to the future, only the past and the present can be used to predict it, but it is doubtful that anyone working on subsidence problems pretends to be a prophet, least of all does the writer make that pretense. The comments on the future will be concerned with what can be done about it, rather than predicting it.

Some common goals on which work can be focused can be recognized. In approaching these goals it is logical to look at the roles and responsibilities assumed by the interested parties. Remedies suggested today hopefully will evolve into increasingly better means of contending with this complex subject.

THE PAST

When underground coal mining began in the Rocky Mountain area over 100 years ago, it is doubtful that any serious thought was given to the subsidence potential that was being created. Mines generally were remote from centers of population, although this is not universally true. The miners doubtless were concerned with safety -- primarily their own safety while they were underground. Any concern for subsidence potential was probably in inverse proportion to the depth at which coal was mined in any given area. Records were kept primarily for mine owners and investors to determine that they were paying their fair share of expenses, and were receiving their fair share of profits. The motivation in mining then was little different than it always has been, and still is: to maximize profits by mining the best material, at the lowest cost. Coal mining was not an easy occupation and as mentioned above, there was little if any concern for potential future subsidence -- after all, such a concern would not have helped working conditions, nor would it have enabled the miner to produce more coal, nor to make more money.

Thus the early miners, and those who worked in many areas as late as the mid-1940's and into the 1950's left their descendants a somewhat tarnished heritage. This gift was not necessarily purposeful, but it created an atmosphere in which much of the subsidence work done today, is completed without as high a level of confidence as might be preferred.

THE PRESENT

The present for the purpose of this discussion includes essentially the post-World War II era. The subsidence hazard we hear most of today is largely confined to areas where recent development has taken place and where development is now taking place.

Subsidence is primarily a man-made geological hazard resulting from the removal of coal from underground occurrences creating void spaces where nature did not intend them. Next to a vacuum, nature probably abhors a man-made underground void more than anything else, particularly if that void is in coal. The only natural subsidence hazard that comes readily to mind is in those instances where fire which started naturally at the surface, burned underground to a sufficient extent to cause subsidence.

The instances of coal mine subsidence which are observed and for which there is potential in the Rocky Mountain area become hazards only when they adversely affect some socio-economic aspect of man's use of the land. Our part of the country is not exclusively affected by this hazard. The subsidence hazard exists in the Appalachian and Mid-Continent coal fields. The potential for this hazard exists wherever underground mining is practiced.

The national scope of this hazard, and several others, has recently become the subject of attention by the National Research Council. The Council established the Committee on Ground Failure Hazards as a result of a report in 1981 by its Task Group on Landslides and other Ground Failures (National Research Council, 1981). For those of us dealing with subsidence as a hazard, it is of interest to know that during the 50-year period 1925-1975, the combined loss from hurricanes, tornadoes and earthquakes totalled nearly $20 billion. During the same period, the losses from only two types of ground failure, landslides and subsidence amounted to at least $75 billion. In 1977 about $30 million per year was attributed to subsidence in the United States. In terms of local and personal impact, the effect of coal-mine related subsidence can be just as dramatic and traumatic, if not more so, than subsidence related to other causes.

If the geographical relationship was present today that existed between mines and population centers in the late 1800's, there probably would be just as little concern now as there was then for subsidence. Generally, the mines were not located near population centers and mine locations usually were known only to locals and to the miners. Those who used the coal were primarily concerned only that the coal was available at an acceptable cost.

In some communities undermining took place and there was concern for subsidence. The earliest record I have (Conarroe, 1978) of this is that in 1895 the Town of Louisville, Colorado, demanded settlement of a claim of subsidence damage from the Louisville Coal Mining Co. Except for undermined towns like Louisville and Lafayette, Colorado, and Rock Springs, Wyoming, there generally was little concern for the subject. People had no incentive to be educated as to why subsidence occurred, nor were they concerned with finding someone on whom to blame the problems associated with it. They just endured subsidence and its effects. After coal mines were closed, surface facilities were dismantled and surface debris was removed. People tended to forget that mines were ever there, or at least they attached no further significance to these mines. Evidence suggests that many, although not all, of those who were aware of mining, and who suffered adverse effects of subsidence, accepted this adversity, lived with it, covered it up when the time came to sell their improved property, and generally downplayed any concern.

The turning point came gradually as surface development moved toward rural areas that had been undermined. People who were in no way tied economically to coal mining began to build. These people had slight, if any interest in the fact that their property or subdivision was directly over or near undermined ground. Tracts of houses began to crop up on what had traditionally been farming and ranching land.

An interesting socio-economic awareness emerged with this creeping urbanization. Planning and zoning entities became involved as laws of essentially an environmental nature became effective. It seems axiomatic that when laws are created to respond to some natural or man-made hazard, a fertile field is prepared for lawsuits. Concurrent with at least part of this urbanization process there occurred a creep in the potential for litigation. Those who gave no thought to becoming educated as to how subsidence might adversely affect them, became fast and willing learners that someone might pay for property damage, reduced property values, real loss, and imagined present and future loss.

Quite naturally when damage occurs, or the imminent potential (real or imagined) for damage becomes apparent, the affected party looks for a responsible entity, known in some circles as "deep pockets". This matter of responsibility can be perceived by the individual(s) and his legal counsel to be the government, and they ask, "Why did the county or city allow zoning for residential development in the affected area of the mine?" They might ask the developer, "Did you know the land was over or near an inactive mine; if so, why didn't you tell me?" The mine owner or operator might be accused of ultimate responsibility, because if he hadn't removed the coal, the problem would not have occurred. Many questions can be asked, but the asking is much easier than the answering.

The first formal study of the relationship of local coal mine subsidence to land-use planning was published by the Colorado Geological Survey in 1975 (Amuedo and Ivey, 1975). This study systematically reviewed the Boulder-Weld coalfield. A similar study (Amuedo and Ivey, 1978) was prepared in 1978 for Jefferson County and several cities within the county. In 1980 the Colorado Mined Land Reclamation Division authorized a contract study of abandoned or inactive mines throughout the state. About 500 coal mines east of the Front Range were inventoried (Amuedo and Ivey, 1983); subsidence was a major concern in this study. Numerous privately funded studies of subsidence have been conducted since 1973 by developers with a view toward improving land in areas where undermining could affect surface stability. The first private study with which the writer is familiar was made in 1969.

GOVERNMENT RESPONSIBILITY

Federal and State governmental agencies have assumed, or had thrust upon them certain responsibilities relating to mine subsidence. The main agencies are the Office of Surface Mining, the Colorado Mined Land Reclamation Division, and the Colorado Geological Survey. Some of the responsibilities of these agencies will be touched on briefly.

State Government - Colorado State law (State of Colorado, 1966) requires that each coal mine operator submit to the Division of Mines a map of the mine workings each six months, and before any mine is to be shut down. There is no indication in the wording of this law that subsidence is a concern nor is it designated as a subject of any reporting.

This law does have a profound effect on most of us who work in subsidence investigations today. Usually the most recent copies of mine maps constitute the most authoritative documentation of the physical aspects of a mine with which we have to work. That is not to say that these maps present all that we need in the way of basic information; they are just all that we have.

The Colorado Geological Survey, reinstituted in 1969 after a hiatus of about 30 years, began mine subsidence investigations primarily as a result of urban growth. The path of growth in Boulder and Weld Counties was toward undermined areas. In 1973 when a study (Amuedo and Ivey, 1975) of the effect of subsidence on land development was contracted by the Survey there had already been concern registered by non-government entities, and damage had occurred to surface structures in towns and communities such as Lafayette, Louisville, Dacono, Firestone, and Frederick. The City of Colorado Springs had earlier felt the adverse effects of undermining.

The Division of Mined Land Reclamation was established as a result of Federal legislation, the Surface Mining Control and Reclamation Act of 1977 (United States of America, 1977). Colorado obtained primacy under law, thus qualifying for Federal money to study, and in some cases remedy, the adverse effects of subsidence. Most importantly, this law provides that subsidence be recognized and dealt with in a manner that would minimize adverse surface effects to on-going and future mining. It is important to recognize that the Federal money referred to comes from coal producers who contribute $0.35 per ton of surface coal mined, $0.25 per ton of underground coal mined, and $0.10 per ton for lignite. The law also provides for emergency action in cases that constitute "a danger to the public health, safety, or general welfare, " if "no other person or agency will act expeditiously to restore, reclaim, abate, control or prevent the adverse effects of coal mining practices."

The County and municipal governments generally work independently and bear a regulatory role generally in two ways, primarily as a consequence of HB 1041. First, they determine whether and to what extent areas with subsidence potential can be zoned for surface development in areas which have already been undermined. Second, they determine whether permissible zoning will be granted for new underground or surface mining activities. As a practical matter the former control is more important than the latter considering the status of coal mining today. Even before rezoning is applied for by a coal operator, as a first step in the permitting process, he must begin to satisfy the requirement for a subsidence-control (monitoring) plan. Likewise, before a developer can obtain rezoning, he must demonstrate that a subsidence hazard will not adversely affect the subject area.

Several agencies of the Federal government are engaged in subsidence-related work. The U.S. Geological Survey has a relatively long history of subsidence investigations and basic research projects relating to the subject. The Bureau of Mines has undertaken studies for many years and maintains a mine-map repository from which is available much useful data concerning mine maps. The Office of Surface Mining is involved largely as an overview agency working independently and through the Colorado Mined Land Reclamation Division. Finally, the Office of Housing and Urban Development (HUD) manifests its strong interest in subsidence, in that it generally refuses to guarantee home loans if there is any possibility for adverse subsidence effects.

PRIVATE SECTOR RESPONSIBILITY

In on-going projects to develop the land surface in areas of potential subsidence, perhaps the greatest responsibility rests with the developer. There generally is little or no recourse to the mine operator who may have passed off the scene. The corporate structure within which the mining was done probably has been dissolved. The present surface owner may or may not own the mineral rights. The developer who proposes to build in an area where there is a subsidence potential should satisfy himself as to the magnitude of that potential, and should inform investors (whether co-investors or property buyers) as to that potential. Responsibilities in the private sector are complex, and in some cases may have legal ramifications.The planning and (or) zoning authority, county or municipal, is the first source of information for the developer. If the potential for subsidence exists on land which he wants to develop, he may be able, with competent help, to determine with site-specific studies that less land is affected than had been indicated on the planning/zoning maps generally derived from regional studies. This is a matter of refining the regional scale data on which hazard maps are usually prepared by planning bodies.

The developer, who stands to gain most from developing the land, should undertake the obligation to educate himself as to any adverse subsidence effects that will be felt where he plans to sell land or build.

Next to the developer, the consultant who determines the extent and magnitude of the subsidence potential of an area, bears the greatest responsibility. The consultant must use all of the information available to him and determine if that data will suffice in his study. If the data is inadequate, he must define the nature and extent of additional studies needed for him to reach defensible conclusions. Perhaps the most important aspect of the consultant's work is complete candor in expressing his opinion(s). He must "tell it like it is" to his client, even if the "like it is" is not what the client wants to hear.

Logically, one will ask where the property or homeowner fits into this picture. It seems that all too often in the past the property or homeowner has been "the last to know". This is changing today because the general public is becoming more aware of the potential for subsidence, particularly in those areas where lawsuits have awakened public awareness. Seldom does the general public take the initiative of self-education as to something like subsidence.

However, if an event occurs that threatens to harm one or one's family, an immediate appeal is made to the appropriate governmental body for help. It could be said that, insofar as natural hazards are concerned, the real estate principal of "caveat emptor" appears to be vanishing.

INVESTIGATIONS AND SOLUTIONS

The biggest problem an engineering geologist faces today in subsidence investigations is the collection and assimilation of data. Initially the most important data with which he has to work is the mine map, particularly the latest map completed at the closing of the mine. Even with this map in hand, there usually are questions that cannot be answered with the degree of certainty one would like to have. It must be remembered that the mine maps are being put to uses today for which they were never intended. There usually is insufficient data relating to coal thickness shown on the map. It is not unusual that the relationship between the surface and underground surveys is of questionable accuracy with respect to the intended use. The most frequent question in using these maps is whether or not the extraction of pillars as shown is correct. Even if the location of pillars is correct, there is the question as to which ones are yet standing. There is a lack of standard symbolization and map legends are not always edifying. In an initial review of a mine map the investigator reaches some point where he has to go on record with the assumption that a map or that part of a map with which he is concerned is correct. Beyond this point, additional factual data must be acquired if his work is to be more reliable and definitive. This commonly involves drilling to determine actual conditions, and to provide access for geophysical and other investigations.

The preparation of subsidence and strain profiles and maps from mine maps generally imposes a higher level of conservatism on the person making the profile or map than would be the case if the mine maps were more accurate. Common use of the National Coal Board subsidence criteria (National Coal Board, 1975) add to this conservation because these criteria were developed for longwall mining, and not room-and-pillar extraction.

In the acquisition of data the strong possibility exists that no consultant will ever find a client who is willing to pay for as much data collection as would make one feel completely satisfied with the results of his analysis (this is not necessarily unique to mine subsidence projects).

One of the most important aspects of subsidence investigations is how they are reported. Proper reporting is necessary but it can add a complexity to the work that is not found in all other types of geological investigations. Subsidence and its causes involve two environments: the surface, and the subsurface, and a complete understanding of the complex relationships that exist between these two is not always attained. Another complexity is that reports are used by a disparate group which is made up of non-technical and technical people, including property owners, developers, other geologists, engineers, planners, and other regulators, and not least important, members of the media. This diverse group generally needs to be educated as to what the relationships of the causes, mechanisms and effects of subsidence are.

Above all a subsidence report should be candid. The consultant should adopt the approach that he will "tell it like it is" regardless of whether this is what the client wants to hear. Statements and conclusions should be justifiable and defensible. This is a protection to the consultant and to his client. Correspondingly, the regulators and reviewers should not accept as gospel conclusions which do not stand normal tests of close scrutiny.

Usually the language of subsidence is poorly comprehended by geologists and engineers not trained in the subject; think how confusing this language must be to the non-technical layman.

THE FUTURE

The subject of the future leads to remedies, and causes one to reflect on what has been done in order to improve procedures in the future.

It is safe to say that subsidence will continue to be a concern in areas that have already been undermined. This concern will be intensified in both urban and rural areas as long as there is economic pressure to develop the land.

It is equally safe to assume that subsidence will be addressed before new underground mines are opened, or old ones are reactivated.

Geologists and engineers working on subsidence investigations should educate themselves first, so that they in turn can educate those who are most affected by subsidence potential.

Likewise, in their zeal to get the job done, geologists and engineers should keep in perspective the relationship between computer-generated data and field observation so that the development of their individual experience and judgmental abilities is increased. Along with this there should be an equal concern that assumption is not based upon assumption without adequate testing.

It should be remembered that in most cases subsidence work is based on the assumption that a mine map is correct, but it should be realized that the only way to really check the accuracy of that map is generally expensive and often will require dedication and courage of one's convictions in arguing for the funding for needed studies.

When the subject of remedy is approached the question should be asked, "What is it we want to remedy?" That is a simplistic question, and the answer to it depends largely on who is being affected most. Asking this question from the viewpoint of the affected parties gives some insight into the future of work on subsidence projects. Determining a priority of affected parties can be likened to "whose ox is being gored, " but a general priority can be established.

HOMEOWNER/PROPERTY OWNER

The homeowner is at the top of the list. First from the standpoint of safety, particularly with respect to utility lines. Other important considerations are peace of mind, comfort, aesthetics, and maintenance of property values. The property owner is concerned largely with whether or not to build, if that was his intention, or for property values, if the lot was purchased simply as an investment.

DEVELOPER

The developer, once he becomes aware of the potential hazard, has many concerns. First, if he has not already closed on the land purchase, should he? Second, if the land is already owned by him, what will it take by way of investigations to reduce the amount of land that is apparently affected by subsidence? Is there a reasonable possibility that he can increase the amount of land available for development sufficiently to make the project economical? What is the liability exposure without development, and what will it be after development?

ZONING AUTHORITIES

In Colorado the county and municipal planning and zoning departments will have geologic hazard overlay maps to guide them in the actions they take. The most obvious action that these authorities can take would be to simply designate areas of potential subsidence hazard as "green belt." Where land has been subdivided and structures have been built, a moratorium could be placed on further building until a site-specific study of the problem area has determined that building would be safe. Zoning authorities do not have an easy task since they must consider whether or not they will be held liable for past actions, if they zoned for development before they were aware of the mines, or if their actions will instigate lawsuits because of reduced property values.

It is apparent the subject of remedies to coal mine subsidence can create an arena for prolific debate. Several aspects of the problem should be reviewed before specific remedies are discussed. There are two broad types of situations to be addressed.

First, there is the remedy for future subsidence in an area that has been undermined. Consideration should be given to prohibiting development of that area until mines have been stabilized to the extent no further subsidence will occur.

Second, there is the remedy that can be undertaken in areas where development already has begun. The problems of maintaining safety, protecting against reduction in property values, and allaying the fears of homeowners must be addressed. The treatment of areas which may be subject to chimney subsidence must be of first priority.

Specific solutions should be recommended only after site studies have been made. Cost-benefit analysis will often be the determining factor in whether a given solution is feasible; however, other factors may also enter into the decision-making process.

FINAL CRITERION

When all the reports are in, all the studies have been completed, all the deliberations and oratory have been expounded, perhaps the answer to one simple question by any of the parties who have been mentioned above should be the controlling factor. The question: "All other things being equal, would I buy a house, or buy a lot on which to build one, in this area?"

SELECTED REFERENCES

Only a few references are referred to specifically in this paper because much of what has been deduced in it comes from personal experience. There is, however, a large body of published data on the subject of coal mine subsidence. These are the working tools of those involved in subsidence investigations and I gladly acknowledge their importance to my understanding and practice of the subject. In addition to the following list, there are many unpublished consultant's reports that are part of the public domain and are available at regulatory and review agencies.

1. Amuedo and Ivey, 1975, Coal mine subsidence and land use in the Boulder-Weld coalfield: Boulder and Weld Counties, Colorado: Colorado Geological Survey, Environmental Geology Report No. 9.

2. Amuedo and Ivey, 1978, Coal and clay mine hazard study and estimated unmined coal resources, Jefferson County, Colorado: The County of Jefferson and the Cities of Arvada, Golden and Lakewood, Colorado.

3. Amuedo and Ivey, 1983, Inactive coal mines of the Front Range area, a mine inventory and an evaluation of hazards arising from past mining: Inactive Mine Reclamation Program, Department of Natural Resources, State of Colorado.

4. Conarroe, Carolyn, 1978, The Louisville story: Louisville Times, Inc., 74 p.

5. National Coal Board, 1975, Subsidence engineers' handbook: National Coal Board Mining Department, London, second (revised) edition.

6. National Research Council, 1981, Report to the Commission on Sociotechnical Systems, National Research Council, Task Group on Landslide and Other Ground Failures.

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FEDERAL RECLAMATION PROJECTS BRANCH

FISCAL YEAR 1985 OBJECTIVES

Donald Donner

Office of Surface Mining

ABSTRACT

This paper details the objectives to be achieved during the Fiscal Year 1985 and the methodology planned to implement them. Specifically it details the management strategy for the forthcoming year. It has been developed partially on consultation with staff members and partially on past experience with similar programs and to a considerable extent on observation of the staff and its past activities from an only slightly distant observer's standpoint. It identifies the steps necessary to establish a more efficient program and at the same time enhance the effectiveness of the program for the abatement of coal mine-related environmental problems.

PRESENT SITUATION

The current staff of the Federal Reclamation Projects Branch (FRPB) consists of 7 persons. This group provides technical support to States, Field Offices, Tribes, and Headquarters but primarily effects Federal projects and emergency abatement in the area served by the Western Technical Center.

The FRPB staff consists of:

1 Branch Chief

4 Project Managers

1 Realty Specialist

1 Administrative Assistant

The Branch Chief is responsible for the overall administration of the Branch. This includes responsibility for scheduling, budgeting, training, quality of work and the quality of work produced by the branch personnel.

The Project Managers are responsible for the conduct and completion of assigned projects, generally in one or more assigned States. This includes the preparation of all documents concerning projects, the guidance of consultants, inspectors or other personnel assigned or otherwise involved in the project.

The Realty Specialist is responsible for assisting the Project Manager in real estate matters such as rights of entry, appraisals, lien determinations, and any other realty matters necessary for the successful implementation of a project.

The Administrative Assistant provides administrative support to all of the staff and serves as a principal liaison between headquarters and WTC in matters of project tracking.

PROBLEMS AND PROPOSED ACTION

Following are a number of problems and areas that are identified for improvement or change during the upcoming year. They are obviously of different importance but are not necessarily listed in any relative rank. Immediately following the problem is a brief description of the anticipated action to improve or correct the situation.

1. Prompt Emergency Response
   Attempt to respond to notification of an emergency situation within 24 hours of notification. This may be by the appropriate Project Manager, a Representative from the Field Office, or a Contractor. Whenever possible an effort will be made, using the SF44 authority, to effect at least minimal protection of the public until a permanent abatement can be performed. This will be implemented by directives to the staff to that effect and follow up to insure compliance. The Staff member will be made responsible for complying, however the actual work may be arranged for and carried out by another entity.
2. Contracting Locally
   The problems that have been encountered in performing all contracting operations through a remote contracting office severely limit our field effectiveness and timely response. This issue is of such magnitude that it is planned to fill the first vacancy within the Branch with a Contract Specialist in order to more promptly and smoothly conduct the work of the group. It is felt that the overall efficiency of the group will be enhanced to such an extent as to more than offset the loss of a Project Manager position.

3. State Program AML Oversight

It is anticipated that there will be a number of requests from the field offices for technical assistance for oversight. Although it will, or may, cover all aspects of the AML work it is felt that much of the need for help by the Field Offices will be in the realty area. This will be furnished, to the extent possible, with existing staff subject to the demands of emergency work. Assistance will be requested from the headquarters staff to supplement local staff as needed.

4. Reports, Closeouts, and Tracking

There has been a near complete lack of the staff posting various records pertaining to project work. There will be major emphasis placed on bringing tracking reports, both locally and the "Ifft" system up to date and also the closing out of cooperative agreements and contracts. This emphasis may go so far as restricting travel of staff members or other punitive measures. It will be included in performance standards as a critical element.

5. Balanced Workload

Oversight activities and emergency response are items over which there is little control and hence it is possible that there may be an imbalance of work for the staff. If this occurs, the distribution of responsibilities will be adjusted to correct this imbalance. Projects that are underway, however, will continue to be the responsibility of the initiating Project Manager.

6. Contracting Out and Training

Contracting out of design and investigations will be minimized and conducted by the in-house staff to the extent possible. Contracting will be used primarily when it is cost efficient and/or technically expedient. A consideration of the contracting will be to enhance training of the staff in areas where skills can be developed. Structured training will be conducted as appropriate and scheduled in such a manner to be made available to the majority of the staff. Internal WTC support personnel will be used to the maximum extent possible.

7. Travel

One of the major expenses of the group is travel. It can be anticipated that limits will probably be imposed and therefore itineraries will be closely examined. Travelers will be queried and wherever possible only trips that are necessary will be taken. Routes will be questioned and the possibility of merging several visits considered.

8. Outcrop Fires

A number of outcrop fires are anticipated in Montana as a result of grass and forest fires that occurred in September. It is planned to cooperate with the State for a EPA infrared surveillance of the impacted area and then followed with a ground investigation of the suspect areas indicated by the photography. Fires found in abandoned mines will be controlled by the State under their emergency program and outcrop fires will be controlled under the provisions of PL 83-738. It is planned that most will be small and a PO type contract will be appropriate.

9. Project Tracking

The currently used system is designed primarily for the Engineering and Hydrology branches. It will be redesigned to make it more useful and meaningful for FRPB use.

COLORADO GEOLOGICAL SURVEY'S ROLE AND RESPONSIBILITY - ABANDONED MINE SUBSIDENCE HAZARDS

Julia E. Turney

Colorado Geological Survey

ABSTRACT

The Colorado Geological Survey's responsibilities regarding inactive mine subsidence hazards are mandated by state statutes that created the present Survey in 1967 and Colorado land use laws enacted between 1972 and 1974. House Bill 1282 directs the Survey to advise local governments and other state agencies on geologic problems; conduct geologic studies; collect and preserve geologic information; and to determine areas of natural geologic hazards that could affect the citizens of Colorado. Senate Bill 35 (1972) requires that a geologic report be completed for subdivisions of land into 35 acres or less, on unincorporated land. House Bill 1041 (1974) defines what geologic hazards are in Colorado and includes surface subsidence, whether natural or man-made. These laws set the stage for the Colorado Geological Survey's review of subsidence investigations, the development of a subsidence information library which includes reports of subsidence investigations, extent of mining maps, and publications. Additionally, the Survey advises other state agencies and local governments on subsidence hazards.

LEGISLATIVE CHARGES

The Colorado Geological Survey's (CGS) responsibilities are mandated by three state statues and land use laws passed between 1967 and 1974.

The first, House Bill 1282, created the present survey in 1967. The specific charges found in the bill are:

To assist, consult with and advise existing state and local government agencies on geologic problems;

To conduct studies to develop geologic information;

To collect and preserve geologic information;

To evaluate the physical features of Colorado with reference to present and potential use;

And to determine areas of natural geologic hazards that could affect the safety of, or economic loss to, the citizens of Colorado.

In 1972 Senate Bill 35 was enacted and is a major land use law. Among many things, this law requires that a geologic report be completed for subdivisions of land into 2 or more parcels of 35 acres or less. The geologic reports are submitted to the counties, and the counties are required to submit these reports to the CGS for review. The law applies to unincorporated areas and does not apply to cities or towns. There are no regulatory penalties for not sending these reports to the Survey or for not following our recommendations, we are an advisory organization.

In 1974, House Bill 1041 was enacted, this Bill identified geologic hazards as matters of state concern and interest and legally defined geologic hazards. Land subsidence, natural or man made, is included as one of the defined hazards. In response to H.B. 1041, the Survey published Special Publication number 6, which defines and discusses each geologic hazard in detail, along with potential mitigating measures. Additionally, the Survey developed model geologic hazard area control regulations. House Bill 1041 specifies that local governments administer identified hazard areas in a manner consistent with these land use guidelines. Money was provided by the state to the counties to identify geologic hazard areas. Most studies were completed by private consulting firms. Some, such as Douglas County, were done by the CGS. Many subsidence hazard areas were identified in these studies. This is a very narrow view of two pieces of broad legislation. Much of Colorado land use laws, zoning and administration are based on this legislation. Additionally, these laws reflect the fact that the land use decision power base is held by city and county government.

LAND USE REVIEWS

In accordance with S.B. 35 and H.B. 1041, most counties and some cities send mine subsidence investigations to the Survey for review. These studies are usually completed by geologic consultants for private land developers during the counties platting processes. The Survey is responsible for reviewing these reports and the proposed surface development and then making recommendations to the local government on the suitability of the development. The County Planning Commission, and County Commissioners, or City Council, acts on these recommendations independently. The number of investigations we receive has increased in the past 5 years, as urban expansion puts pressure on subsidence prone areas, and awareness of the potential hazards increases. Not surprisingly, the largest numbers of investigations come from Boulder County, with 32 studies, and El Paso County with 16 investigations. Of the studies we know about, a total of 67 studies have been completed since 1980, 22 prior to that time.

In the past, the Survey reviewed development applications for FHA and VA insured loans for the Federal Governments. Currently, FHA requires that the potential for subsidence hazards be reviewed on an individual application basis when their appraisers find a house is in, or close to an abandoned coal mine area.

As an extension of H.B. 1041 and an attempt to learn more about potential inactive mine subsidence hazards, the CGS contracted with the consulting firm of Amuedo and Ivey to complete a subsidence hazard evaluation of the Boulder-Weld Coal field. This report, published in 1975 as Environmental Geology Number 9, produced detailed extent of mining maps for this area and subsidence potential maps with low, moderate and severe hazard ratings. The ratings were based on available information such as depth of mining, if pillars were pulled, age of mining from the Colorado Division of Mines and other records. No drilling was done. The EG-9 Maps were used as a basis for Boulder and Weld Counties hazard maps and are still used today. These maps were a good land use planning tool and taught us a lot about how the public uses maps and understands technical information. For example, these maps were never meant to replace detailed investigations. However, often a low subsidence hazard potential is perceived as no problem instead of an area that has a low potential for subsidence yet needs to be studied further.

Up until July of 1983, two thirds of CGS employees salaries, including the six engineering and environmental geology staff members were paid by general state funds. Other employees salaries were paid from Federal grants. All of our review activities were free of charge to counties. At the start of the 83-84 Fiscal year our general fund support level was cut from 16 full-time employees to 3. We didn't disappear; at that time we were given the authority to cash fund our review activities and get all the additional outside funding we could manage. This has meant charging the counties for our reviews, and they in turn pass the costs along to land developers. This unfortunately does not cover the cost of time spent answering questions from the public on many issues including subsidence hazards.

SPECIAL PROJECTS

Coincidently, much of the work on inactive mine subsidence hazards performed by the CGS in the past 3 years has been done in cooperation with the Mined Land Reclamation Division, Inactive Mine Reclamation Program, and with financing from that program. One such project was a subsidence investigation of the Dacona, Frederick and Firestone area in Weld County. This study included 85 rotary drill holes and 11 core holes. The results of this study included detailed extent of mining maps showing the mine rooms and pillars overlain on aerial photos of the towns. Potential subsidence hazard maps were also produced for the area. This was the first community wide investigation completed in Colorado. Another project developed a suite of Extent Of Mining Maps for the 12 Front Range Urban Corridor counties that have abandoned coal mines. These maps are on the U.S.G.S. 1:50,000 county map series and each county is reproduced on 1 plate for easy reference. Each plate shows the extent of mining and any available information on mine openings, subsidence features, fires, drainage and reclamation. Each map is accompanied by a mine data table that lists mine names, dates of mining, any known information on the mines and written descriptions of the special features noted on the maps. Extent of mining maps for the western slope coal fields have been compiled on U.S.G.S. 1:24,000 scale topographic maps, these maps are also accompanied by coal mine data tables.

We are in the process of finishing detailed extent of mining maps showing room and pillar workings on airphoto bases for Canon city and Walsenburg areas.

Another important part of the Surveys role is providing geologic information to the general public. We have written and published a non-technical book on inactive mine subsidence hazards in Colorado, targeted specifically for homeowners.

As mentioned before, a large number of subsidence investigations have be done in Colorado. To preserve these reports and extensive drill hole information, we have completed an annotated bibliography summarizing the information in each study. We received many of these reports as part of review requests and many private consultants were very generous in obtaining permission of us to get copies of reports we didn't have on file. We believe the bibliography is fairly complete. However, we would appreciate getting copies of any additional studies that are available. These investigations, along with information and publications pertinent to Colorado subsidence are on file as part of a subsidence library at the C.G.S. We hope to maintain a clearinghouse of subsidence information for use by anyone. Hopefully, getting the word out and maintaining information will help prevent the cyclic nature of subsidence awareness. We're located in the same building as the Colorado Division of Mines, which has maps of Colorado's inactive and active coal mines. This provides a unique information resource for Colorado.

SUMMARY

The Colorado Geological Survey reviews subsidence investigations for local governments; has completed a pilot community subsidence investigation; maintains a library of subsidence information; publishes subsidence related information and assists the public, and State and local governments.

Because there has been concern and funding from the State and private sector, a large amount of research is being done and much valuable information is being made available. We hope to preserve this data for future use and research for Colorado. Copies of the publications and maps prepared for the Mined Land Reclamation Program are available from the Inactive Mine Reclamation Program at no charge.

HISTORY AND EVOLUTION OF MINING AND MINING METHODS

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ABSTRACT

The underground coal mines that are currently of concern to subsidence professionals in Colorado were generally mined between 1860 and 1960. This 100-year period saw the coal mining industry advance from the use of picks, hand augers, black powder, and mules to the use of continuous miners and electric motors to mine and haul coal. As technology changed the method by which coal was mined and transported, the design of the typical Colorado room-and-pillar mine also changed. Depending on coal conditions, room size and shape often changed to better accommodate shovel or scraper loaders and shaker or belt loaders. These advances were not, however, adopted simultaneously by all coal mines. Although large corporate mines, like those of CF&I and the Union Pacific, began using such equipment before 1920, some of the smaller Colorado mines were still using hand augers and mules into the 1940's. Therefore, careful study of dates of mining, production records, mine maps, and interviews with former miners can aid in predicting current mine conditions.

INTRODUCTION

Subsidence has been a problem since underground coal mining began in Colorado in the 1860's. The camps that were established for the immigrant coal miners and their families at the mines were the only areas affected in those early days. However, some of these early camps have become urban or suburban areas, such as Colorado Springs, Louisville, Lafayette, and southern Jefferson County.

Although only skeletons remain of most of the underground mines in Colorado, the problems left by the coal industry remain. Although we cannot go into most of these abandoned mines, we still need answers to our many questions. Questions such as: How were coal mines designed? How was early coal mining carried out? What techniques were used to mine and haul coal?

HOW WERE COAL MINES DESIGNED?

The underground coal mining industry in Colorado utilized the same basic mine design throughout its 100-year history, due to the generally soft, gently dipping subbituminous coal found in the State. This method of mine layout is called the "room and pillar method", a design brought to the State in the 1860's by Welsh and English miners. The entrance to a room and pillar mine could be vertical, called a "shaft", or horizontal or sloping, generally referred to as a "slope" (downward from entrance) or "pitch" (upward from entrance).

At the bottom of the entrance shaft or slope would be the main passageway into the coal seam, generally called a main "entry", "haulageway", or "motor road" (when electric motors used for haulage of the coal). This entry was nearly always a "double entry", two parallel tunnels oriented such that fresh air was blown in one tunnel, circulated through the mine for ventilation, and exhausted through the second tunnel. The two halves of this double entry were separated by a chain pillar about 50 feet wide (Fig. 1). This pillar was interrupted by "cross-cuts", or connections between the haulageways about 60' apart. The sides of haulageway were supported by 50- to 100-foot wide flank pillars. At right angles to the main haulageway were a number of cross entries, called, for example, "3rd & 4th South", that were separated by 30-foot wide chain pillars. At right angles to the cross entries were the "rooms" or "entries", which averaged 18- to 20-feet wide and were separated by 20- to 30-foot wide pillars. The length of these rooms varied, depending on the location of the room in the mine and the period during which it was mined. When adjacent rooms were mined to their final length, the pillars between the rooms were mined, or "pulled" as the miners retreated from the room.

Steeply dipping coal seams, as in the Jefferson County Field near Golden and Grand Hogback Field near Newcastle where dips ranged from 30 to 90 degrees, presented special problems for supporting the overhanging roof. In these fields, the rooms were driven above the entries in technique called "battery-breast" mining (Fig. 2). A "battery" is a row of timbers that support the loose coal as it is being mined. A "breast" is the equivalent of a room in horizontal mining. In this mining method the miner stands on loose, previously mined coal as he drills and blasts the face above him. "Manways" were cut beside the breast to be used for entrance for the miners and the air. Coal was then loaded from chutes into cars,

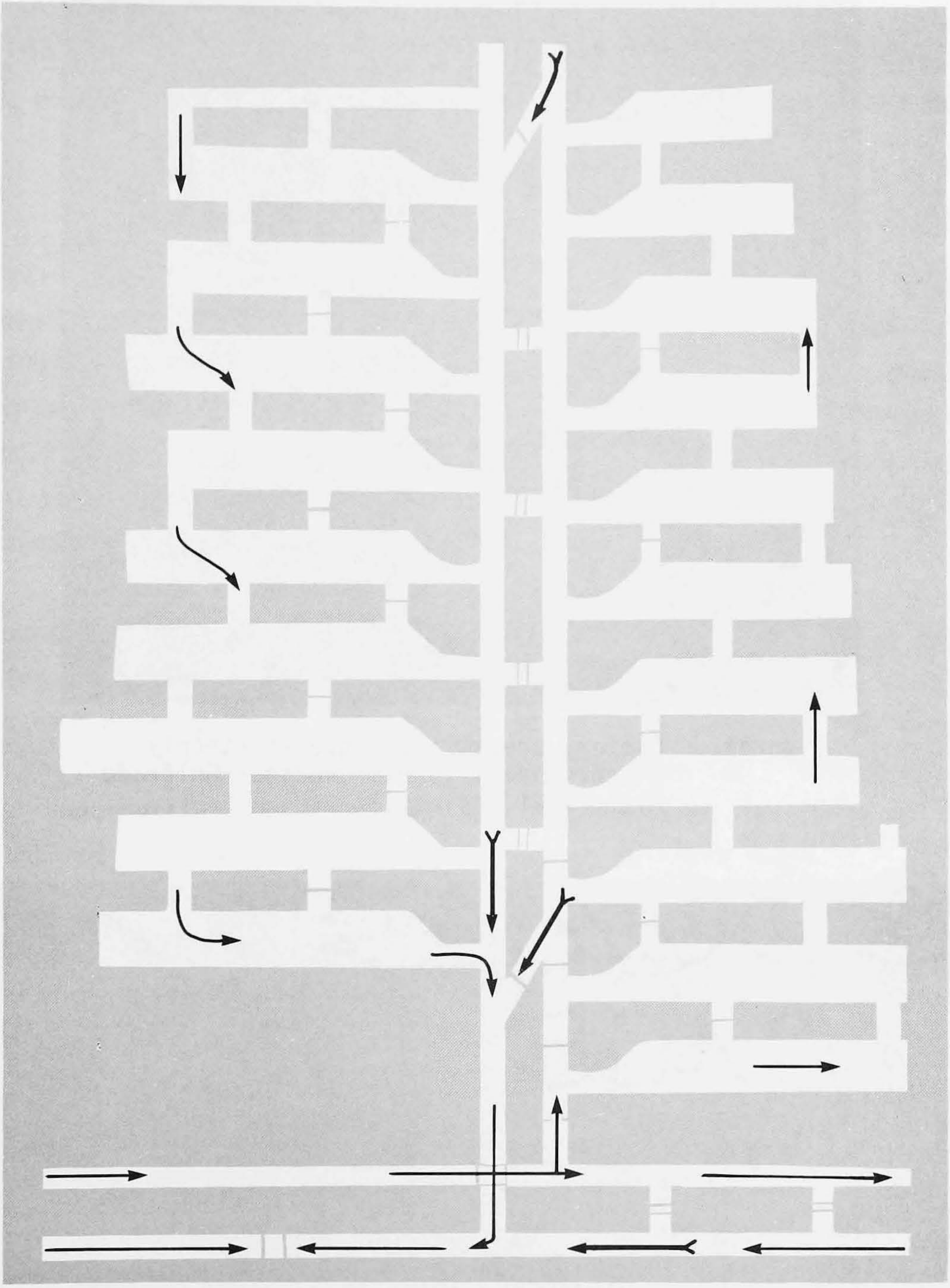

Figure 1. Typical room-and-pillar mine layout; arrows indicate ventilation scheme.

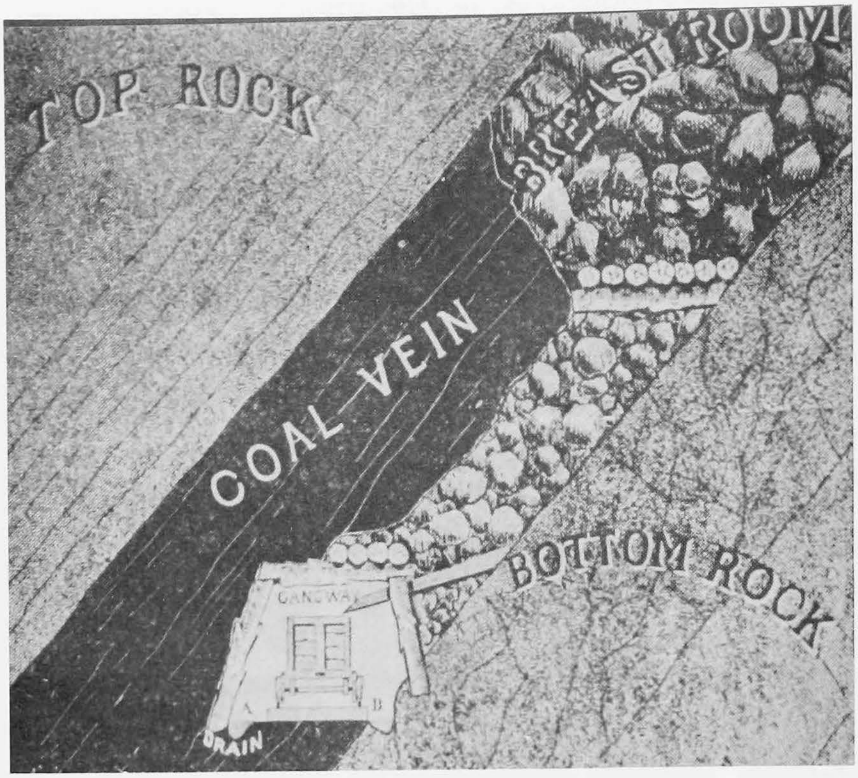

Figure 2. Battery-breast technique in steeply pitching seam (photo courtesy Colorado Historical Society.)

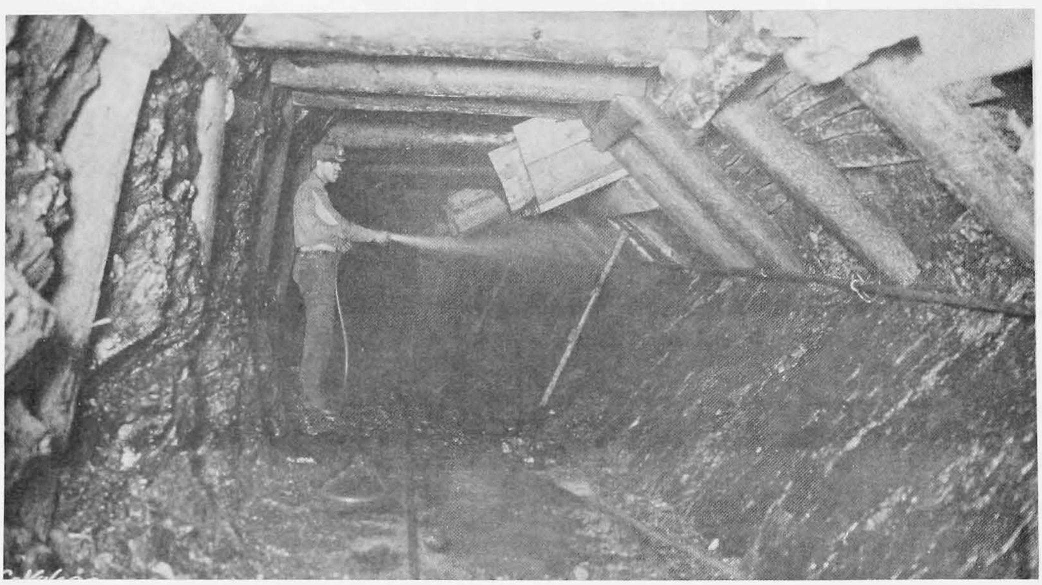

Figure 3. Coal chute into haulway in steeply pitching coal seam near New Castle (photo from Denver Public Library, Western History Department.)

as shown in Figure 3. In this photograph of the Garfield-Vulcan mine near Newcastle, notice the dip of seam and the differences in angles of the timbers.

HOW WAS ROOM AND PILLAR COAL MINED?

The earliest & simplest technique for mining coal in Colorado was "pick mining", as shown by the late 1800's miners at Starkville near Trinidad shown in Figure 4. The open-flame oil lamps and soft caps used by the miners in the photograph are indicative of the pre-1910 mining era. The demand at this time was for large lump coal with little waste and picking was most efficient way to create large lumps. The daily production rate for a two-man crew of pick miners was generally 8- to 10-1.5 ton cars, or about 12-15 tons per day.

As more uses for coal were found and smaller coal could be used efficiently, undercutting of the face and blasting came into general use. By sitting on the mine floor, or even lying on his side, a miner would undercut the face with his pick. He and his partner would load the valuable pick coal, then drill and blast the face. Undercutting the face was necessary because "shooting on the solid" weakened the roof rock and produced smaller, less valuable lumps.

About 1880, the first labor-saving coal mining machine was introduced in Colorado coal mines, the Ingersol punching machine. The puncher was a pneumatic (compressed air operated), three-pronged pick which cut an angled trench below the working face, as shown in Figure 5. The puncher allowed a 50% increase in production, which was very important at a time when miners were on contract and were paid by the number of tons of coal delivered at the tipple.

In 1900, the first "cutting machine", a large, electric, horizontal chainsaw, was introduced in Colorado by 2 manufacturers--Sullivan and Jeffrey. These machines were used to cut a 6-inch high kerf 6-feet deep behind the face. The face was then drilled and blasted. These machines revolutionized mining because production nearly doubled, increasing to 20-25 cars/day or as much as 40 tons/day per crew. The machines also created a mechanics job for the man running the machine, who was paid hourly instead of being paid by the ton. Cutting machines were still being used in smaller mines throughout the State until the decline of mining in the 1940's.

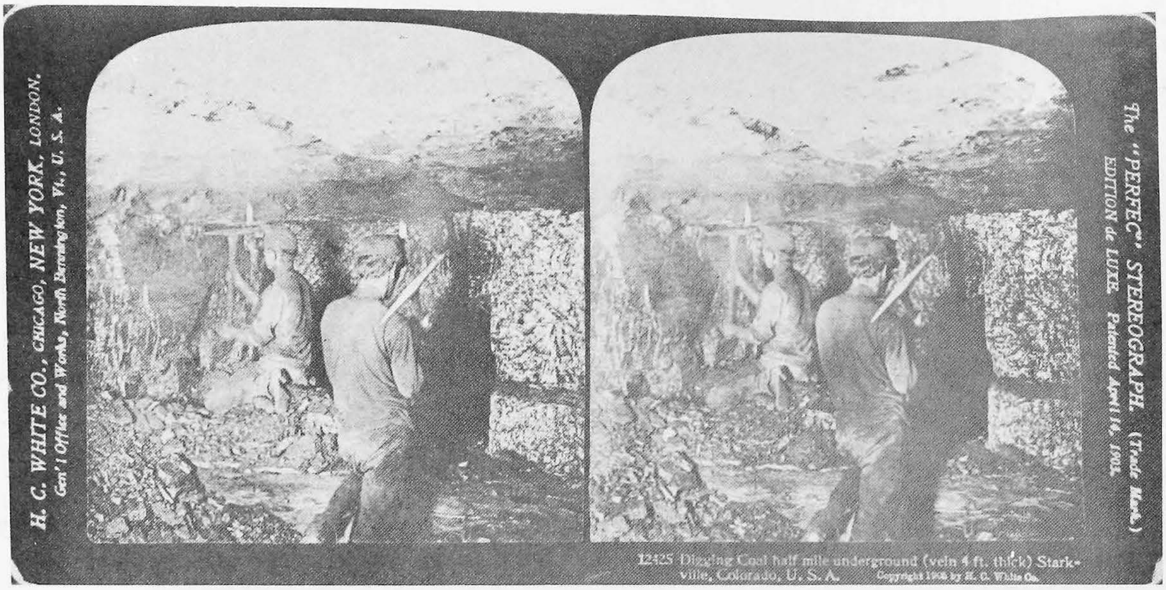

Figure 4. Stereoscopic photograph of pick mining at Starkville (photo courtesy Colorado Historical Society.)

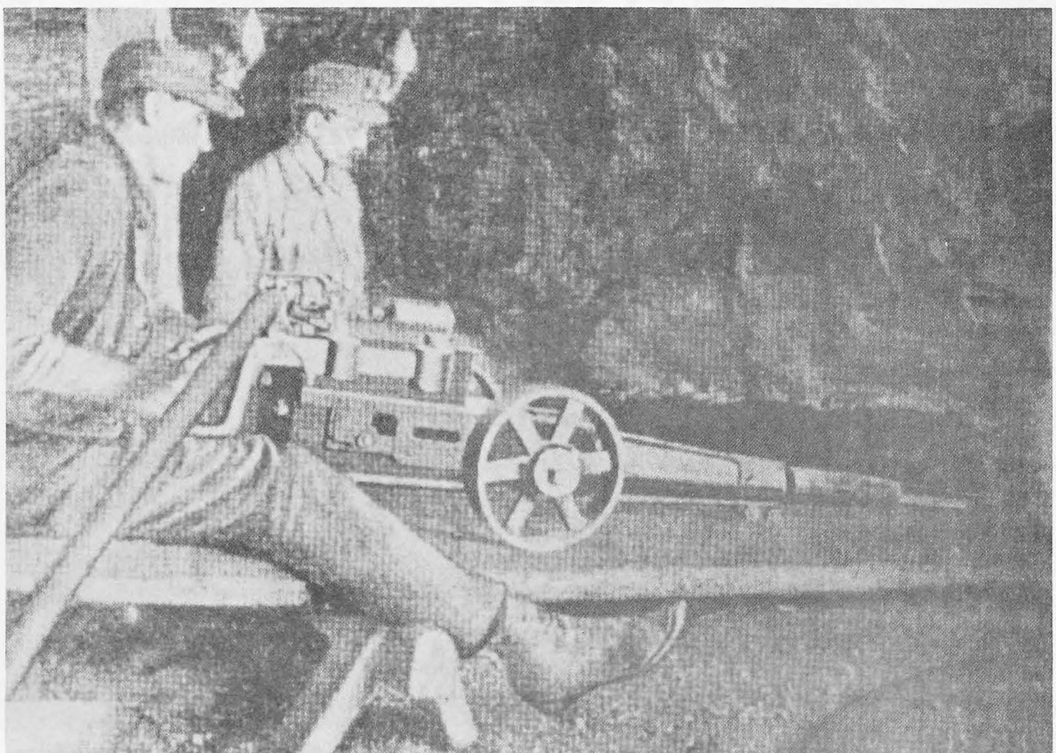

Figure 5. Ingersol pneumatic punching machine (photo courtesy Colorado Historical Society.)

HOW WAS COAL DRILLED AND BLASTED?

In the early days of Colorado coal mining, a "breast auger", a hand-held, hand-operated, 6- to 8-foot long drill, as shown in Figure 6, was used to drill shot holes. Black powder cartridges were then rolled by the miner and tamped into the shot holes with a wooden rod. The hole was then plugged with clay and a long, small diameter, copper (to prevent sparks) needle was inserted to open a hole into the cartridge. A "squib", a long bottle rocket, was then placed in the hole and lit with the miners open-flame head lamp. Later, mechanical augers were used to drill and Federally-approved explosives, electrically detonated by a professional shot firer, were used for blasting.

Roof support in mines often determined mine profitability--too much time and money spent on timbering could drive a mine into the red. Main haulageways were often timbered on 2- to 5-foot centers using "square sets", two posts supporting a heavy roof beam with a lagging of unpeeled wooden slabs, if more support were needed. Rooms were timbered initially by miners with "props and caps", a single heavy post with short horizontal cap at the top, as shown in Figure 7. These props might be every 5 feet initially, but be moved further apart if the roof were hard sandstone or closer together if the roof were weak shale. These props were generally pulled so that they could be reused, but might be cut or blasted if they were wedged too tightly to be pulled. Pulling timbers allowed for roof collapse when a room was completed, so that the roof strain on adjacent, unmined coal could be relieved. The pulled rooms generally collapsed in a few hours to several days, but some stayed open for months. If floor squeeze (heaving due to overloaded pillars) was a problem, the timbermen often sharpened the bottom of the posts or the timbers not pulled. If the roof was very weak, a cribbing of horizontal timbers filled with rock (Figure 8) was sometimes used, but was nearly impossible to pull.

HOW WAS COAL HAULED FROM ROOM TO SURFACE?

Coal was initially loaded with a #2 shovel, such as that shown behind in the miner in Figure 7. A mine car could hold 2500 to 3000 pounds when the lump coal was stacked around the edges and the center filled with smaller pieces. The primary method of hauling the full and empty cars from the rooms to the bottom of the shaft or slope was by mule (Fig. 9). Even into the 1940's, mules were still in

Figure 6. Typical breast auger (photo from Denver Public Library, Western History Department.)

Figure 7. Props-and-caps type roof support (photo from Denver Public Library, Western History Department.)

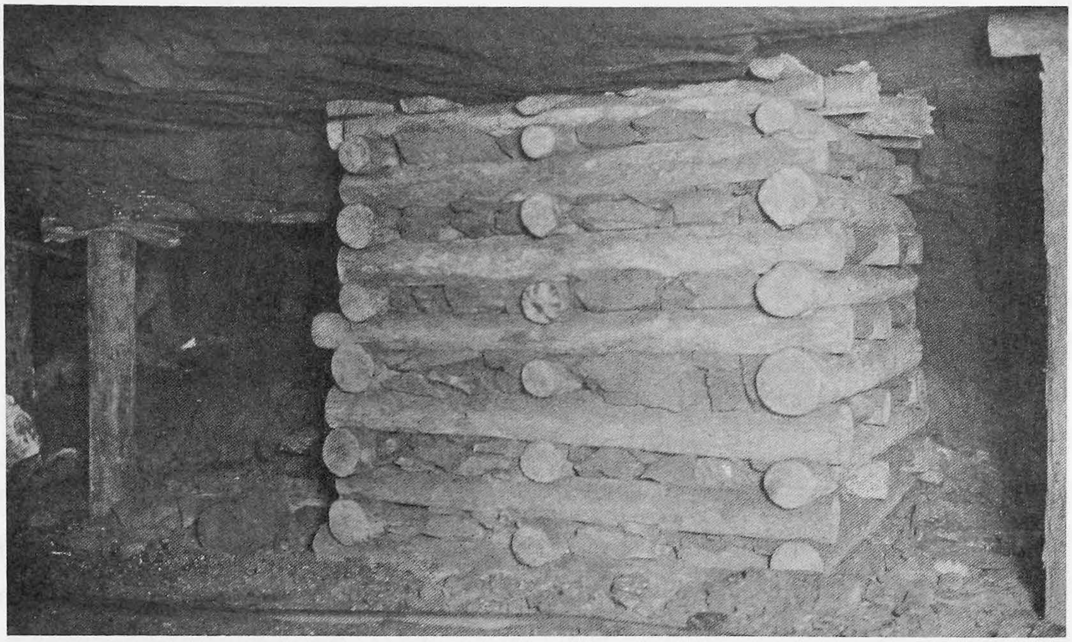

Figure 8. Rock filled cribbing supporting very weak roof (photo from Denver Public Library, Western History Department.)

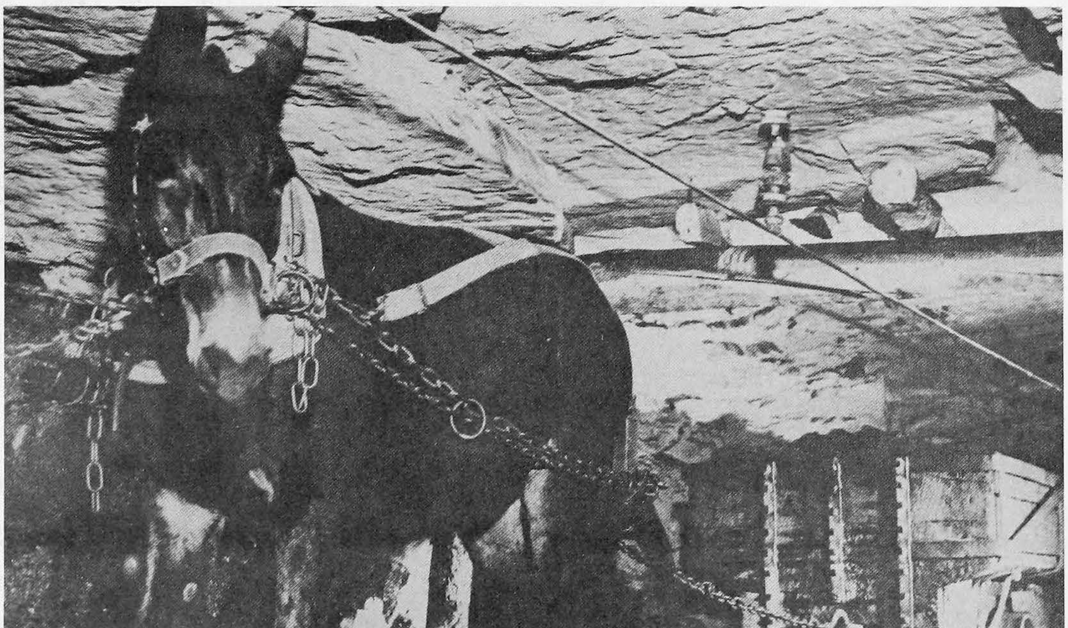

Figure 9. Mule hauling coal cars (photo courtesy Colorado Historical Society.)

use at some small mines in Colorado. A good mule could haul 6 or 7 loaded cars on level grades.

The first electric motors were invented in 1890, but were used only in large mines of the CF&I and Northern Colorado Coal companies until after the 1910-1915 strike. These "motors" were used to haul the loaded cars to the bottom of the shaft, where cars were raised by a hoist, or to the tipple of slope mines as shown near Trinidad in Figure 10.

The first mechanical loaders were used in Colorado during World War I due to the shortage of men to work the mines. The Joy loader, first used in 1919, later common throughout the Colorado coal fields, increased production about 50%. This was less than expected because loading was only part of the job of the miner. Loaders loaded coal directly into mine rail cars in some mines, but generally loaded into shuttle cars, "Buggies", which, in turn, loaded rail cars. Shuttles were generally battery operated, but some were cable-reel operated.

During the mid-1920's, conveyors were first introduced for hauling coal from rooms to rail cars. The first common type was the sectional shaker conveyor, called a "pan line" by miners, which could be moved in 6-foot long sections weighing 125 pounds. A major manufacturer was the Jeffrey Company, which built the pan line shown in Figure 11 in the Monarch #2 near Louisville. Combined with duckbill or Joy loaders, conveyors increased output per crew to 50 to 60 tons per day by the mid-1930's.

By the late 1930's, continuous mining machines with cutting heads, loaders, & conveyors built into one machine had been invented. Continuous miners were not generally used in Colorado until after World War II due to war production priorities. Because coal was being displaced by natural gas for domestic heating at the same time, only a few, large, generally new mines could afford them. Production rates with the continuous miner increased to 100 to 150 tons per day per crew, but the biggest advantage was the speed of mining. A room that had taken a month for pick miners could be done in one day, so little or no timbering was necessary. As shown in the photo of the Lincoln Mine near Frederick (Figure 12), the shape of the room could also add to roof stability, since an arch roof is stronger than a flat one. Rock bolts were also beginning to be used at this time in main haulageways and cross-entries.

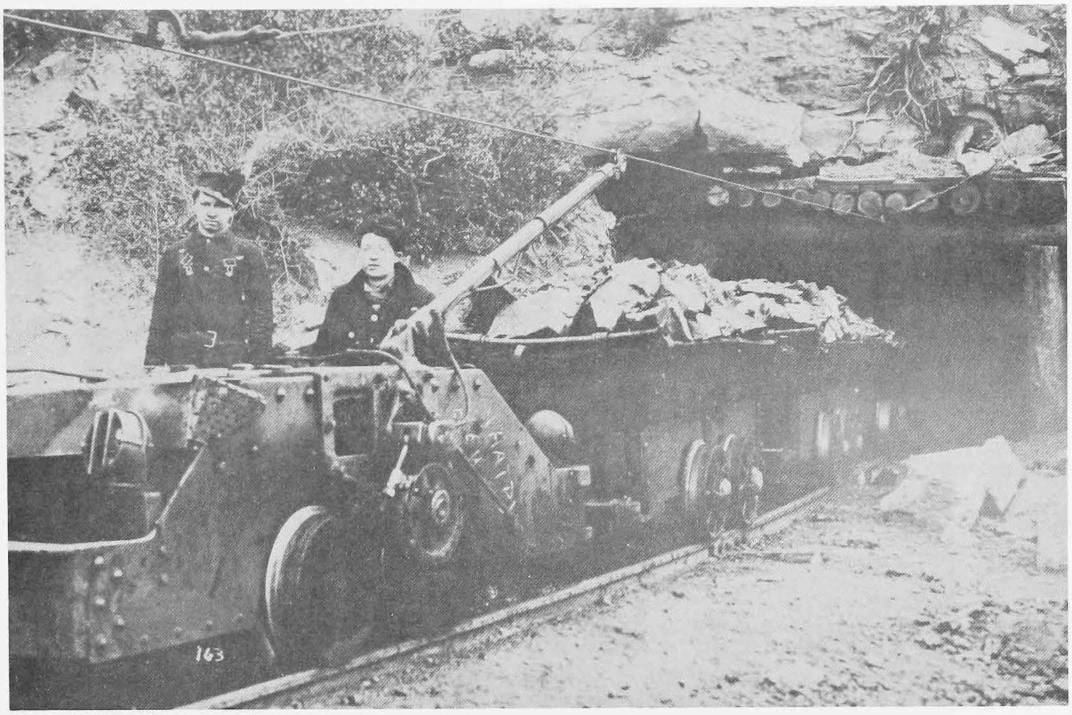

Figure 10. Electric haul motor (photo from Colorado Historical Society.)

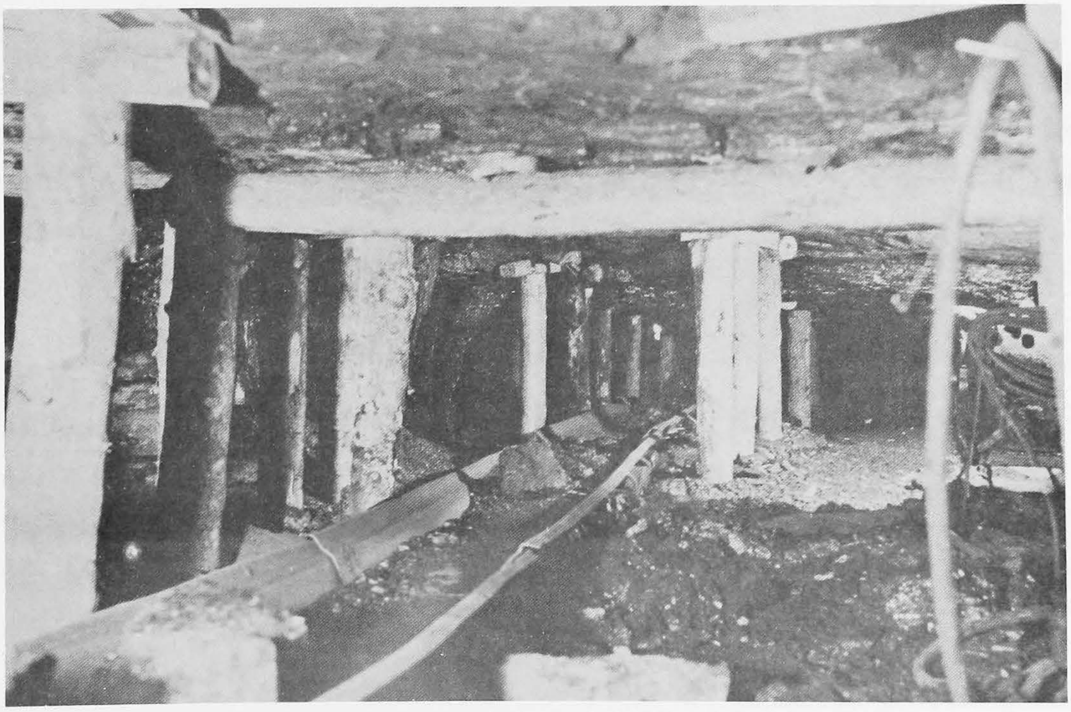

Figure 11. Coal conveyor (photo from Colorado Historical Society.)

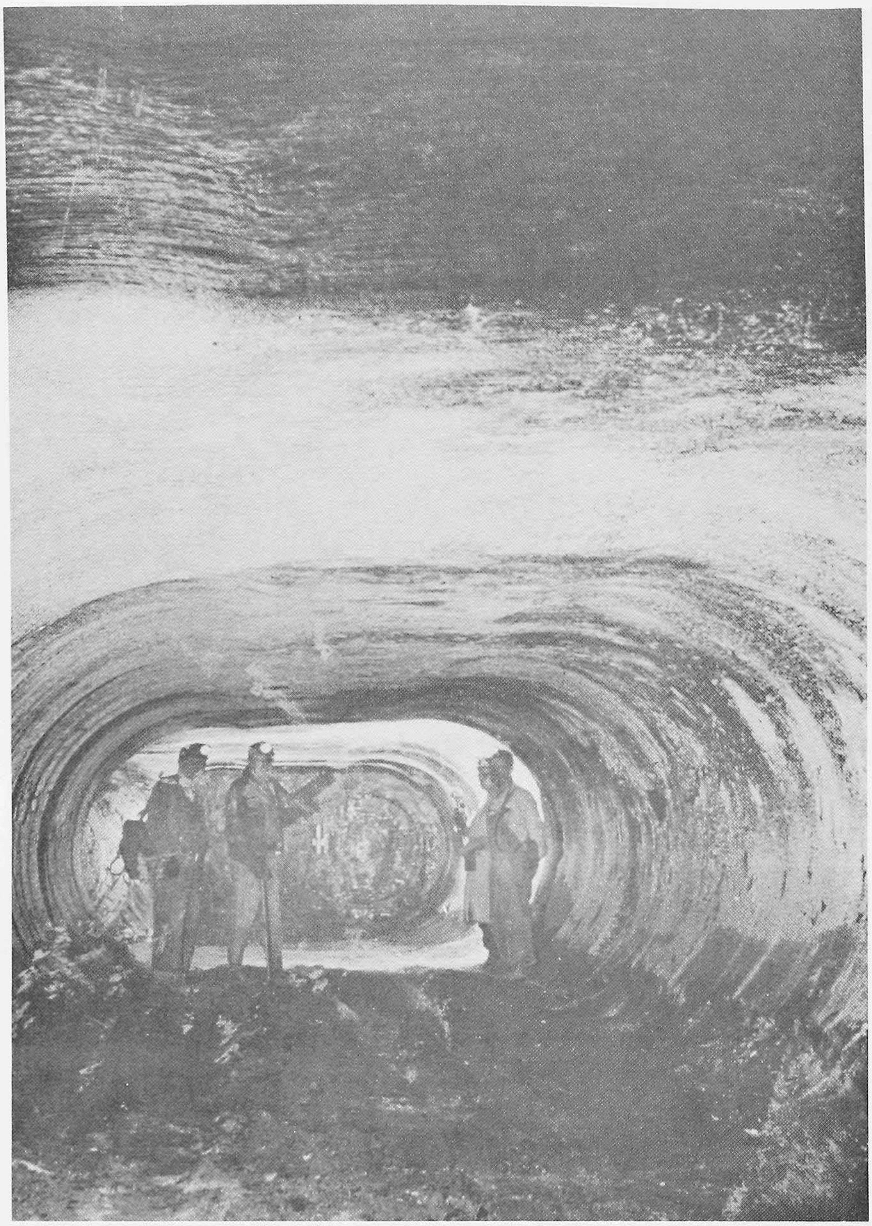

Figure 12. Room made by a continuous miner (photo from Denver Public Library, Western History Department.)

HOW FAST WAS COAL MINED?

Rooms varied in size with the era of the mining. In the days of pick coal and black powder, rooms were 50-feet wide, including pillars, by 100-feet long. At a 4-foot per day rate of advance and retreat, it took 2 men 2 months to lay track, timber, mine, and load one room. Therefore, the roof in one room had to remain stable for at least this period and heavy timbering was required.

With the coming of automatic loaders and conveyors, rooms became longer--up to 300 feet long due to the time and effort required to set up and take down the conveyor. Due to mechanization, however, these long rooms could be mined in the same period of time as the older, smaller rooms.

Continuous mining machines could create a 50- to 100-foot long room in one day. Therefore, rooms became shorter, but only had to remain open for a few days, not months.

SUMMARY

In conclusion, a knowledge of the period of mining and the techniques used in mining can aide in determining the potential for subsidence over abandoned mines that cannot be re-entered. This knowledge may be gained through the use of mine maps, historical documents, and interviews with miners.

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CHARACTERIZATION OF EXTENT OF MINING, MINE FIRE, AND SUBSIDENCE: A CASE STUDY AT MARSHALL, COLORADO

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ABSTRACT

We studied several of the underground, abandoned coal mines of the Boulder-Weld Coalfield that are located near Marshall, Colorado to characterize the possibility of subsidence and the hazard posed by those mines, including the few that are on fire. Our initial goals were to determine the extent of undermining and to understand the hazards posed by mine subsidence and mine fire only to the local study area. However, a subsequent objective became to define the specific techniques that were especially useful to our study, so that similar studies in the future could benefit from this information. We feel our results are applicable not only to other mines in the remainder of the Boulder-Weld Coalfield but to other coalfields, as well.

Mines in the study area contain possible subsidence hazards representative of mines located throughout the coalfield. Much subsidence already has occurred in this part of the coalfield, however our work shows abundant underground voids remaining, consequently there is a likelihood of additional ground collapse in the future. The area near Marshall is sparsely populated so subsidence threatens only a few dwellings and commercial buildings. Other parts of the coalfield, however, underlie entire towns, and in these cases the potential damage from subsidence is much greater. Subsidence in the Marshall area also threatens two major state highways, other county roads, irrigation ditches, and a high pressure, interstate gas line. Finally, subsidence may threaten the undermined dam to Marshall Lake, just east of the study area.

The Marshall area is the only part of the coalfield that presently has burning mines and these could present a local danger of fire and gas

explosions and of fire-exacerbated subsidence. Our results, however, suggest no urgent or substantial hazard from the mine fires, at present, and this may be the case in the future as well, as it is likely that much of the coal in the mines that could burn already has. However, the area should be monitored in the future for renewed fire activity.

The extent and type of possible subsidence varies throughout the area. Localized subsidence over individual mine rooms has occurred and likely will continue in the future, but it will be minor in lateral extent and amount of upward migration, due to bulking of the subsided rock. The mined coal seam in the Marshall area seldom exceeds 10 feet in thickness; assuming an average bulking coefficient of 0.1, the Marshall area mines deeper than about 100 feet should not cause any disturbance of the ground surface from subsidence over the mine rooms. The greatest local subsidence risk, posed by all mines in the area, will be the collapse of vertical or steeply inclined ventilation, haulageway, or entrance shafts, where the subsidence pits potentially could become large in diameter and depth. There is a possible localized subsidence threat to Highways 93 and 170 that should be determined by additional drilling. The other possible type of subsidence in the area could be regional caused by the regionally extensive undermining and the collapse of thin pillars of coal left in the mine to support overlying rock. Regional subsidence also has occurred and may occur again in the future, posing a hazard to utilities in the area, especially to the high pressure gas line. Finally, we note that due to unrecorded mining activity the undermined area, which is the area with potential subsidence problems, is larger than depicted on the mine maps.

The research methods that were most useful or helpful in our study were: drilling, borehole logging, geological/structural interpretation, and a tracer gas injection experiment. Our study also included background information provided by miners, a local historian, and old mine maps. The mine maps, while abundant, were old and of poor quality and could have been misleading if taken entirely as factual.

For other similar studies or further studies of the Marshall area we recommend the use of a borehole camera, which would be particularly helpful in characterizing the condition of the underground cavities and, thus, much about the extent to which subsidence may occur. Also of use would be the establishment of a well-surveyed grid of elevation control points used to monitor local and, especially, regional subsidence. At the Marshall area this would be particularly useful to help determine the continuing risk of regional subsidence to the high pressure gas line. Finally, overlapping, stereo-pair air photos of the area, which have the advantage of relatively low cost while providing widespread, detailed coverage, should be obtained every 4 or 5 years. The photo coverage permits monitoring of existing or newly developed local subsidence features, such as individual sinkholes or reopenings of the mine entrance.

Because of our extensive characterization of the area and the variety of interesting geologic hazard problems associated with subsidence and mine fires, we feel that the Marshall area is an excellent test site or demonstration site for new techniques, especially those that attempt to characterize the extent of mining or predict subsidence. The area also is useful as a calibration site for existing techniques.

INTRODUCTION

Purpose

We studied several of the abandoned coal mines near Marshall, Colorado, as a model for characterizing the study of abandoned coal mines and the associated problems of potential subsidence and mine fire. The coal mines examined in this investigation are a part of the Boulder-Weld Coalfield, which consists of approximately 130 abandoned mines in Boulder and Weld Counties in Colorado. The coalfield begins in Marshall, immediately southeast of the city of Boulder, Colorado, and extends slightly more than 20 miles to the northeast into the southwest portion of Weld County. Width is about 10 miles. Besides the community of Marshall, the coalfield underlies the towns of Superior, Lafayette, Louisville, Erie, Firestone, Frederick, and Dacono.

The scope of our study differs somewhat from other similar studies in the area, most of which focused on the entire coalfield. We restricted our study to a relatively small part of the coalfield, but examined this area in considerable detail using several techniques. We have concentrated on this small area because it contains the types of geological hazards that could occur throughout the remainder of the coalfield. Also, it is the only part of the coalfield that presently is on fire.

We have maintained a part-time study to investigate and monitor mines in the Marshall area during the past 5 years. We have concentrated our efforts towards understanding the extent of mining and threat posed by subsidence and fire in the abandoned mines specifically near Marshall. However, our dual intent in this paper is to document the results of those local investigations and, more importantly, to show how those results suggest useful approaches that can be used in other, similar investigations. We feel many of the techniques used in our study are applicable to other similar, undermined areas, thus we will both note those successful techniques and suggest others that we were unable to use but felt would have been useful to other studies of subsidence in undermined areas.

History of Mining

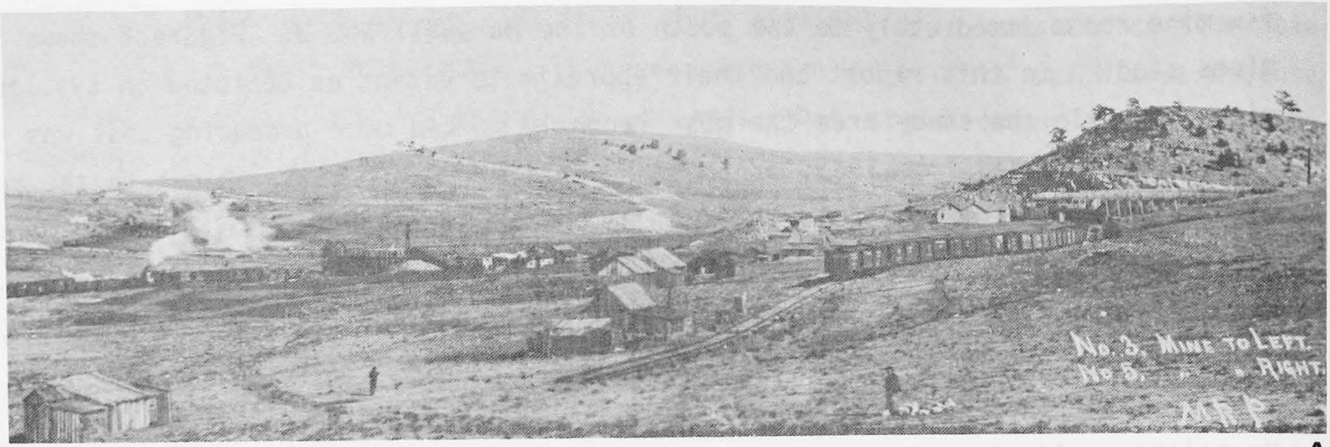
The first mines in the Boulder-Weld Coalfield opened in the 1860's. The initial market for the coal was for heating and steam power in Denver, but the coal became more important as a source of steam power generation for the developing precious metal mines in the Rocky Mountains. A few of the coal mines near Marshall that we studied, some shown in early operation in Figure 1, include the first mines worked in the Boulder-Weld Coalfield. Coal crops out in the Marshall area, hence Marshall became the discovery locality and site of original development in the coalfield. Subsequent development of the coalfield occurred rapidly over the next few decades towards the northeast, in which direction the coal seams generally deepen as a function of a regional, gentle eastward dip of the coalfield. Northeast-trending listric faults, dominantly with dip slip movement, break the coalfield into alternatively elevated and lowered blocks and, consequently, greatly limit the lateral extent of individual mines.

Mines studied in the Marshall area include: Marshall No. 1, which is the original mine in the coalfield; Marshall No. 3; Peerless, which subsequently was renamed the Lewis No. 2; and El Dorado, shown on mine maps as just a vertical shaft and few mine rooms immediately to the south of the Marshall No. 3. Figure 2 shows the mines studied in this report and their approximate extent as depicted on available mine maps. In the study area the most recently worked mine producing coal was the Lewis No. 2, worked from 1935, or possibly earlier, until 1945. Mines in the rest of the Boulder-Weld Coalfield, especially in the northeast portion, were worked until as recently as the late 1970's. Over its lifetime the coalfield has produced about 107 million tons of coal, 39% mined in Boulder County and the remainder from mines in Weld County (Kirkham and Ladwig, 1979).

Hart (this volume) summarized and discusses mining methods used in the Colorado coal mines. Basically, mining in the Marshall area was done principally using the room and pillar method, rather than other types of underground coal mining, such as longwall, commonly in use. Room and pillar mining leaves unmined, supporting pillars of coal between the mine rooms to hold up the roof rock. Whether these pillars have been pulled out at the end of mining is of great importance to the type of subsidence that may occur in the area.

Some of the history of the early mining operations has direct relevance to the present consideration of potential subsidence in the coalfield. Within the early mines much of the haulage power was furnished by donkeys, which were used to drag coal cars up long inclined haulageways, or adits, to the surface. The few vertical shafts that existed in these early mines were used mostly for ventilation. Later, as use of steam-powered hoists and winches became more common, vertical or steeply-inclined shafts were used more frequently for coal haulage. These vertical and long, inclined shafts have important consequences to possible future subsidence and are discussed further in a subsequent section of this report.

The history of the mining in the area has other direct importance to the study of subsidence. Mining began in a time when record keeping and mine mapping was not rigorously done. Consequently, only a few maps exist of the earliest mines and they are of limited quality. Locations and early surveys may not be accurate and data on depth-to-workings are seldom given. Also, the first half-century of operation of the mines coincided with periods of mine labor conflicts and strife throughout the nation. These occurred particularly during the early 1900's as well as during the great depression of the 1930's. In these times many small



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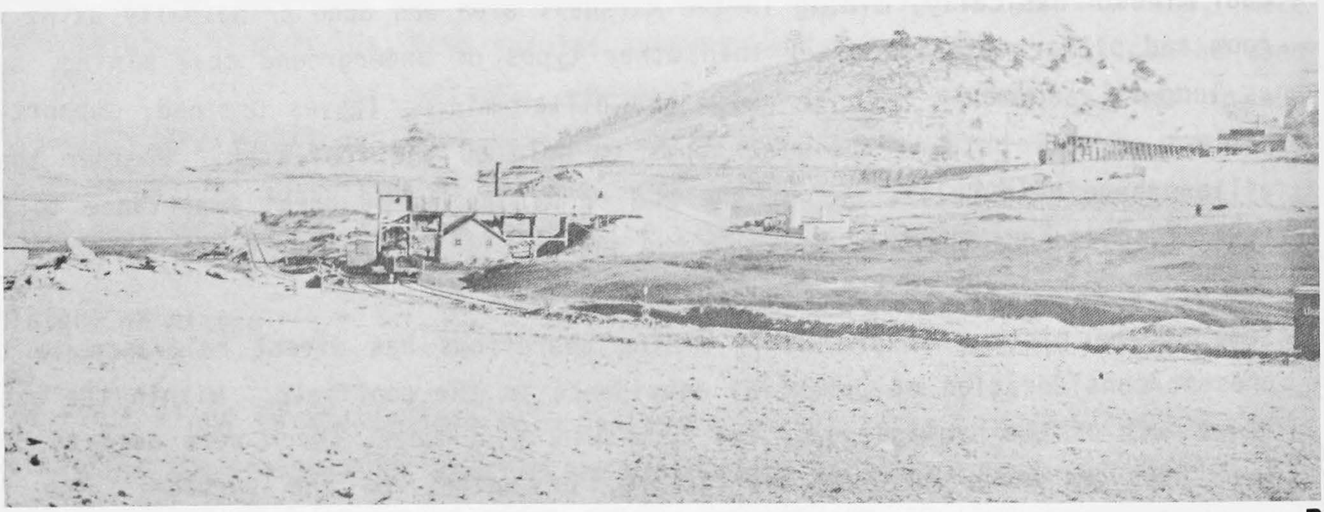


B

Figure 1. Pictures of the old mines in the area, circa 1900. The steam powered hoist of the Marshall No. 3 Mine, foreground of picture B, was located over the main adit, which was on the east side of the mine. A second hoist and elevated haulageway, for the Marshall No. 5 Mine, can be seen on the right side of both pictures. Coal was winched out of the mine then along the elevated runway and at the end of the runway, or tipple, was dumped into waiting railroad cars, below, for transport. The mound of rock appearing in the photo under the haulageway, excavated for the adit to the Marshall No. 3 Mine, still exists. The bunkhouse for the miners is at the foot of Pine Ridge near the right edge of photo A. There is almost complete absence of trees on Pine Ridge, which today is tree-covered, probably due to the trees being used for mine timbers. Old photos can be extremely useful--we needed a core through the mined seam from an unmined area and were able, using this old photo, to choose a drill site likely to be unmined, in this case the area underneath the tipple to the Marshall No. 3 Mine. The location was not undermined and we were able to recover a continuous core through the coal seam and its overburden and deeper rocks.

companies would start then quickly fail with little or no record of their mining activity. Also, independent or illegal mining occurred during these times of hardship, again with no record of activity. The implications of this bit of mining history towards understanding the extent of mining are that for several mines few or no records exist concerning the extent of mining or that when records and maps do exist they are conservative in showing the extent of workings. Because unrecorded mining commonly occurred after the most updated mine map, the records of activity and existing mine maps are only a minimum indicator of the extent of workings. This presents two problems. First, because the documented extent of workings is perhaps considerably smaller than actual extent, any study of subsidence threat to an area of mining requires a program to establish the actual limits of that mining, rather than simply using mine maps believed to be accurate. Second, depth-to-workings data is usually absent or of poor quality. Thus, it becomes difficult to predict subsidence in an area even with drilling information into subsidence cavities, because accurate depths to the original mine levels are unknown. Consequently, it is not possible to know the rate of migration of the collapse cavity. In order to properly establish the history of subsidence, it becomes imperative to use a research program that not only examines depths of present stopping below the ground surface but that also determines depths to original mine workings so that the ongoing record of subsidence can be determined.

Previous work

Several State, Federal, and private agencies have conducted previous studies of the Boulder-Weld Coalfield. Many of these studies either contain information useful to characterizing the extent of mining and subsidence or they specifically have been directed towards understanding the subsidence potential within the coalfield (Colton and Lowrie, 1973; Myers et al., 1975; Spencer, 1961; Kirkham, 1978; Kirkham and Ladwig, 1979; and Colorado Inactive Mine Program, 1982).

Previous studies of the geology and rock structure of the Marshall area are listed in the section on geology in this report.

In addition to the above-referenced sources of information, much additional material resides within various federal government agencies that have examined the

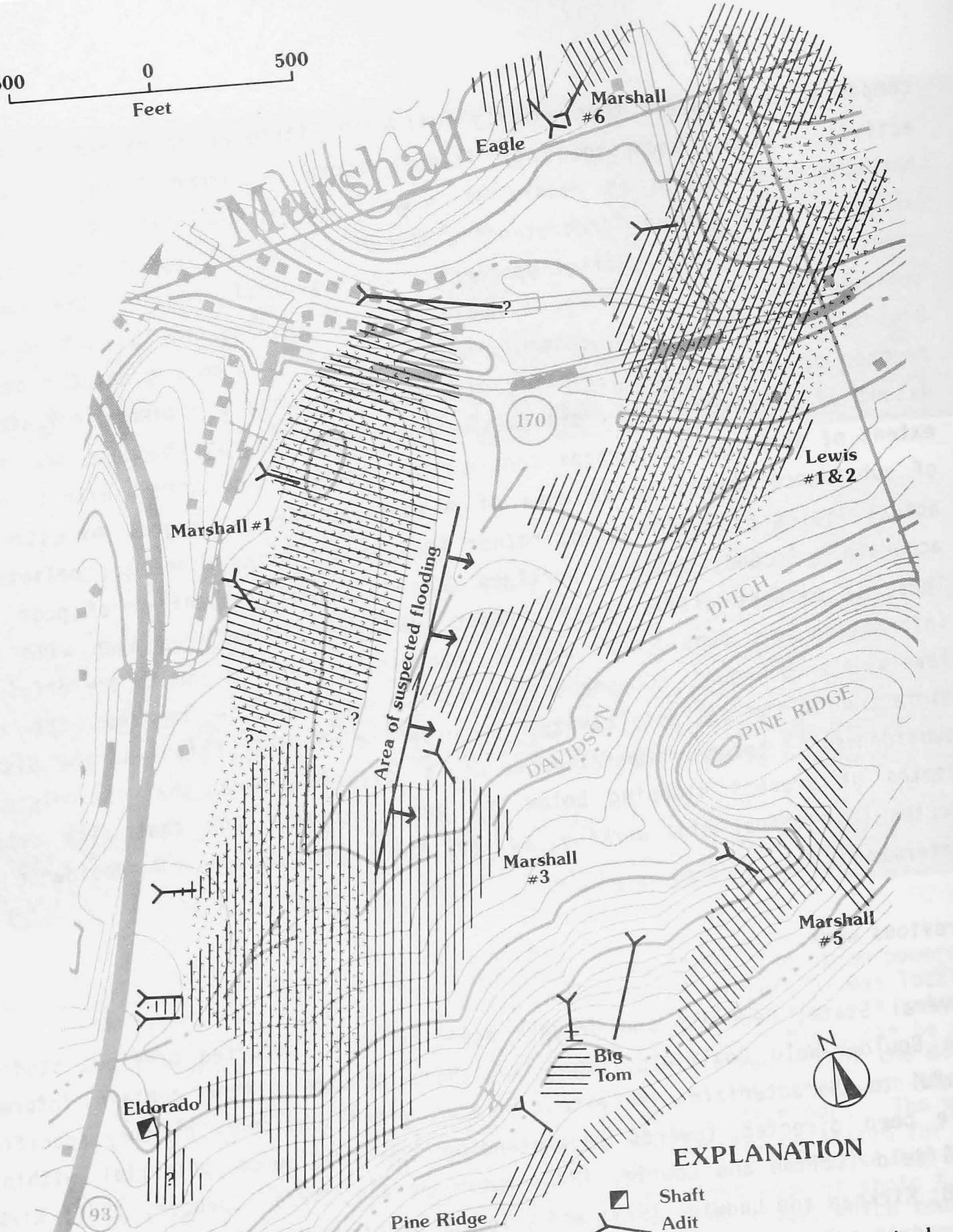


Figure 2. Index map of the mines studied in this project. Contour interval 10 feet; Source: U.S.G.S., Louisville Quadrangle., photo-revised 1974.

locality or used it as a test site for various investigatory studies. For example, the Environmental Protection Agency, at the request of the Office of Surface Mining, mapped the area in early 1982 using thermal infrared imaging overflights to look for thermal signatures from the burning coal mines. Their study includes both in color and black and white air photos, as well as thermal infrared.

The Marshall area coal mines have been the subject of considerable study from the Colorado School of Mines, particularly from students and faculty of the Geophysics Department. Thesis studies, many student projects, and laboratory classes in geophysical techniques have been conducted in the area.

Nature and History of Subsidence

Subsidence has been an ongoing occurrence in the coalfield. In the case of some of the very shallow coal mines it is likely that subsidence reached ground surface within a few years of the end of mining, whereas other parts of the coalfield containing deeper mines have subsided a few or several decades after mining ceased. Throughout the coalfield, subsidence cavities periodically have opened up at the ground surface or buried shafts have caved into the mine workings leaving deep or large-diameter openings in the ground. Subsidence damage to property and structures overlying the coalfield, as documented in Myers, et al., (1975), has so far been minor, but the extensive size of the coalfield and the existing or proposed development over it leaves many people and an immense amount of property and structure at risk. For example, much of the town of Louisville as well as parts of the towns of Superior, Dacono, and Frederick are underlain by various mines of the coalfield. Other cultural structures besides towns, such as highways and reservoirs, also may be at risk. In particular, old mine maps show the northern portion of the nearby Marshall Lake Dam to be undermined by the extensive Gorham Mine, consequently there is risk of subsidence leading to failure of the dam or of hydraulic breaching of the dam through the mine workings.

In the Marshall area only a few buildings and businesses are located over mine workings and potentially threatened by subsidence. However, the threat of subsidence in the area is not restricted to buildings. For example, there is a clear potential subsidence risk to two State highways and a county road. Two major irrigation ditches also cross the mine workings in this area and have in the past been affected by ground collapse. A major high pressure gas line crosses over the workings of the Marshall No. 3 Mine in places where ongoing subsidence has been noted along with baked rock due to fire in the mine.

Much of the area around Marshall is not commercially developed and thus, subsidence might seem not to be much of a future problem. Part of the reason for this lack of development in the area is that the extent of underground mining is known or suspected and much of the area consequently is zoned as hazardous and development is restricted. Thus, even the potential for subsidence has become an obstacle in restricting development of what otherwise would become prime buildable land close to the city of Boulder. Much of this undermined area at Marshall has been deeded to the city or county as public park land and this conservative approach of non-use other than park seems to be the most practical use of the land at present, unless explicit definition of the possibility of ground collapse can be determined in the future.

Fires in the coal mines in the Marshall area have been common since at least 1930's and, perhaps, much earlier. Much of the Lewis No. 2 Mine has burned and, according to retired miners, this mine was finally forced to close from the problems created by the fire. Evidence of the past fires can be seen where overlying rock, coal spoil piles, or coal dumps have been baked to a red, hard consistency, known as clinker, by the heat. This baking of the overburden rock is especially common and visible over the western portion of the workings of the Marshall No. 1 and No. 3 mines, as well as overlying the Lewis No. 2 east of Cherryvale Road. In the past few decades various eyewitnesses and long-term residents have documented temperatures as high as 1100°C near the ground surface and explosions of methane gas with plumes of fire soaring tens of meters into the atmosphere. Past intense fires in the Lewis No. 2 Mine, when they have been close to Cherryvale Road, have melted the asphalt pavement. Fire has plagued other parts of the coalfield, as well. Some of these instances have been tabulated by Kirkham and Ladwig (1979). The Marshall area, however, has a greater incidence of mine fire because most of the mines in the area are shallow and subsidence has facilitated the access of fire-supporting oxygen from the air.

Fire imposes a greater incidence and extent of subsidence over coal mines than if the mines were not burning. This occurs because the supporting pillars of coal in the mines burn and leave an unsupported roof, which then collapses into the mine workings. Examples of this type of fire-exacerbated subsidence have been discussed by Dunrud and Osterwald (1980) for burning coal mines near Sheridan, Wyoming.

Resources of Background Information on the Marshall Area

In the course of our study we used several resources, not all of which may be available for study of other mines in the coalfield or in other coalfields. Our principal information resources for background research were several air photo collections, numerous mine maps, and interviews with miners who had worked in or at least visited the mines of interest.

An air photo collection maintained by the U.S. Geological Survey has been used to examine the area for history of subsidence. The record of air photos extends from the 1930's until 1983. Other government agencies, such as the Environmental Protection Agency and the Department of Agriculture, have obtained air photo coverage of the area and should be contacted in any subsequent study of this area or of other coalfields. Unfortunately, few of the air photos are of suitable photogrammetric quality for basemap preparation that would provide the elevation control to monitor future subsidence. However, the principal advantage of this time-extensive air photo coverage is that it provides a history of local subsidence. For example, using stereo pair air photos, we determined that the backfilled shaft to the El Dorado mine subsided sometime between 1976 and 1980 when the shaft again opened at least 30 feet down into the mine workings. This shaft was backfilled again in 1981 and subsequently was used as the injection site for our tracer gases experiment. Finally, we note that several of the photo collections include photos taken in the early morning, which provides the greatest air clarity and, more importantly, the low sun angle necessary to show subtle features of ground surface disruption. We recommend a similar approach for subsequent studies.

We found the use of eyewitness accounts of the size and extent of the underground mines to be extremely useful and suggest that any similar studies attempt to use this information resource, although there can be limitations to this type of resource. Miners are not usually familiar with the local or regional geology or geological behavior of rocks and can be a source of confusion in understanding underground structure, especially faulting and multiple coal bed correlation across faulted blocks. However, miners who worked in or visited the mines of interest often have accurate recollection of the nature and extent of the underground workings. The best use of this resource is to have the miners compare their knowledge of the extent of underground workings with that shown on available mine maps. Additional information, such as whether the pillars were removed, mining extended beyond the edge of the mine map, or interconnection of adjacent mines, is invaluable in understanding the potential for and degree of subsidence that might occur over the mines. In our study a particular example of the usefulness of eyewitnesses was that we were able to obtain information about the connection between the eastern part of the Marshall No. 1 and the Lewis No. 2 Mines at a common point south of Highway 170. This information was extremely helpful in understanding the geological structure of the Laramie Formation in the area. Specifically this information helped resolve our structural interpretation that both the Lewis No. 2 and Marshall No. 6 Mines, even though separated by approximately 100 feet vertically in the northern part of the study area, were in the same coal seam, as there was a common point to the south. Consequently, the Fox Fault, which is included on most geological maps of the area, is of hinge type, with little, if any, apparent vertical displacement throughout the Marshall No. 3 mine workings and increasing vertical uplift of the east side of the fault relative to the west in the northern part of the study area.

Another advantageous use of eyewitnesses is interviewing long-term residents in an area to document the history of subsidence. In our study some of the long-term residents provided useful historical information about the dates and extent of subsidence as well as useful information about the activity of the mine fires.

RESULTS

Extent of Mining

We determined that the extent of mining as shown on mine maps is indeed conservative, compared to what actually has been mined. In particular, the area south of the El Dorado shaft, based on drilling and tracer gas results, appears to have been extensively mined, but is not shown as mined on any of the mine maps that we obtained. Also, the area east of the original mine in the area, Marshall No. 1, clearly has been mined out as far east as the western limit of the Lewis No. 2 Mine.

The techniques that were particularly useful in our determinations of areas of additional undermining were drilling and the tracer gas injection experiments. Finally, the geological analysis of the area was helpful in defining areas with minable coal in which we could concentrate our search efforts to determine extent of mining and could exclude areas where, clearly, there was no coal, hence no need to search for evidence of coal mining.

Subsidence

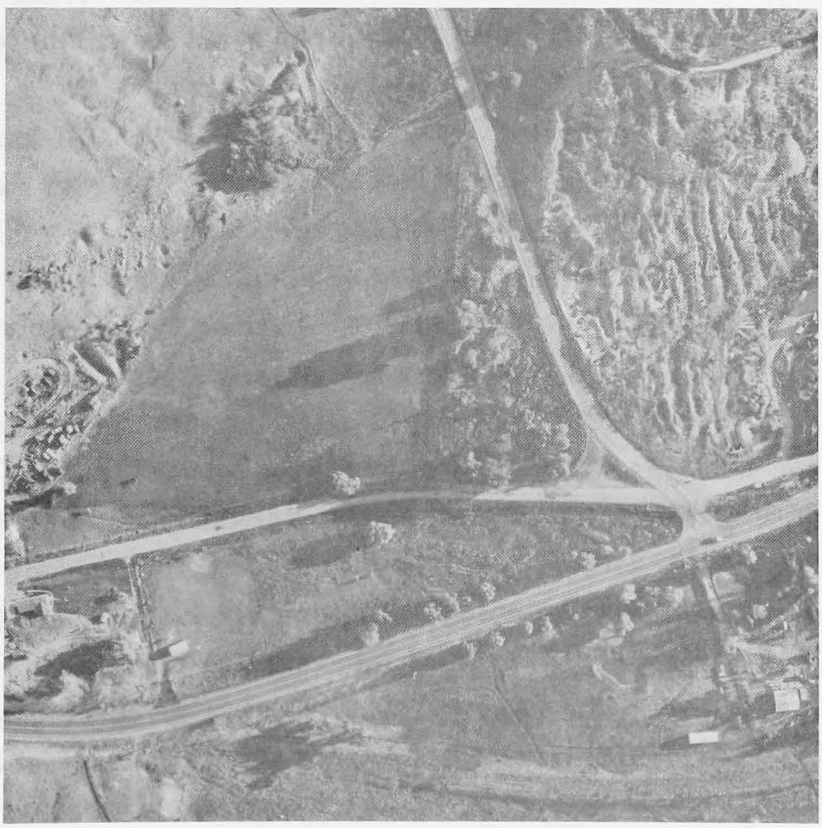
Much of the documented subsidence in the Marshall area appears to be of a local nature. There is, for example, the well developed collapse overlying the Lewis No. 2 Mine, shown in the air photo in Figure 3, where the subsidence on the overlying ground precisely corresponds with the layout of the mine rooms shown on the mine map. Evidence of local subsidence overlying the Marshall No. 1 Mine can also easily be detected from the air photo and seen on the ground. However, there is the possibility of regional subsidence in the area, as well. Regional subsidence is here defined as any collapse more laterally widespread than stopping of rock directly overlying each individual room of the mine. It therefore includes the rock either overlying several mine rooms or overlying the entire mine collapsing as a unit. Rate of subsidence is immaterial and the regional failure could have been slow or sudden.

Regional subsidence would be more likely to occur where a single mine is laterally extensive or where many smaller mines exist adjacently. Regional-type of subsidence also is more likely than local if the pillars in the mine have been removed or pulled at the end of mining or if only a few coal pillars or wood cribbing pillars were left in place as roof supports and these have collapsed gradually from the weight of the overlying rock. We are suspicious that the area overlying the Marshall No. 3 Mine may have undergone such regional subsidence, especially on the western side of the mine. This idea is based on reports from eyewitnesses or long term residents of the area who remember areas of the ground surface over the mine as being at higher elevation by about 5 to 10 feet, the

A

Figure 3. Local subsidence over mines in the Marshall area. The air photos were taken in 1980; figure A is a high sun angle mid-day panorama. The bottom two photos show areas in greater detail and were taken in early morning at low sun angle. The subsidence features, in shadow on the photo, correspond precisely to the rooms of the Lewis Mine as shown on the available mine maps.

B



C

thickness of mining here, relative to adjacent land than they are at present. However, without any elevation control grid and periodically checked benchmarks it is not possible to know for certain or to what extent this has occurred.

Regional collapse of the ground poses problems different from those of local subsidence. Among the problems presented with regional types of ground collapse are those created by extreme tensional forces at the edges of the area of regional collapse. Structures in the middle of regional collapse may remain relatively unaffected, while those at the margins of the regional collapse are affected greatly. Thus, an example of a problem caused by regional rather than local subsidence would be a rupture threat to the high pressure gas line that overlies the subsiding mines in the area. While the pipeline may have the sufficient bridge strength necessary for unsupported suspension across local collapse craters, it may not be able to survive the extreme tensional forces transmitted to the pipeline at the boundaries of a collapsed region.

The extent of subsidence above a mine room is largely controlled by the bulking, the volume increase of rock after it subsides. Subsided volume of the rock is always greater than the original, in-place volume prior to collapse. Thus, a void becomes more filled by the volume of rock that collapses into it than the volume occupied by that rock prior to collapse. Consequently, collapse progressively fills the original volume of a void and meanwhile the void "migrates" progressively upward as stopping rock falls to the floor of the cavity but leaves new void volume at the top of the cavity. When the void is filled no further collapse is possible. Higher coefficients of bulking, the ratio of the volume after collapse to the uncollapsed rock, mean that the collapsed rock will more quickly fill a void. Bulking coefficients in turn are dependent primarily on lithology and secondarily on moisture content, jointing in the rock, and conditions in the mine where collapse occurs. In the case of the rocks in the Marshall area we made no direct measurements of bulking coefficients, however, based on our core recovery and lithologic logs we know that the lithology of the area is mixed and varies rapidly over short vertical and horizontal distances. Therefore, it becomes important for any studies of the bulking coefficients of rocks in the area to characterize each distinct lithologic type as well as the combinations of lithologies, rather than attempting to characterize the entire area with a few measurements on so-called bulk rock. Also, most rock and especially sandstone in the Marshall area is highly jointed, with the predominant joint direction usually paralleling strike of the rock. These jointed rocks have higher bulking coefficients and, hence, greater consequent volume after collapse than if they were unjointed. Of final note is that much of the underground mine workings in the area are water-filled at present. Thus, any swelling clay minerals present will produce larger than normal bulking of the collapsed rock than if the rock collapsed into a dry cavity. Alternatively, water can act to reduce the apparent collapse volume of the rock by facilitating its disaggregation then lubricating subsequent gravitational flow and removal of the debris downhill if the mine workings are sufficiently inclined. Any further study of subsidence in the area must consider all of these elements in attempting to understand how and to what extent the rock collapses.

Overburden thickness over the mine becomes important to the possibility of subsidence reaching the ground surface. The distance of vertical movement of the subsidence cavity can be calculated by dividing the original mined thickness by the ratio between the difference of the final and original rock volumes divided by the rock volume before bulking as,

$$D = T \; / \; [V_f - V_i)/V_i], \qquad \text{(Equation 1)}$$

where D is the vertical distance above mining over which subsidence will occur, T is the thickness of mining, and V_f and V_i are the final and initial volumes of the same rock mass before and after subsidence, respectively. The ratio $(V_f - V_i) \; / \; V_i$ is the bulking coefficient. This assumes reasonably flat-lying coal seams, which is the case in the Marshall area, but not in all remaining parts of the Boulder-Weld Coalfield. At Marshall a typical thickness of coal mining is approximately 6 feet. If we assume a bulking coefficient of 0.15, or a 15% increase in volume of the subsided to the original rock, then the maximum vertical migration of the subsidence cavity above mining will be 40 feet.

Conventional models of subsidence also note that cavity migration can have a lateral component as well as vertical. This is an important consideration for estimate of hazard to structures located near to but just off the extent of undermining. The lateral extent of cavity migration is determined by the angle of draw, or departure from vertical, through which the rock can fail. Usually this angle is reasonably constant. Thus, deeper mines can produce effects farther away from the vertically projected extent of workings than can shallower mines. Note that this concept underscores the importance of knowing depth-to-workings data, which in the Marshall area are difficult to obtain.

These simplistic models of subsidence work satisfactorily above the mine rooms in this area, but the model breaks down over vertical or inclined shafts to the mines. This subsidence of overlying ground into vertical or steeply dipping shafts of the abandoned mines appears to be one of the more serious threats of ground collapse in the Marshall area. Over a mine room stopping of rock collapsing into the cavity progressively fills the cavity due to bulking and continual collapse of the overlying rock and, if the overburdened thickness is sufficient, subsidence may terminate prior to the cavity reaching the ground surface. In a vertical shaft, or even a long, gently-inclined shaft or adit, it is possible for the slumped rock to move gravitationally downward further into the workings of the mine after collapse, thus allowing room for additional material to subside. In this case the collapse cavity can continue to grow larger rather than progressively decreasing in size. Consequently, the opening over a vertical or inclined shaft can migrate to the ground surface even in relatively thick overburden cover and the resultant opening at the ground surface can be huge. The same problem also can occur over the rooms of the mine when the mine is in a steeply dipping coal seam. Here, stopped material that collapses into the mine room has the possibility of further removal downdip, which allows room for additional stopping from above and into the room. This type of collapse is a violation of the approximate rule that the maximum surface subsidence can be no greater than the thickness of the mined coal bed, mentioned, for example, by Myers et al. (1975). It appears that this type of subsidence over vertical or steeply inclined shafts offers the greatest collapse hazard in the Marshall area.

A final point of discussion of subsidence is multiple seam mining at a single locality. This introduces additional complexities into the consideration of potential subsidence. All mines in the Marshall area are single seam mines, but multiple seam mining in the coalfield does occur, particularly in some mines nearby and underlying the towns of Louisville and Lafayette.

Extent of Burning and Fire

In the past much of the mined-out area at Marshall has burned. Fires in the area have been noted by eyewitnesses since the 1930's and may have occurred prior to this time, as well. Origin of the fires is due either to spontaneous combustion of coal in the mines or to accidental or intentional ignition by coal miners. The areas of past mine fire can be determined by the residual magnetic signatures left from the heated, but now cooled, rocks. A study of the heating using remanent magnetic techniques has been conducted recently by the Colorado School of Mines. The map of the area in Figure 2 shows areas previously known or thought to have been on fire. Presently, activity from the fire is minimal. In 1982, a smoldering area south of the liquor store and overlying the westernmost portion of the Marshall No. 3 Mine was covered with a thickness of 2 feet of fill dirt to smother the fire as part of a reclamation program of the area conducted by the Office of Surface Mining. Residual heat still occurs in the area as indicated by drill hole temperature measurements, by snowmelt patterns, and by geophysical studies conducted by the Colorado School of Mines.

Other effects of the mine fires can be seen, for example, where fire-related subsidence over the workings of the Lewis No. 2 Mine, just east of Cherryvale Road, has undermined the Davidson Ditch and allowed the ditch water to flow into the mine. The ditch previously had been lined with concrete and steel flume sections, but these had failed along with the ground underlying the ditch. In early 1986 the Abandoned Mined Land Reclamation Division of the Colorado Department of Natural Resources began a novel reclamation project on this section of the ditch, using money provided by the U.S. Office of Surface Mining. The reclamation effort involves lining the ditch with reinforced concrete that is bolted to the underlying rock into backfilled holes. The intent is that collapse will move off to the sides of the ditch while the strength of the lined ditch holds the immediately underlying rock together. During excavation beneath this portion of the ditch additional voids, roughly the size of a car, were discovered underground. Also, the workings in a few local areas were still smoldering. Depth to workings was estimated as shallow as 20 feet but could have been deeper, up to 70 feet, in places.

We feel that to date much of the combustion that could occur in the Marshall area mines already has occurred. However, this area still should be monitored periodically in the future for additional incidence of mine fire, particularly since this burning could greatly accelerate subsidence by removing any remaining supportive coal pillars. Finally, the subsidence in this area mostly is local, but removal of the remaining supporting coal pillars through combustion also would allow further subsidence to become more regional than local.

Geology

Any attempt to understand the potential of a mined-out area to subside requires an understanding of the geology, specifically the stratigraphy and structure, of the area. This becomes most important when, as in our case at Marshall, few depth to workings data exist and there is considerable suspicion that unrecorded mines may have been developed in areas not shown as mined on the mine maps. In this latter case an understanding of where minable coal can occur helps to resolve the need for an exploratory drilling conducted in areas nearby to those mined to search for unrecorded mining.

Stratigraphy

The Fox Hills sandstone and the overlying Laramie Formation, both Late Cretaceous, are the only formations that crop out in the study area. Late Cretaceous Pierre Shale underlies the Fox Hills Sandstone and is exposed immediately to the west of the study area (see Figure 4).

The Pierre Shale is a thick marine unit consisting of lead gray to brown and black shale that weathers to olive gray and brown. Its thickness is estimated to be in excess of 8000 ft. in the Marshall area (Spencer, 1961). The contact with the overlying Fox Hills Sandstone is transitional with thin-bedded sandstones and silty to sandy shales occurring in the upper part of the Pierre Shale. Two drill holes, PR-1 and T-4 (see Figure 5), penetrated a short section of the upper Pierre Shale and in both drill holes, the contact with the Fox Hills Sandstone was exhibited in drill cuttings by an upward coarsening sequence that begins with a medium-dark-gray silty shale, passing upwards through an interval of light-gray siltstone and sandy shale, and finally into a light-gray, fine-grained sandstone. This uppermost 20 feet of the Pierre Shale is more distinctive and identifiable in drill cuttings or core than it is on geophysical logs, where, because of the transitional, sandy nature, the change in lithology is subtle and difficult to detect.

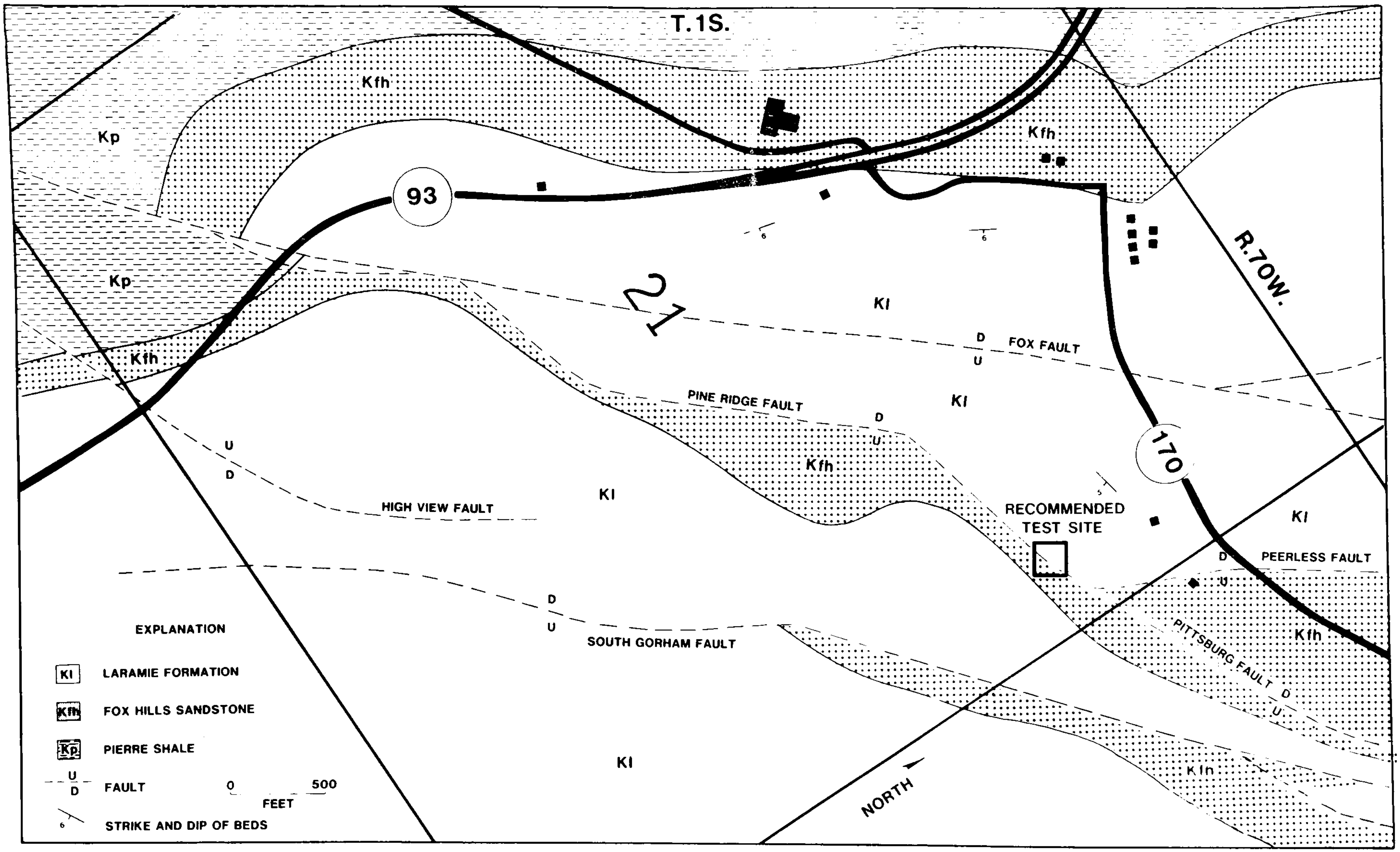


Figure 4. Generalized geologic map of the study area in Section 21, T. 1S., R. 70 W. Locations of faults and formation contacts approximate. Modified after Spencer (1961).

The Fox Hills Sandstone is a massive tan to buff-colored sandstone that often weathers white on outcrop. Drill cuttings indicate that the Fox Hills Sandstone is dominantly a light-gray, fine to medium-grained, subrounded sandstone containing some carbonaceous material and thin shale beds. Thickness varies within the study area from 125 feet in drill hole PR-1 to 115 feet in drill hole T-4. Rahmanian (1975) concluded that the Fox Hills Sandstone in the Marshall area was deposited in a shallow marine environment. The contact with the overlying Laramie Formation is conformable and is placed at the base of a 1 to 2 foot-thick coal bed occurring immediately above the Fox Hills Sandstone in the study area. Near the top of the Fox Hills Formation there frequently is a zone that gives a kick on the natural gamma log probably due to slight enrichment of uranium. The lateral pervasiveness or stratigraphic consistency of this zone is unknown.

The Laramie Formation, believed to represent brackish to freshwater deposits (Spencer, 1961), commonly is divided into 2 major lithologic units (Weimer, 1976). The lower unit ranges in thickness form 150 to 250 feet and consists of more or less equal amounts of shale, sandstone, siltstone, and claystone with interbedded coal. The upper unit, which is dominantly claystone with minor sandstone, varies in thickness from 200 to 800 feet. Only the lower unit is present in the study area and is characterized primarily by sandstone intercalated with sandy shale, clay and coal. Coal seams are confined to roughly the lowermost 100 feet of the lower unit. Also in this section are laterally continuous sandstones as thick as 20 feet, which can be identified on geophysical logs from our drill holes within the study area. These sandstone lenses at outcrop can cause interpretative difficulties by being confused with the Fox Hills Sandstone, which has profound consequences to the interpreted structure of the rock units and, hence, to the presence and extent of minable coal.

At least 4 persistent coal beds occur throughout our study area, while in the rest of the coalfield as many as 6 seams may occur at a single locality. Seven minable seams, described by Lowrie (1966) occur in the coalfield, but it is seldom that more than a single seam has been mined at any locality. By convention coal beds in the Boulder-Weld Coalfield are named by number from the bottom upwards (Lowrie, 1966). The most commonly mined seam in our study area is the Number 3 seam, also called the Gorham Seam. This coal seam ranges in thickness from 2 to 11 feet in our study area and averages around 8 feet thick where mined. Spencer (1961) feels

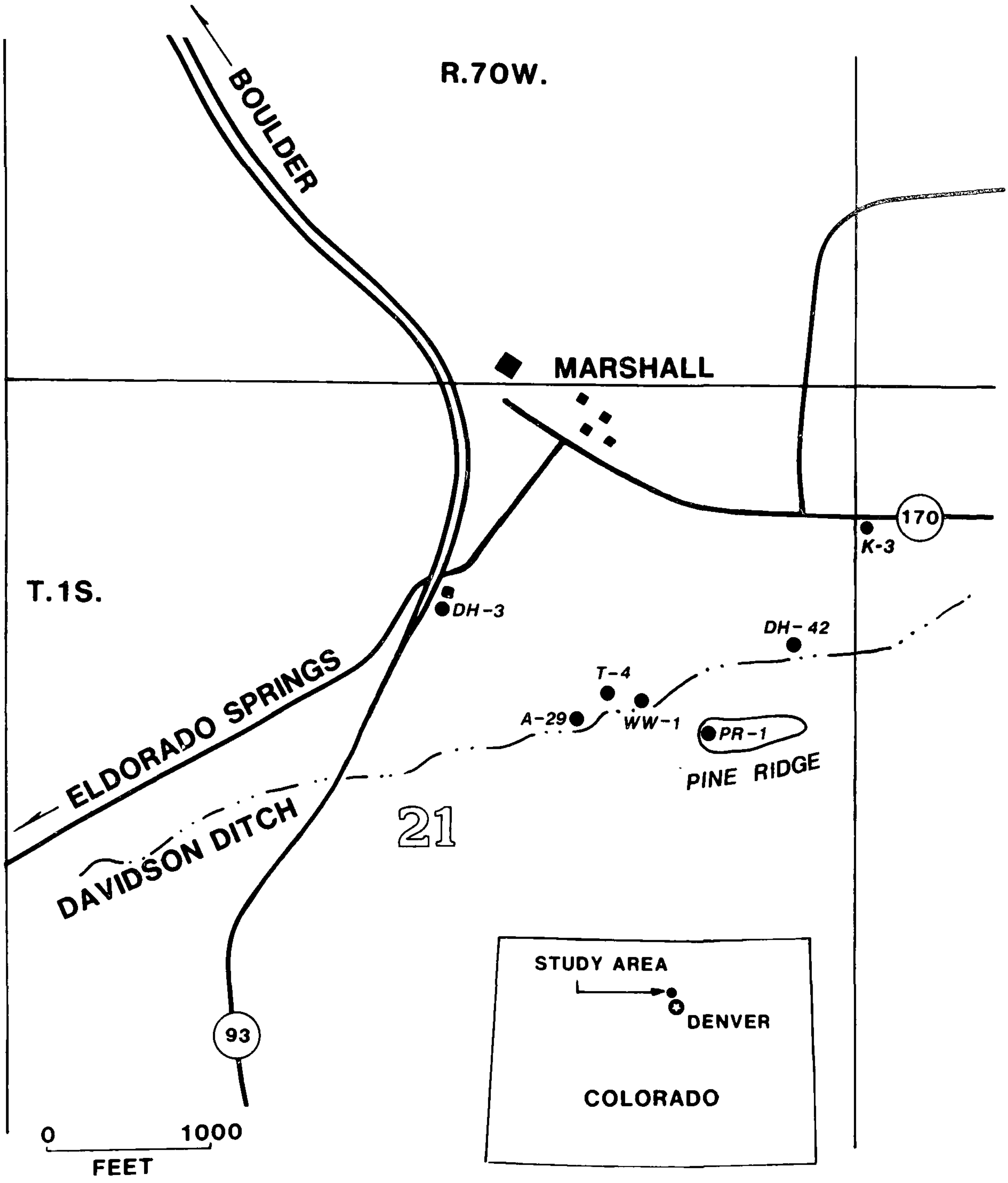


Figure 5. General location map showing the study area (shaded) and drill hole locations of wells used in this report.

that when the Gorham exceeds 6 feet in thickness and contains partings, it has probably coalesced with an overlying Number 4 bed. Figure 6 illustrates the change in the character of the Gorham coal as seen on geophysical logs from drill holes. In DH-42, the Gorham coal is 6 feet thick and occurs 5 feet below the 3 foot-thick Number 4 bed. The lower coal bed used as a datum is one of two laterally continuous coal beds which occur within 30 feet below the Gorham coal throughout the study area. In drill hole T-4, the Gorham and Number 4 beds have coalesced to form an 11 foot-thick coal bed with no partings. Core samples of this bed indicate an apparent rank of Subbituminous B.

In our study area only the Gorham Seam has been mined to any appreciable extent. In other parts of the coalfield, however, there have been instances where more than one coal seam was mined at a single locality. This occurs, for example, in the mines under the town of Louisville. The coal zone is confined to the lower part of the Laramie Formation and ranges in thickness from 50 to 275 feet (Kirkham and Ladwig, 1979).

Structure

The Marshall study area is located on the western limb of the Denver Basin, a doubly-plunging, north- and south-trending basin approximately 50 miles wide and 100 miles in length. On the western side of the basin rock strata generally dip eastward, with dip angles increasing sharply near the western margin. Numerous high angle faults, generally trending northeast, developed a system of horsts and grabens in the Upper Cretaceous strata. Detailed structural interpretations for the west-central Denver Basin are presented in Spencer (1961), Colton and Lowrie (1973), Weimer (1977), Rahmanian (1975), and Kirkham and Ladwig (1979).

The Fox fault and the Pine Ridge fault transect the study area (see Figure 4). Both faults are indicated on mine maps and locations of the faults are based on these maps, as well as the previous work of Spencer (1961) and new information derived from drill holes. The northeast-trending Fox fault was described by Spencer (1961) as a high-angle reverse fault with an inferred maximum displacement of 150 feet. In the central part of the study area, displacement along the Fox fault is considered to be relatively minor. No significant offset is indicated on the mine maps and mining has continued uninterrupted across the fault. In addition, little or no disruption in the attitude (strike and dip) of Laramie Formation strata is apparent in cross-sections of drill holes generated across the fault (see Figure 7). In the northeastern part of the study area, near Highway 170 (see Figure 4), displacement along the fault seems to increase. This is indicated by an abrupt change in the attitude of Laramie Formation rocks across the fault in this area (see Figure 4). The Fox fault is not exposed here and interpretations are derived from drill hole data.

The Pine Ridge fault is also considered to be a high-angle reverse fault. Location of the fault is based on mine maps, drill hole data, and previous mapping of Spencer (1961), but also has been confirmed by out drilling, as well. Displacement along this fault, as indicated by correlations between drill holes PR-1 and T-4 (see Figure 7), is on the order of 260 feet. The Pine Ridge fault is a major structural feature and generally forms the southern boundary of mining on the downthrown block in our study area. There are several, generally small mines, however, to the south and east of the fault on the upthrown block that we did not study. These include, for example, the Marshall No. 5, Pine Ridge, and High View mines.

Drilling

The Branch of Coal Resources (BCR) of the U.S. Geological Survey conducted drilling in the project area during the spring and fall of 1982. The recovery of core samples of the Gorham coal and obtaining additional stratigraphic information were primary goals of this drilling project. Cooperative drilling projects by other agencies included the Bureau of Mines and the Office of Surface Mining.

Drill hole T-4 (Figure 5) is located at the site of the old tipple for the Marshall No. 3 Mine. Total drilled depth was 275 feet. The lower 150 feet of the Laramie Formation, the Fox Hills Sandstone (115 feet-thick), and the upper 10 feet of the Pierre shale were penetrated by this drill hole. Core samples of the Gorham coal and a 15 foot interval bracketing the Laramie Formation/Fox Hills Sandstone contact were recovered. Three other holes, including PR-1 on Pine Ridge (see Figure 5) and 2 shallow holes which penetrated old mine workings were drilled as part of the study.

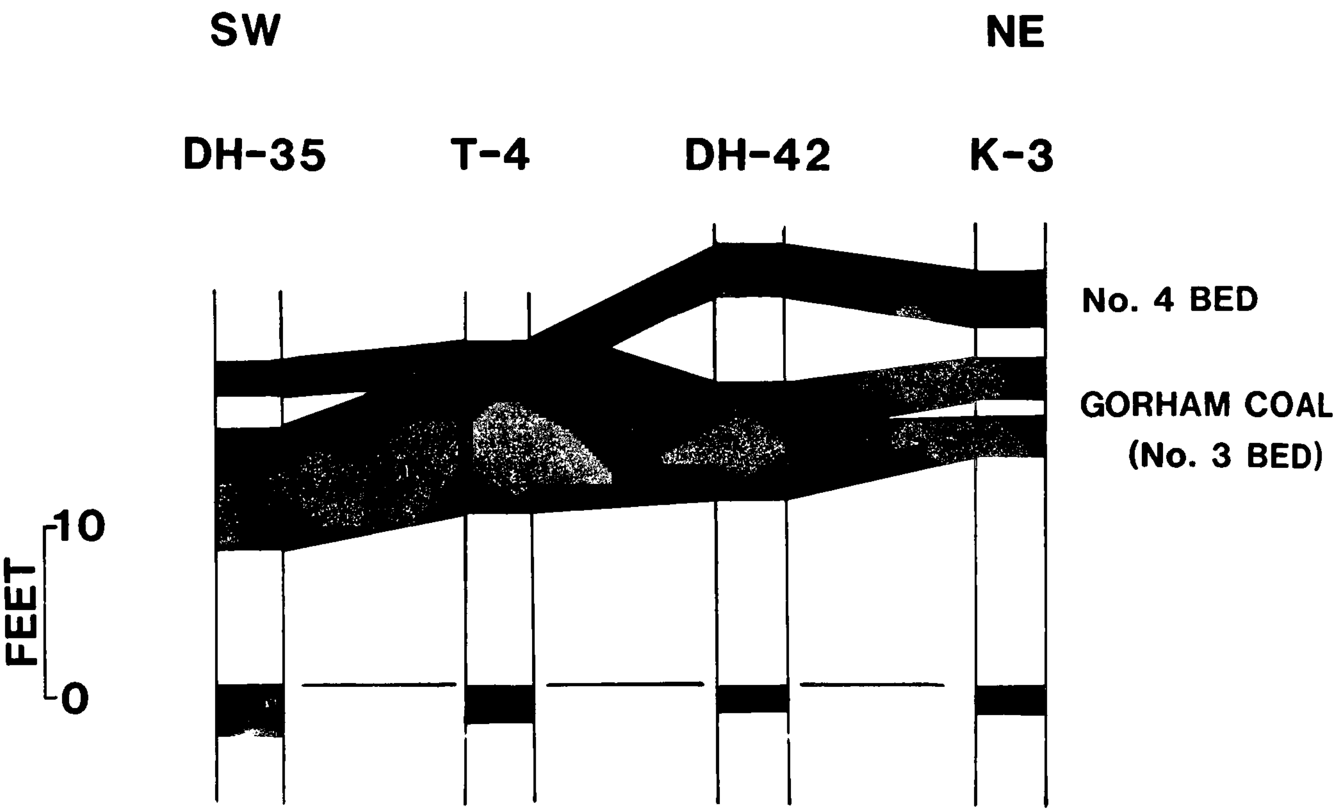


Figure 6. Schematic cross-section of drill holes showing lateral relationship of the Gorham coal and overlying No. 4 coal bed within the study area. Thickness and occurrence of the coal beds and associated partings were determined from natural gamma logs.

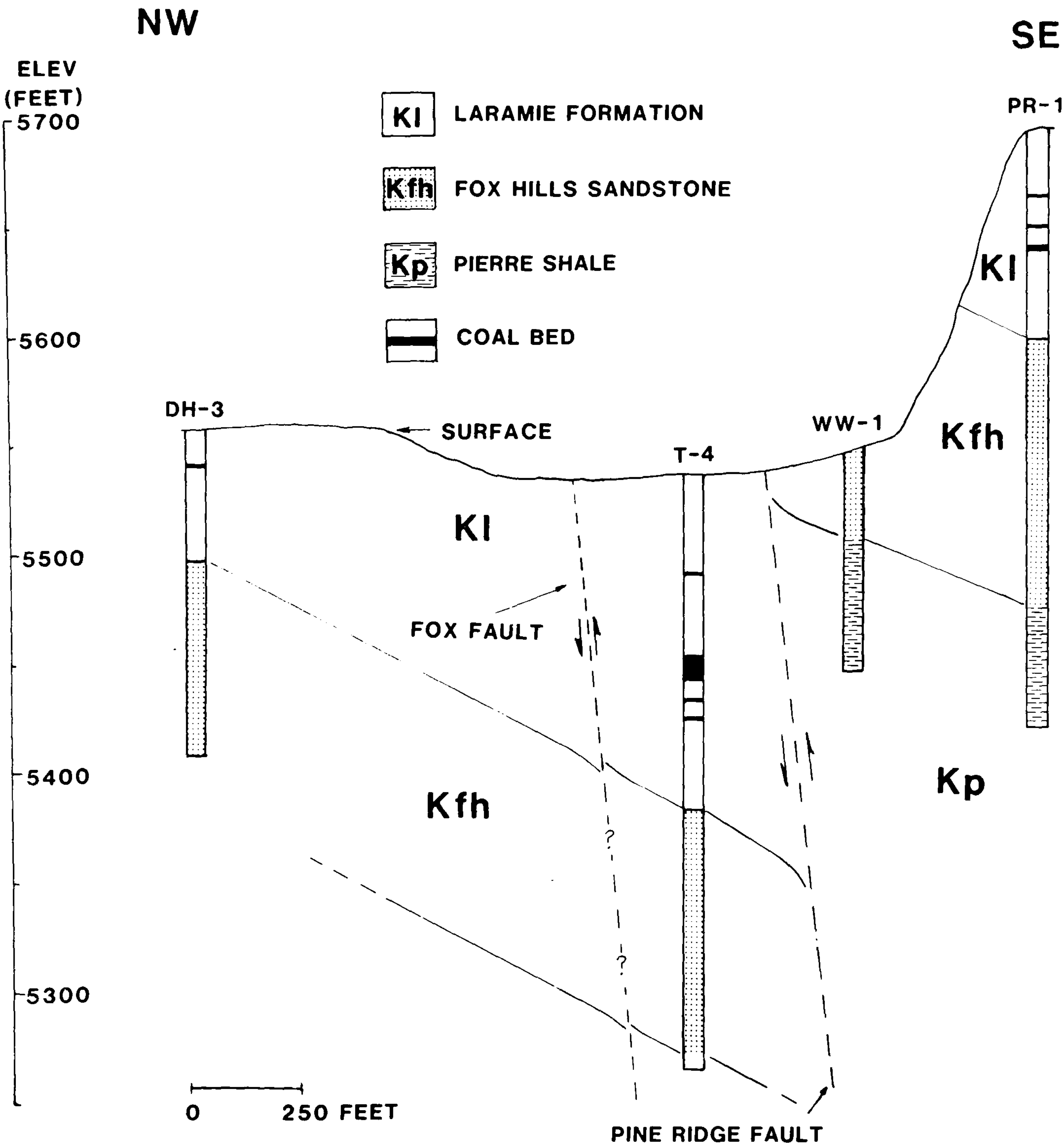


Figure 7. Cross-section and correlations based on geophysical logs from 4 drill holes in the study area. Fault locations are approximate and subsurface traces are inferred from previous descriptions of the faults by Spencer (1961).

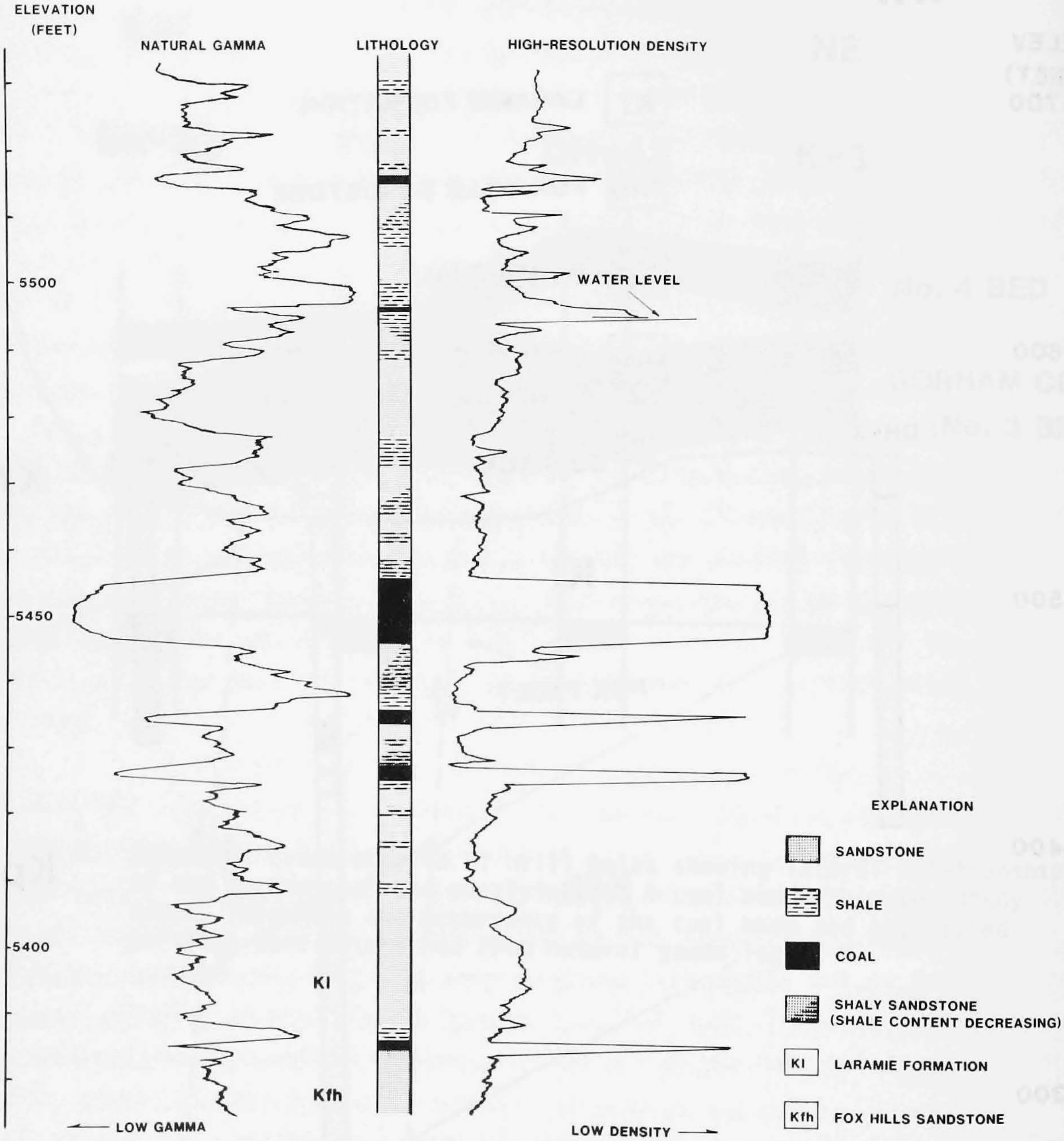


Figure 8. Natural gamma and high resolution density logs of the Laramie Formation (Kl) in drill hole T-4. Coal beds indicated by heavy black lines. The contact between the Laramie Formation and the Fox Hills Sandstone (Kfh) is placed at the base of the lowest coal bed shown.

The drilling was done with truck-mounted Gardner-Denver 17W and Portadrill 524 drill rigs. The primary circulation medium was air with a fine mist water injection. In porous or fractured rocks it was sometimes necessary to add a foaming agent to the water to aid in the recovery of cuttings samples. Rollercone (tricone) bits designed for use in medium-hard formations proved very successful, yielding average penetration rates of about 100 feet/hour. Coring was done using a 15 foot-long conventional mining barrel with split inner tube sampler which recovered a 3 inch-diameter core. Carbide core bits produced excellent results and 100% core recovery was achieved at all times.

Cuttings samples were collected at 5 foot intervals using a screen basket placed at the well head. Samples were examined and lithologic changes were noted to aid to interpretations of coal bed correlations or interpretations of the geophysical logs taken of the drill holes.

Geophysical Logging

The standard suite of logs recorded in the drill holes includes natural gamma, gamma-gamma density, resistance (in fluid-filled holes), and caliper. Two logging systems were used. One was a small, single-conductor unit which records only one log per trip downhole. The other system was a more sophisticated multi-conductor logger with the ability to record 4 different logs simultaneously.

The natural gamma log is a measure of natural gamma radiation emitted by all rocks. Typically, coal is very low in natural gamma radiation and this produces a low deflection on the natural gamma log trace. A similar response would be expected in large voids which might develop where coal has been mined out underground. In this case, the natural gamma log would be a measure of the low "background" radiation occurring in the air filling the void. Figure 8 illustrates this response. Depending on the characteristics of the material being measured, probably 90% of the gamma radiation detected by the probe originates within 6-12 inches of the borehole wall (Keys and MacCary, 1971). Thus, the major influence on a natural gamma probe suspended in a large void or cavity will be the surrounding air, and a low natural gamma response will result.

The density log is a record of the intensity of gamma radiation emitted from a gamma ray source in the probe after it has been backscattered in the drill hole and by the surrounding rocks (Keys and MacCary, 1971). Backscattering is determined by the density of the medium through which the gamma rays pass. The density of coal is quite low with respect to other lithologies and this induces a sharp, low density deflection on the geophysical log. Figure 8 shows the response for the density log in coal beds found in drill hole T-4.

The density log is greatly influenced by washouts, fractures, and voids because of the ease of backscatter of the radiation in the low density mediums of air or water (borehole fluids). The resulting response is a low density deflection, very similar to that in a coal bed. This characteristic makes the density log a very effective tool for locating mined out areas (voids) and fractures that may develop in weakened strata over old mine workings. It is also useful in determining bed boundaries and thickness.

The resistance device used in this study is a single-point tool which measures the resistance (in ohms) of the rocks lying between an in-hole electrode and a surface electrode. This log is useful for qualitative determination of lithology, bed boundaries, and identification of fractures in resistant rocks (Keys and MacCary, 1971). Coal is indicated by a high resistance deflection on this log. The characteristic of this log most useful in a mine subsidence study would be its response to fluid-filled fractures. The sharp, low resistance deflection induced on the log by such fractures is essentially a measure of the resistance of the fluids filling these fractures. compared to the surrounding resistant lithologies, this value would be quite low. As with the density log, the resistance log is very effective in locating fractures which might indicate weakened zones above old mine workings.

The caliper log is a measure of the average diameter of a drill hole. Any deviation from the drilled diameter will result in a deflection indicating the increase or decrease in the borehole diameter. Figure 9 shows the response of the natural gamma and caliper logs in a void which developed in old mine workings. The caliper tool used in the Marshall study consists of 3 feeler arms which follow the borehole wall as the probe travels upward. The record as shown on the log is calibrated in inches (see Figure 9) representing the average hole diameter. The length of the feeler arms is 9.5 inches and the maximum diameter the probe can measure is 16 inches. As a result, determination of the lateral extent of voids larger than this is not possible.

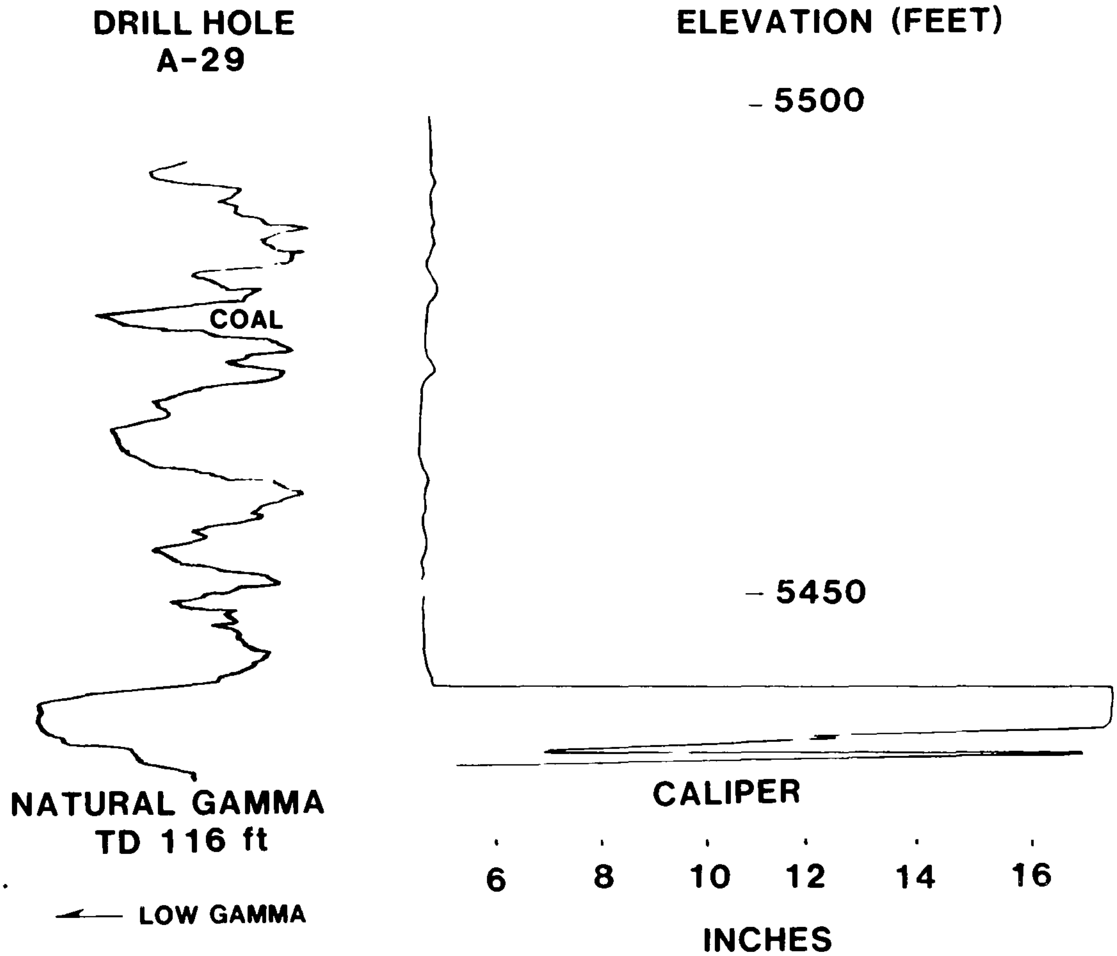


Figure 9. Response of natural gamma and caliper logs from drill hole A-29 indicating a large void at the bottom of the hole.

Temperature Logging and Temperature Measurements

The temperature log is a continuous record of the temperature of the environment immediately surrounding a sensor in a borehole (Keys and MacCary, 1971). The probe used for this project is calibrated in degrees Celsius. it was lowered into the drill holes at a rate of about 5 feet/minute and stopped for about 5 minutes every 20 feet. A basic problem in the quantitative evaluation of the Marshall temperature logs stems from the fact that most of the drill holes were not fluid-filled, and the sensor was recording the temperature of the air in the hole rather than that of the rocks. For this reason, the logs were interpreted qualitatively and any temperature deviation from a normal range of 10 to 15°C was considered the result of an underground heat source such as a burning coal bed.

Other temperature measurements were made using penetration thermometers in the ground surface. In the active smolder area on the west side of the Marshall No. 3 Mine, a series of temperature measurements made in 1982 showed a thermal anomaly of 15°C at the ground surface. We also found snowmelt patterns to be particularly useful in interpreting where the mines were actively burning. The best conditions for this observation are in the early morning before appreciable sun heating and immediately after one of the frequent winter snow storms, which uniformly deposit a thickness of a few inches of relatively dry snow under conditions of no wind. Winter conditions of cold, calm mornings also are especially good times to look for vents of steam and warm gases from the burns. Burning coal has a unique odor and we were able to locate several small vents of gas from the smoldering coal by detecting the odor and following it upwind to the source.

Sulfur Hexafluoride and Helium Injection Experiment

The experiment consisted of injecting 2 tracer gases underground at one locality then analyzing air samples taken from drill holes and soil at other locations for those gases. The detailed purpose, results, and conclusions from this study are reported elsewhere (Herring et al, 1985; Herring and Reimer, in preparation; Reimer and Been, 1985). Basically, the principal purpose was to demonstrate the utility of gas tracers in helping to understand the extent of mining and the combined hazards of fire and subsidence from the abandoned workings. Specifically we sought to define: (1) the extent of abandoned workings, (2) diffusion rates of the two gases through the partially collapsed workings, and (3) extent of intercommunication throughout the mines. This last consideration is of interest regarding the spread of fire from one part of a mine to another or from one mine to another. Finally, the technique has application to determination of underground volume, porosity and permeability of stopped material in the underground cavities, as well as the loss rate of gas through overburden to the mine.

We injected small quantities (2 m^3, at standard temperature and pressure) of the stable, nontoxic gases helium and sulfur hexafluoride (SF_6) underground and monitored their dispersion throughout the mine workings over time by taking air samples from drill holes into the mine workings and from soil samples taken over the workings. The particular choice of gases principally was due to sensitivity of detection. In the case of sulfur hexafluoride, detection limit using inexpensive, field-portable equipment with data obtained in real time is on the order of a few parts per trillion, an incredibly sensitive limit that provides many useful tracer applications.

The injection site used for the tracer gas experiment was the shaft of the El Dorado Mine, a previously-backfilled shaft that had subsided open and caved downward into the workings. A stainless steel catheter, approximately 10 m long, was inserted into the shaft and the shaft again backfilled, effectively sealing the opening. We had no direct evidence of the mine interconnection but simply hoped that this shaft and small mine connected to the rest of the Marshall mines. It turned out that this indeed was the case.

Our results show that we have been able to provide additional information on the extent of mine workings including obtaining some idea where the workings are flooded, and have modeled the dispersion of gases throughout the mine workings. The interconnected areas mined are indeed larger than those shown on the mine maps. Note the area on Figure 2, where the gas dispersion data clearly show additional areas of mining as well as continued interconnection within the mine. Areas are identified on the figure where we interpret the workings to be flooded. This interpretation is due to the indicated workings shown on the mine map and collaborated by drilling but failure of the gases to penetrate to the drill holes into the workings at these locations. Total subsidence would also provide a barrier to gas dispersion, but these parts of the mine appear to be flooded from the occurrence of water in drill holes. Also, there is no extensive gaseous interconnection with some of the nearby mines, notably the Eagle and the adjacent Lewis Number 2 at this time. In the case of the latter mine, since mine maps indicate direct connection of the workings with the Marshall No. 3, we again are speculating that flooded workings or collapse serves as a barrier to gas dispersion into the Lewis Mine. Finally, much of the mine remains connected, not only throughout its own extent, but also to other, adjacent mines. Should the mine fire continue to smolder or increase its intensity of burning it therefore is capable of spreading throughout much of the mine that at present is not on fire and to other, neighboring mines, as well. This threat of combustion applies to the flooded parts of the mine, as well. In this case, should there be a drop in the ground water level and, hence, in the water level in the mine, there is possibility of the newly exposed, wet coal igniting, as wet coal tends to have a higher incidence of spontaneous ignition (Herring and Rich, 1983).

Dispersion rates of the gases underground were on the order of 100 days per mile of underground workings. Dispersion rates of tracer gases in applications to other underground mine systems will depend on the extent of intercommunication underground, degree of collapse, which introduces a tortuosity function to gas movement, complexity of the mine plan, effects of surface barometric pressure changes on ventilation in the mines, and whether the mines are on fire.

In general, there was a good correlation between concentrations of helium and sulfur hexafluoride in samples taken from drill holes as well as those taken from soil samples. The He/SF_6 ratio is greater than would have been expected from the injection ratio probably due to the leftover helium in the mine from an earlier helium injection experiment.

Our conclusion based on gas dispersion rates is that eddy diffusive processes greatly dominate those of molecular diffusion in the dispersion of gases throughout the mine workings. Soil gas concentrations for both gases are particularly large where the mine workings are shallow, within 25 feet of the surface. It is likely that especially large concentrations of SF_6 and, probably, those of He as well, correlate with areas of soil directly overlying rooms in the mine, while lower concentrations of both gases occur in shallow rock and soil over mine pillars.

USE OF MARSHALL AS A TEST SITE

We conclude that the Marshall area can serve as a useful test site for a variety of techniques that investigate or purport to characterize the extent of mining and subsidence. In our study a relatively small area has been examined in considerable detail, but even with this intensive level of study uncertainties in understanding still remain. On a relative basis, however, more is known about this area than any other part of the coalfield, and, because of the variety of problems and the degree of characterization, the Marshall locality is useful as a test site. Thus, the Marshall area can serve usefully either as a test site for development of new techniques or intercomparison or calibration of existing investigative techniques. For example, one local area, noted in Fig. 4, provides an example of both mined-out and unmined areas. The boundary between these areas, a fault of at least 200 feet vertical displacement, is sharp. Dissimilar rock types are juxtaposed by this fault, which is useful for testing of surface geophysical methods that attempt to discriminate among rock types. Finally, the mine workings in this area still contain some pillars, of interest to investigatory techniques that claim to distinguish between rooms and remaining pillars underground.

CONCLUSIONS

Summary and Conclusions Based on Drilling

The methods of drilling employed by BCR in the Marshall study proved successful and informative. The combination of air and water injection as a circulation medium resulted in rapid penetration rates and generally good sample recovery. Problems such as lost circulation and poor sample recovery did occur when a drill hole penetrated old mine workings and disturbed rocks (fractures) associated with the workings, but the addition of foaming agents helped in sample recovery. Boreholes penetrating mined out areas had a tendency to collapse immediately above the workings and passage of geophysical probes to the total drilled depth was impeded. A system of casing through the interval in the old workings may alleviate this problem and allow the passage of geophysical tools to the bottom of the hole. It is also important that drill holes continue below the mined-out interval and penetrate a continuous and identifiable rock unit below the mined seam that can be used as a datum level in the construction of cross-sections and, more importantly, in the correlation between drill holes. The Fox Hills Sandstone in the Marshall area is a good example of such a unit. Drilling and logging to know datum levels also helps resolve structural difficulties or ambiguities in the strata, for example that mentioned earlier on Laramie Formation sandstone lenses.

Conventional core drilling with a mining barrel provided good samples (3 inch-diameter) for chemical analyses. Carbide core bits yielded good penetration rates and core recovery. Only coal samples were analyzed in this initial study, but future coring plans should include the recovery of roof and floor rock associated with the mined out intervals, and geotechnical studies (for example, point load, slake durability, etc.) performed on the core.

Geophysical Logging

The suite of logs, including natural gamma, density, resistance, and caliper, is very effective in determining the location and extent of mined out areas. The nuclear logs, natural gamma and density, are important because they function in both cased wells and open holes. The natural gamma log, in addition to identifying coal beds and large voids, is a good log for qualitative determination of lithology. The substantial effect of fractures and voids on the density log response make it an ideal tool for locating mined out areas and fractured rocks resulting from weakening above the mines. The density log is also useful in determining bed boundary and thickness. The resistance log is more limited in that it requires fluid-filled holes and will not operate in cased wells. However, a sensitive single point resistance log is an excellent tool for location of fractures when used in conjunction with the caliper log. The caliper log is essential for the correction of other geophysical information as well, particularly density logs. It is also useful for examining borehole conditions, as for washouts, as well as for locating fractures and large voids. It is perhaps the most useful tool in a mine subsidence study. A 3-arm caliper is recommended for a more representative response over the 1-arm type, which has the limitation of the single arm becoming stuck or striking rubble in the cavity and not revealing the true size. Also, a comprehensive study should use two caliper tools: one of small size, for example twice the hole diameter, and a second as large as possible. The smaller probe is quick-responding and is not limited in its response by long arms, which may be pinned by the hole sides and not open until completely free of the drill hole and into the void, even though the probe with its depth marker may already have entered the void. Consequently, a long-armed probe will show the cavity as being thinner than it really is. Thus, the smaller caliper provides more accurate information as to the true depth and thickness of the void, while the larger tool provides more accurate information about the true lateral extent of the void.

ANALYSIS OF MINE FIRE AND SUBSIDENCE HAZARDS AT MARSHALL

Our interpretation of the potential subsidence hazard at Marshall is that there will continue to be subsidence over the abandoned mine workings in the future, since we and others have detected voids still remaining underground. These cavities will continue to subside in the future, however the rates of this subsidence cannot be predicted based on the present study. Specifically, we know that many cavities still exist underground, but we know very little about their extent, interconnection, and filling. Of interest is that cavities above the deeper (eastern) half of the Marshall No. 3 Mine, where it is overlain by the high pressure gas line, in most areas have not migrated more than 20 feet towards the surface. This would indicate an average subsidence rate not exceeding 1 foot of vertical subsidence per 5 years. Unknown, however, is whether there has been some regional subsidence simultaneously with the local stopping in the mine, which may have affected the subsidence rate for the entire area. Furthermore, because no subsidence rate measurements exist between the end of mining and prior to ours, it is impossible to know just when this subsidence occurred--early after mining ceased, progressively, or recently. Subsequent subsidence could behave the same or differently. Finally, all of the other complexities that we have discussed also affect this subsidence rate, as well. For example, water in the mine, degree of burning, rock fracture, etc. also will be important in determining future subsidence and its rate. In summary, this calculated subsidence rate is only an indication of the possible rates that will occur in the future in this area.

Because of the limited development of property at Marshall at this time few commercial or private structures are at risk from subsidence. The roads and highways in the area, however, are at greater risk. Our study shows that mining, especially from the western sides of the Marshall No. 3 and El Dorado Mines, extends to the eastern right-of-way of Highway 93, however none of the drill holes on the west side of the highway detected any mine cavities. We recommend that the State Highway Department further investigate the possibility of undermining beneath the highway. Also, Highway 170 is undermined in the area from Cherryvale Road west. Finally, we conclude that there is a subsidence threat, particularly from regional type of subsidence, to the high pressure gas line where it crosses the Marshall No. 3 Mine. It would be useful to have a follow-up drilling program that used a borehole camera to explicitly characterize this threat.

We conclude that future risk from mine fire is minimal and probably most of the area that could have burned has already been on fire. However, a drop in the water table in the area could expose unburned coal and lead to renewed combustion, so the area should be monitored periodically for emissions of steam, other coal combustion gases, or heat.

RECOMMENDATIONS FOR SIMILAR STUDIES

Useful information about some of the underground cavity conditions can be obtained when drilling by using an experienced driller who can "feel" the conditions inside a collapse cavity. However, due to the vagaries of drilling conditions, such as weight of the drill string or seizing of the string by clay-containing rocks, it may be difficult if not impossible to determine much about the underground conditions within the mine simply by drilling. In our study we frequently detected underground voids by noting when the drill string rapidly fell, but we were unable to tell whether these voids were empty or partially filled with rubble.

Our study did not include the use of a borehole camera for direct observation underground, however we strongly recommend the use of such a device for other similar studies. In particular, the borehole camera device is the most useful technique for determining the actual nature of the underground workings, whereas drill hole information usually allows one only to infer what these conditions may be. The camera sees the actual conditions in the mine room or subsidence cavity and, if visibility is good, can easily determine the cavity size, extent of fill, and other conditions that are extremely difficult to know from ordinary drilling or other indirect methods. Of particular importance using such a borehole camera would be to determine the nature of fill or rubble inside any mined-out cavity, the degree of stopping, whether the pillars remain, size of the rooms of the mine, and whether the mine rooms are partially or completely flooded. The most useful camera for this type of study should have a continuous display with some type of recording ability, such as videotape. Such a camera also should be waterproof in case mine workings are flooded and, most importantly, should be in a protective casing in the event of rock collapse into the drill hole. The camera also should have auxiliary light sources to see in the dark mine rooms. Finally, we recommend that both camera and light source in their casing be lowered and raised using a sturdy steel cable attached to the protective casing rather than by using the electrical cables used to power the camera or transmit images. Steel cable enables pulling on the casing with considerable tension if the camera becomes stuck in the drill hole.

We further recommend in any similar study, especially if determining potential subsidence is a principal goal, that rigorous elevation control be established in the area to monitor any future subsidence. Baselines with benchmark control and individual benchmarks can be established over potential problem areas to monitor either local or regional future subsidence. We endorse the establishment of lone baselines especially in areas where there is a possibility of regional subsidence.

Another useful recommendation for similar studies is to establish periodic coverage of problem areas with stereo pair air photo coverage. This should include periodic follow-up coverage after an initial study to monitor future subsidence. Periodic photo coverage is inexpensive, especially useful for examination of large, remote problem areas and it still provides sufficient detail to determine local subsidence events. This would be especially useful to monitor future collapse of backfilled mine shafts.

Finally, we conclude with a reminder to those conducting similar studies that the drilling program, which usually becomes the most important part of a typical study, has some inherent dangers. For example, the weight of a heavy drill rig on top of potentially unstable, subsiding ground should be considered. Also, a fire and explosion hazard exists in old workings filled with methane. Finally, drilling into and through mine cavities usually loses circulation of the drilling fluid, prevents return of cuttings for analysis, and risks collapse of the rubble in the cavity onto the drill pipe, possibly trapping the drill string and bit in the hole.

RECOMMENDATIONS SPECIFIC TO THE MARSHALL AREA

1. Further hazard assessment of the subsidence risk to Highways 93 and 170 and to Cherryvale Road, should be undertaken.

2. Subsidence risk to Western Slope Gas Line should be determined, with particular emphasis placed on the hazard posed by extreme tensional forces of regional subsidence.

3. Subsidence risk and risk of hydraulic breaching through mine workings to Marshall Lake Dam should be determined.

4. The Marshall area should be monitored periodically for renewed mine fire activity.

5. The Marshall area should be monitored periodically using stereo pair air photo coverage to look for new or continuing subsidence features.

ACKNOWLEDGMENTS

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ESSENTIAL COMPONENTS OF A MINE SUBSIDENCE INVESTIGATION

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ABSTRACT

Many factors affect the reliability, accuracy and usefulness of the results of a subsidence investigation above abandoned coal mines. Some of these factors are beyond the control of the investigator and some are not.

Within the control of the investigator are several organizational and data acquisition requirements which are critical to the success of any study. These include: 1.) acquisition and proper orientation of the best available mine map and development plan; 2.) careful consideration of the number, type and location of drill holes; 3.) appropriate use of down-hole geophysics; 4.) determination of the need for sampling and testing of relevant materials; 5.) a survey of the site and adjacent area for evidence of previous or on-going subsidence; and 6.) development and demonstration of the adequacy and appropriateness of the method or methods used to evaluate the site with respect to the hazard and degree of risk associated with the proposed use.

One of the original objectives of the Tri-Towns Subsidence Investigation was to use it as a prototype to obtain insight into techniques applicable to other, similar studies throughout the undermined areas of Colorado. While formal guidelines are not appropriate at this stage, several observations and recommendations can be made to assist future investigations of the same general type.

Prior to developing a drilling program, the mine maps for the area should be reviewed and compared to determine the location of representative areas and trends such as depth to mining, date of mining activity and type of mining method employed. This preliminary information is essential to determining if a subsidence risk exists and, if necessary, in designing a drilling program that will efficiently address as many of the subsidence related questions as possible.

Accurate orientation of mine plans and maps of existing or proposed surface features to the same control points and to each other is essential to a successful study. All data should be plotted to a common, scale such as 1:2,400. This is the most frequently used scale for coal-mine maps and is sufficiently large to accurately locate drill-hole sites. In many instances surveying may not be necessary to locate drill holes. However, minimum accuracy requirements should be established and appropriate stationing procedures used. Chain-and-Brunton compass methods from field-verified control points appear to be suitable for the level of accuracy needed in a community-wide study.

Drill-hole density and location relative to particular mine features and other drill holes of the study are very important considerations in subsidence investigation. Balance needs to be achieved between acquiring sufficiently detailed information to characterize the mines to the desired degree and the cost associated with subsurface investigations. If prior drilling data is available in the area, it should be evaluated to determine if it can be incorporated into the present study. The site-specific nature of any drilling program generally precludes using rules-of-thumb. The investigation of the Tri-Town Area consisted of 97 holes distributed throughout an area of approximately 2.5 square miles of which about two thirds is undermined. This represents a drill hole density of just less than one hole per 10 acres.

The more detailed study conducted in the northwest corner of Frederick consisted of nine holes on a tract of between 7 to 8 acres, achieving a density of just over one hole per acre.

In both of the above cases the density used was considered adequate for the specific level of the investigation undertaken. Drill-hole spacing equivalent to those in this community study could be used for the preliminary planning and costing phases of developing a similar community-wide study. However, in a different area it is quite likely that the unique character of the mining and surface development (existing or proposed) could require large variations in order to develop the level of detail needed for a particular area of interest. The less uniform the conditions being evaluated are in the area of interest, the greater the required drilling density will be.

Drill-hole location becomes more complex and critical when the study takes place in an already developed area. Great care must be taken to ensure that the subsurface investigation does not damage or endanger the buried utilities in the area, especially water and gas lines. A careful review of mine plans should allow the investigator to choose alternative drilling sites when the presence of critical underground structures or overhead electrical lines precludes a given hole location.

Rotary drilling and lithologic logging augmented by down hole geophysical surveys appear to provide the most usable data for the lowest total cost per foot. The use of the geophysics to actually pick the lithologic changes makes sampling at 10-foot intervals plus noting pronounced changes (i.e. coals, water table, hard sandstones) more than adequate. An important aspect of maximizing the retrieval of pertinent drilling data is the continuous observation of drill-rig and drill-string behavior by an experienced professional to ascertain the physical conditions of the strata in general and the mined interval and immediate roof rock in particular.

A vicinity investigation should incorporate at least one full core hole with an accompanying suite of geophysical logs. This assists considerably in correlation, comparison, and analysis of the other subsurface information. Spot coring in the coal seam can help arrive at a quantitative analysis of the pillar strength by collecting samples and performing rock mechanics testing.

If significant horizons can be forecast in the roof rock, such as competent sandstones of regional extent, they too should be sampled and tested.

Coring through highly variable strata such as the mudstones, soft sandstones, and coals such as those of the Laramie Formation can be problematical. The principal considerations are to achieve a satisfactory penetration rate and yet recover a high percentage of quality core. If coring is commenced in a mudstone two feet above a selected coal horizon, hours may be lost. Additionally the bit may be fouled with the mud and clay so that even when the coal is reached, poor core is obtained.

Several techniques were evaluated during this investigation to find a satisfactory method of obtaining good spot core results. The following method proved to be the most successful.

The hole in which spot coring was to take place was identified and all adjacent holes were drilled before coring it. Based upon data from adjacent holes, the spot core interval was selected and rotary drilling proceeded to within 5 feet of the top of the core zone. At this point circulation (pumping mud and rotating the bit without drilling farther) is carried out until the return flow is free from drilling chips. This usually takes several minutes at 200 to 300 feet. The hole is then drilled two (2) more feet, samples are taken and the hole is circulated again. The hole is then advanced in one-foot (1) intervals and circulated until the desired lithology is found in the return flow. At that point, the predetermined spot core interval is cored.

For coal coring, a diamond bit with moderate rotation and moderate fluid flow combined with fairly short runs, approximately 5 feet, produced the best core. For competent sandstones, carbide bits with high rotation and moderate fluid flows produced the best core. Run length did not seem to have any appreciable effect on the recoverability or quality of the sandstone cores.

Additional coring should be carefully evaluated on a case by case basis. In the Tri-Towns Study coring was about fifteen times more costly per foot than rotary drilling. In most cases, once a representative full core has been acquired, it would probably be more cost-beneficial to have fifteen more rotary holes and logs than an additional core.

Drilling prognoses should always be made, both for the depth to the mined interval and the anticipated mine feature to be encountered. Comparison between the expected and actual conditions is essential for determining the accuracy and validity of the mine plan. Comparison of the agreement or lack of agreement between predictions and actual results can be very valuable to prove or adjust the mine location and orientation with respect to the ground surface.

A survey of the ground surface of an undeveloped area should be performed to catalog any existing subsidence evidence. Review of previous aerial photography can be very valuable if prints of adequate scale and quality can be obtained. Likewise, interviews with owners or leasors of the of the property can yield worthwhile information. Special attention to linear features which may have been altered, such as fencelines, ditches, rail lines can give semi-quantitative information which may be of considerable help in developing or supporting a subsidence prediction model.

If the property is already developed actual damage may be noticeable and measurable on some of the affected structures. Caution must be exercised to be sure that the damage is directly due to mine subsidence and not some other process such as swelling soil or hydrocompaction. Also it should be noted that the absence of visible subsidence damage to existing structures does not guarantee that damage has not occurred. Much subsidence damage has been repaired or covered up by property owners who are often less than totally forthcoming about the problem.

The ultimate fruit of all of the above labors is, of course, to be able to demonstrate what the present and future potential for significant subsidence is. This will require the use of some method to predict the magnitude and perhaps the probability of future subsidence events. There are several, generally accepted models available which can be modified to more closely fit individual circumstances at a given site. Each method has its own advantages and drawbacks and there is certainly room for improved models or refinements in the modification of existing models.

The critical issue here is to arrive at a model which can be shown to be applicable to the specific physical conditions present at the site under investigation. The quantity, quality and logical relationship of all of the various components of the investigation must support and corroborate to the extent possible the model chosen if the study is to have the necessary validity to serve as a planning tool to the safe development of the property. Standards of scientific reliability and conservatism must be maintained.

As the body of information on subsidence in the Rocky Mountains increases we should be able to substantially improve and refine our ability to render sound, defensible predictions.

There will inevitably be areas that are not amenable to any recognized analytical method and thus remain unevaluated even though it is probable that they include moderate to high subsidence potential. Such areas will still require detailed site by site investigations if the hazard is to be properly evaluated.

However, both the hazard evaluation and the delineation of areas too complex or poorly known for a proper analysis can provide information that is extremely valuable to either public officials or private sector developers in guiding new or redevelopment planning in a way that minimizes costs and future risk to area residents.

The more diligent our attempts to properly evaluate the mine subsidence hazard today, the sooner will come the time when the number of areas too complex to evaluate will be nil.

ASSESSMENT OF SUBSIDENCE RELATED DAMAGE TO STRUCTURES IN LOUISVILLE, LAFAYETTE, COLORADO

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ABSTRACT

Considerable concern within the Louisville/Lafayette area has been raised about the potential for subsidence related damage to structures built on areas adjacent to or underlain by abandoned mine workings. Presently, many theoretical methods are available to estimate subsidence induced horizontal ground strains. However, no evidence exists as to the magnitude of ground strains developed from collapse or the type and amount of structural damage that can be expected.

To quantify the above questions, the author conducted an investigation of structures that are underlain by mine workings, but were built prior to mining. The majority of the investigation was conducted in and around Louisville and Layfayette, Colorado where the conditions described above exist.

Based on our results and the results of previous subsidence studies in the area, a relationship between theoretical ground strains and actual structural damage was identified. Also, as part of this investigation the author identified other structural parameters such as size, structure length, foundation type, etc , that may have been a factor in the amount of structural damage that occurred.

The results of this investigation are intended to provide a better understanding of theoretical subsidence related ground strains and their effect on structures. Additionally, practical design techniques that will minimize damage to structures built within areas of high theoretical ground strain are identified.

INTRODUCTION

The art of subsidence prediction above abandoned coal mines within the Boulder/Weld Coal Field is alive and well. All mining engineers, geologists, and civil engineers involved with subsidence investigations have developed their own individual strain and/or subsidence prediction techniques. These methods, whether based upon influence functions or empirical relationships require the determination of a subsidence factor (Vz). This numeric function can only be effectively determined through observation. No well documented investigations of subsidence above operating coal mines within the Boulder/Weld Field have been performed. Therefore, all strain prediction models currently in use, with respect to site specific Boulder/Weld studies, are flawed.

The intent of this investigation is to begin to develop, unfortunately without the benefit of direct observation, a specific Boulder/Weld Vz factor. This value, to be useful, should be able to be incorporated into all subsidence/strain prediction methods. An additional practical benefit from the study was the identification of subsidence resistant construction techniques.

IDENTIFICATION OF STRUCTURES

To proceed with this study, given the constraint of no possibility for direct observation, it was determined that an assessment of damage to structures in use prior to and during historic mining would be performed. The first step in such an investigation is to identify and locate those buildings meeting the previous requirements. To do this municipal records were reviewed, the files of the Louisville and Lafayette Historical Societies researched, the collection of original mine maps showing where surficial features occurred were studied, and local residents familiar with their neighborhoods were contacted. By no means do we infer that all pre-mining structures were located only a sufficient population to provide statistical validity.

This exercise resulted in the location of approximately 100 structures built prior to, and in use during mining operation. However, subsequent field observations showed that only twenty-three of the nearly 100 buildings still utilized the original foundations. This results in approximately 80% of the original pre-mining structures having undergone major foundation repair or replacement. These repairs most often occurred from the late 1940's through the present.

Detailed observations of the remaining twenty-three structures were then conducted. Each building was cataloged as to the following:

1) Location
2) Current Use
3) Type of construction (frame or brick)
4) Type of foundation
5) Maximum foundation length
6) Name of Mine occurring beneath the structure
7) Depth and thickness of mined interval(s)
8) Foundation damage assessment with repair history

Review of the completed catalog sheets showed that the surviving original structure and foundations had several similarities. All but four buildings were single story wood frame, all had shallow (less than 3 feet deep) foundations and all of the foundations were either native sandstone block or brick.

An additional observation gained from review of historical photos was that no two-story brick building built prior to mining survived through the late 1920s. Of particular interest are original photos of the Bermont Store and the Miners Trading Company Building as they appeared around 1905 (See Figure 1 and 2). Both photos show extensive cracking, broken windows and attempts to repair and reinforce the buildings. By 1907 the Miners Trading Company Building, built in 1893, was condemned and the Bermont's Stores (built 1892) second story was declared unsafe for occupancy.

ASSESSMENT OF DAMAGE CATEGORY

Following the cataloging and description of foundation damage it next became necessary to categorize, by group, the damage to the structures. To complete this phase one major assumption was made, that is, all damage to the buildings was caused by subsidence, not soils or material failure.

Figure 1. Bermont Stone, Lafayette, Colorado. Photo taken about 1910.

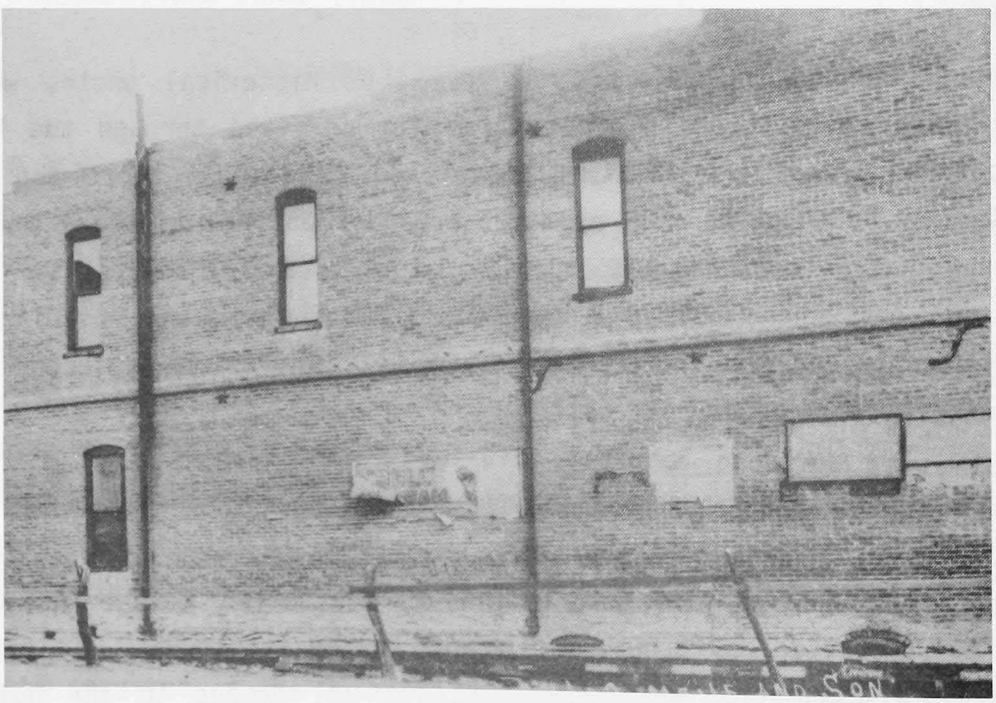


Figure 2. Miners Trading Company, Louisville, Colorado.

The individual damage categories were taken from the British National Coal Board (NCB) Subsidence Engineers Handbook (See Figure 3). Using the NCB damage descriptions, categories from slight to very severe damage were chosen for each structure.

SUBSIDENCE/STRAIN REQUIRED TO PRODUCE DAMAGE

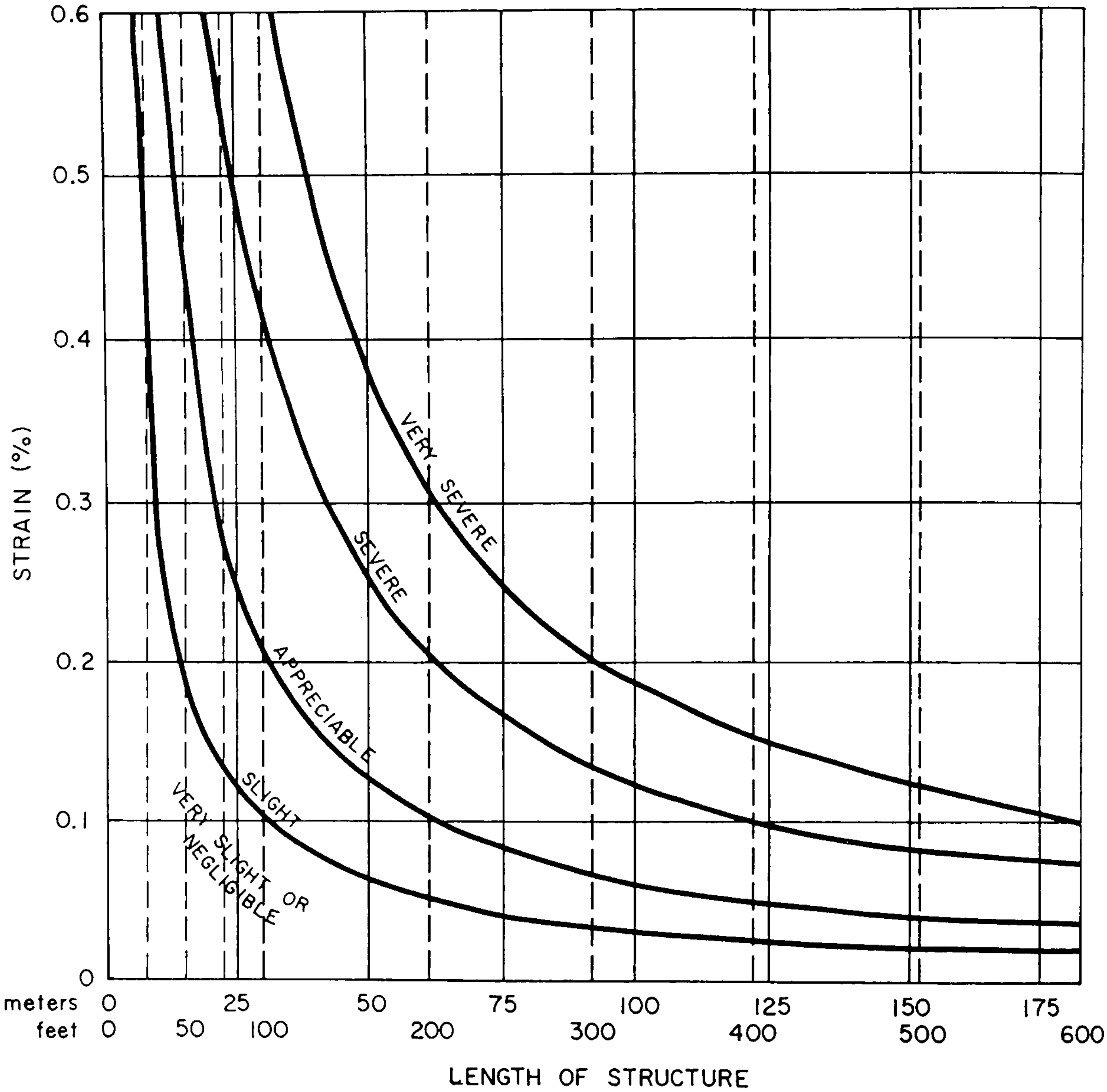
Following the placement of damage categories on the individual structures these categories were evaluated as to the strain required to produce the damage. Again it was necessary to utilize NCB charts relating maximum foundation length to percent strain (See Figure 3).

The maximum foundation length of each of the twenty-three pre-mining buildings was taken from the data sheets. This length was located on Figure 3 and compared to the lower limits of the damage category chosen for that structure. Subsequently the strain necessary to produce that level of damage was read from the chart and noted on the data sheets.

Figures 4 and 5 are the results of the strain to foundation length comparisons. The inferred strains for structures within Louisville and Lafayette were plotted with their relationship to individual structures square footage. Square footage was chosen over maximum foundation length to allow for easier application of the results to proposed future development plans.

As is noted from visual comparison of these two figures the slopes for each data cluster are significantly different. A possible explanation for this observation is that multi-seam extraction occurred beneath Louisville, thus significantly increasing the potential subsidence whereas only single seam mining occurred within the majority of Lafayette. An additional observation is that in both towns the maximum inferred strains occurred to brick structures.

The next step in this evaluation was to back calculate, using the NCB profile curve method, the subsidence necessary to produce the inferred strains. Using the drill hole data base developed by the author on previous subsidence investigations, the approximate depths to, and thickness of the mined interval(s) beneath each structure was determined and placed on the data sheets.



CLASS OF DAMAGE	DESCRIPTION OF TYPICAL DAMAGE
VERY SLIGHT OR NEGLIGIBLE	SLIGHT CRACKS SHOWING IN WALLS AND CEILINGS INSIDE BUILDINGS, BUT NOT VISIBLE ON OUTSIDE.
SLIGHT	SLIGHT CRACKS SHOWING INSIDE THE BUILDING. DOORS AND WINDOWS WILL NOT CLOSE.
APPRECIABLE	SLIGHT CRACKS SHOWING BOTH OUTSIDE AND INSIDE BUILDING. DOORS AND WINDOWS WILL NOT CLOSE. DRAINS, SEWERS, AND GAS PIPES FRACTURE.
SEVERE	DRAINS, SEWERS, AND GAS PIPES FRACTURE. OPEN FRACTURES THROUGH WALLS OF BUILDING. WINDOW AND DOOR FRAMES DISTORTED, FLOORS NOTICEABLY SLOPING, WALLS LEANING OR BULGING NOTICEABLY. SOME LOSS OF BEARING OF BEAMS ON WALLS. PORTICOES AND FLOORS BUCKLE.
VERY SEVERE	WORSE THAN ABOVE AND REQUIRING PARTIAL OR COMPLETE REBUILDING. ROOF AND FLOOR BEAMS LOSE BEARING AND WALLS LEAN BADLY AND NEED EXTERNAL SUPPORT. WINDOWS BROKEN AND DISTORTED. SEVERE SLOPES, BUCKLING AND BULGING OF ROOFS AND WALLS OCCUR.

(FROM N.C.B.)

Figure 3. Strain percent to length of structure.

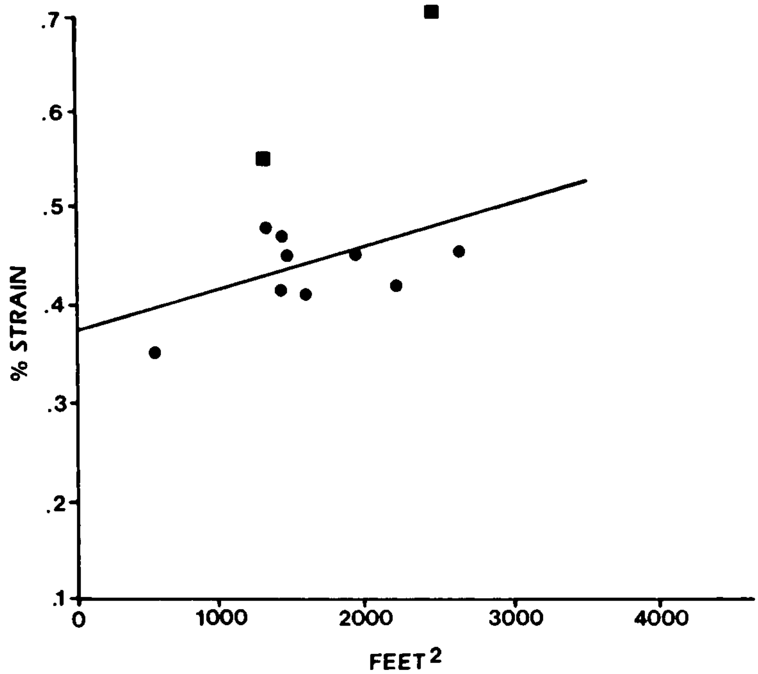


Figure 4. Comparison of percent of strain versus foundation size for Lafayette, Colorado.

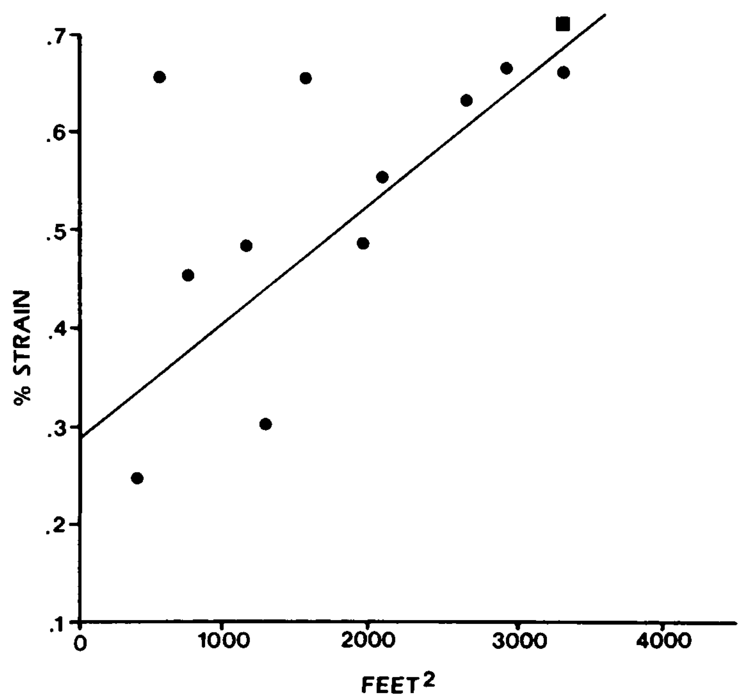


Figure 5. Comparison of percent of strain versus foundation size for Louisville, Colorado.

Note: Square indicates brick construction.

Three assumptions were required to proceed with study. These are: 1) "Trough" subsidence would predominate beneath the structures, 2) all panel widths are assumed to be super-critical and, 3) the subsidence ratio (Vz) would be taken as halfway between the solid stowing value (.45) and the caving value (.90) for supercritical widths (W/D ratio greater than 1.2).

The "back calculated" maximum subsidence value (Smax) was then compared to the actual seam thickness and the NCB Smax (Vz x seam thickness). This resulted in the average NCB Smax for Louisville being 11.2 feet based on 16 feet of coal extracted from two seams, and 5.6 feet for one 8 foot thick seam extracted beneath Lafayette. However, using the same criteria the average "back calculated" Smax for Louisville and Lafayette was 1.18 feet and 1.4 feet respectively. The "back calculated" Smax was substantially less than that of the NCB value. This would tentatively indicate that the Vz for the Boulder/Weld field would be on the order of 20% of the NCB value. From a practical stand point the results confirm the conservatism of the NCB strain prediction method.

ARCHITECHURAL TECHNIQUES TO REDUCE THE EFFECTS OF SUBSIDENCE

From the previous results, the following observations of strain resistant architechural techniques are presented for possible incorporation into proposed developments within undermined areas of the Boulder/Weld Coal Field:

1) Avoid two-story masonary structures
2) Limit maximum building footprint square footage to approximately 1300 square feet
3) Utilize shallow foundation techniques
4) Recommend the use of frame construction

DISCUSSION

The previous investigation was performed to provide a basis upon which to begin to understand the physical aspects of subsidence within the Boulder/Weld field. We in no way feel that the results of this preliminary study are of sufficient scientific validity to be incorporated into any subsidence prediction model. However, the general conclusion that the NCB divided Vz value is, if not accurate, at least conservative within the Boulder/Weld field, and the need to stress the overestimation of strains above abandoned mines bodes ill will for its use.

What is of significance are the architechural similarities of the structures surviving the undermining and the similarities of construction methods for buildings which failed. The incorporation of the subsidence resistant architechural designs into future development would go along way toward protecting investments. Conversely the stressing of the development of prediction methods based upon invalid or nonexistent observations is only an exercise in engineering arrogance.

CORE RECOVERY OF SOFT OR POORLY CONSOLIDATED MATERIALS

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ABSTRACT

The problems of core recovery in soft or poorly consolidated material are very broad and encompass numerous varieties of conditions and materials. It may be expected that methods and techniques for core recovery will also have much variety and involve special innovations particularly fitted to problem situations. It is only for the firm soils and the firm, hard rocks that coring methods have been narrowed to relatively standard procedures and techniques. The study (O'Rourke and others, 1978) described in this paper concentrated on areas of problem core recovery which range between soil sampling and rock coring. Soft ground and poorly consolidated materials are viewed as one extreme of the problem. Heavily fractured rock and materials containing broken rock and coarse gravels are viewed as the other extreme. In between, there are many variations to consider, such as, whether the soil or rock is fractured, friable, granular with mixed particle size, of plastic or non-plastic characteristics, of varying degrees of hardness, and whether above or below the groundwater table. The problem of core recovery also involves consideration of the mechanics of drilling, such as: types of coring bits, drilling fluids and additives, borehole size, and equipment for various material types and conditions. These items and other supporting equipment and techniques to core recovery methods are essential aspects of the overall problem, though not all can be discussed within the scope of this paper.

INTRODUCTION

The baseline for the literature review undertaken for this study was the classic publication of the American Society of Civil Engineers by M.J. Hvorslev, "Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes" dated 1949. This report was the product of an extensive research study of the Committee on Sampling and Testing in the Soil Mechanics and Foundation Division of ASCE with objectives that were closely related to the present study, and provided an initial background for core sampling of "soft" ground and unconsolidated materials together with the problems and difficulties of that time.

This appraisal of progress in coring techniques since then included review of worldwide technical publications written since 1949 and a canvas of the opinions of experienced Woodward-Clyde engineers and geologists throughout the United States. The emphasis of this approach was an assessment of practicality, reliability, and cost effectiveness of all the candidate core recovery techniques currently available. The results of the technique experience survey are presented in a table.

Out of this study, two rating matrices were developed. One matrix rates each technique as to its reported or expected success for sampling over a variety of soft or poorly consolidated materials, and the second matrix rates the performance characteristics of each technique within its relevant range of geologic applicability. Selected topics from the study, and the details of the matrices will be discussed in this paper.

DRILLING AND SAMPLING FOR CORE RECOVERY

Good core recovery is dependent to a significant degree on good drilling practice. When advancing a borehole for the purpose of recovering core at selected depths, a driller is primarily interested in advancing the hole as quickly as possible with little regard for downhole conditions. However, when drilling to recover core, the driller must utilize recommended techniques while lowering the sampler down the hole, while advancing the sampler into the material being sampled, and while removing the sampler with core from the hole. These techniques depend on several factors, including the method used to advance the sampler. The three methods most commonly used are driving, augering and rotary core drilling.

The cost and the time requirements involved in the performance of core recovery programs vary widely from the relatively low cost, rapid use of a drive sampler in a shallow hole, to the costly, time-consuming use of a rotary core barrel in a deep hole. Most commercial drillers are equipped to perform all three methods of sampling since more than one method may have to be used on a given subsurface investigation project, depending on factors that include geology, groundwater conditions, sample quality desired, and economics.

Drive sampling is commonly used in soils ranging from peats and soft clays to hard clays and very dense sands, both above and below the watertable. In some special cases, continuous drive sampling serves the dual function of advancing the hole and recovering core. Hvorslev (1949) classified the various methods used to force a drive sampler into the soil as: hammering, jacking, pushing, single blow, and shooting. Based on test results, Hvorslev recommended pushing for general use to obtain good quality samples. Hammering is used primarily in conjunction with performing a simultaneous standard penetration test in which a preliminary assessment of in situ soil properties can be made by determining the number of hammer blows required to advance a drive sampler a distance of one foot.

Augering is a common drilling method used to advance a borehole in soil independent of sampling operations and a rotary drill rig can be fitted for auger drilling with a spindle and auger adapter. The primary advantage of augering over rotary drilling is that it eliminates the need for drilling fluid to remove loose soil from the bottom of the borehole. The development of auger type samplers has made it possible to further exploit this advantage, but such sampling methods are limited in use to sands, silts and clays above the water table.

Rotary core drilling is a widely-practiced method which offers the most versatility in sampling since it can be used to obtain samples of rock as well as soil. Equipment costs are relatively substantial, as are time requirements for most sampling techniques used in conjunction with rotary drilling.

An important development in rotary core drilling equipment has been the standardization of drill rod, casing, core barrel, and coring bit dimensions through the efforts of the Diamond Core Drill Manufacturers Association (DCDMA). The principal involved in setting these standards is that the inside diameter of casing is large enough to permit drilling with the same designated size of coring equipment or for inserting the next smaller size of casing equipped with casing bit, casing shoe or casing drive shoe. Among the many practical implications of this standardization is the compatibility of drill tools supplied by different manufacturers (who subscribe to DCDMA standards). Also, the DCDMA is currently in the process of developing standards for auger equipment.

Sampling depth is essentially limited by the weight of drill rod, couplings, subs, sampler, bit and sample that can be safely handled using a given drill rig. A procedure used to maximize sampling depth is to use drill rods and core barrels of different designations, such as NW core barrel and AW drill rods. The latter is smaller and therefore lighter than NW drill road, and can easily be coupled with a NW core barrel using a standard adapter. Drill string weight and the rated capacity of the drill rig then represent the most significant limitations on sampling depth.

A number of other factors must be considered during any sampling operation, with rotary core drilling techniques involving many more variables than either drive sampling or augering techniques. Among the factors which must be considered are coring bit rotating speed, bit pressures and penetration rate, as well as the properties, circulation rate and pressure of the drilling fluid. Consequently, the most important consideration in any sampling operation is the ability and incentive of the driller to deal with all these factors successfully.

Drilling mud refers to a mixture of water and various additives having a greater specific gravity and viscosity than water alone. The science of drilling mud additives involves chemical technology which was considered beyond the scope of the study. Prepared commercial products under numerous trade names are available from industries specializing in this technology. The basic material used for drilling mud is a high-grade sodium bentonite and adjustments are generally accomplished by the quantities mixed with water. From the literature it appears that mixture weight of about 9 lbs per gallon is most commonly used.

Drilling mud can assist core recovery methods in soil in a number of ways; it provides borehole stabilization (which it accomplishes in part by increasing specific gravity and in part by the formation of a relatively impervious lining or "mudcake" on the side walls of the borehole), lifts drill cuttings, and assists in holding core in the sampler during recovery. Various adjustments must be made in the percentage of bentonite and chemical additives depending on the needed improvement in operation. When coring in rock, drilling fluid is used to perform additional functions such as cooling the bit, lubricating the drill pipe, and mitigating wear and corrosion of the drilling equipment. Expert advice on drilling fluids for specific sites and jobs can had for the asking from most suppliers of these products.

RELATIONSHIP OF SAMPLE SIZE TO SAMPLE QUALITY

Rowe (1971) discussed the relationship between sample size and sample quality from the viewpoint that the sample should reflect the fabric or microcharacteristics of the soil or rock being sampled. However, a more basic and practical point of view was taken by Hvorslev (1949) when he showed that during drive sampling most sample disturbance occurs at the top, bottom and along the sides of the sample, and that the interior of the sample is relatively undisturbed. Consequently, as sample volume increases the size of the "undisturbed" interior zone increases. In the case of rotary sampling, the torsional resistance of a core increases parabolically with the core diameter, thereby increasing the resistance of the core to being broken in torsion. The conclusion which can be drawn from these facts is that sample quality will increase as sample diameter increases. More recent research has shown this to be a valid conclusion (Bozozuk, 1971, Eden, 1971), although Osterberg (1969) cautions that it is unwise to jump to quick generalizations about the effect of sample size on disturbance. A summary of sample sizes for various testing or classification purposes, as recommended by Hvorslev is given in Table 1.

General State of Practice

Sampling and coring techniques may be broadly grouped into the following categories, wherein all categories are related to the type and condition of the material (soil or rock) to be sampled:

(A) Drive samplers
(B) Auger samplers
(C) Rotary coring samplers - soils
(D) Rotary coring samplers - rock
(E) Special techniques

Equipment in each of these categories is described in detail by Hvorslev in his study on core sampling (1949). The practice of core sampling has not seen a great deal of technical innovation since then. The technological advances that were made include somewhat improved mechanical equipment for general sampling tools, though mainly towards more power, more convenience, and improved mechanical details, and some relatively customized tools for sampling in special geological conditions. There has been relatively little change in the essentials of making borings and in the methodology of sampling (Osterberg, 1969).

Generally speaking, it has become common practice to use thick-walled open drive samplers, (e.g., STP sampler, California sampler) and thin-walled open drive samplers (Shelby tube) in subsurface exploration and sampling of soils whenever possible, particularly for small to medium size construction projects. Although engineers consider the number, location and total depth of borings to be made, there is not as much thought given to the number of samples to be taken or the depths at which they should be taken. Generally it is recommended practice that samples be taken every 5 feet and at each change in strata. Engineers tend to rely heavily (sometimes almost exclusively) on the use of "Standard Penetration Test" split spoon samplers, conditions permitting, to obtain a log of penetration resistance with depth as well as to obtain samples for identification purposes. The acceptability of results from this common practice is greatest in situations where an engineer has had experience with the soil conditions in a specific location and where the work is performed by reputable drillers. The driller's talent has significant effect on the standardization required for meaningful results.

In the case of large, important, or special construction and mining projects there is no such definitive standard of practice. Split spoon and Shelby tube samplers still form the basis for the bulk of such subsurface exploration, and consideration is given to obtaining additional quantities of good quality samples for broader categories of laboratory testing. A common acceptable procedure is to perform preliminary explorations using augers and split spoon samplers, and then a more detailed exploration using thin-walled piston samplers, Pitcher samplers, Dension samplers, and "M" design double tube core barrels for obtaining samples of soil and soft rock.

In almost all cases the need for reputable drillers to perform the work cannot be overemphasized since it is possible for a good driller to get better quality samples using a thin-walled open drive sampler than a bad driller can get using a more elaborate or special sampler. Since commercial drillers do not generally carry "special" samplers as part of their equipment, the burden is on the engineer to supply the sampler as well as technicians to instruct the driller. Drillers are amenable to using just about any type of sampling device provided that a good working relationship is developed between the drillers and engineers and that appropriate contractual arrangements are made. The economics involved in this situation are usually justified in the case of large, important or special subsurface investigations.

ASTM has established a standard method for diamond core drilling for site investigation (ASTM Standard D2113-70). Recommendations are made as to the apparatus and procedure to be used as well as the information which should be contained in field reports. The specification includes a listing of the Diamond Core Drill Manufacturers Association standards for core barrel and casing dimensions. Details of techniques are not given, but brief listings of equipment that are now considered standard are given.

ASTM has also established a standard recommended practice for investigating and sampling soil and rock for engineering purposes (ASTM Standard D420-69). A short but detailed summary is given of sampling significance, apparatus, reconnaissance of project area, soil-profile determination, subsurface profile, sampling, classification of material, interpretation of results, and information which should be contained in field reports.

Soft or Poorly Consolidated Materials Practice

No one technique is appropriate for sampling all the soft or poorly consolidated materials considered in the study. However, within a particular category of techniques such as rotary soil samplers, several samplers may be useful for sampling the same types of unconsolidated materials. An objective evaluation was made to determine which techniques can be used to sample the various materials most efficiently.

The efficiency of a coring or sampling technique was determined by considering not only its reported success in sampling of soft or unconsolidated materials, but also the technical characteristics of its operation and use. Sampling techniques range from simply driving a tube into the subsoil to the sophistication of a special rotary, double-tube, swivel-type core barrel which envelops the core in a rubber sleeve as it enters the core barrel. Although the capability of a sampling technique to obtain quality samples of a wide variety of materials increases with the amount of mechanical sophistication, this also increases the cost, the complexity of operation, and the susceptibility to malfunction. The most efficient sampling techniques will be those which may be used to obtain quality samples of a wide variety of materials with a minimum of sophistication.

In order to deal with the large variety of samplers and range of soft and poorly consolidated strata conditions considered in this paper, a Technique Experience Table (Table 2) was prepared based on the information compiled from the review of over 100 published papers, plus manufacturers technical data. Candidate samplers presented in the table are those which were reported in the literature as reasonably successful for obtaining samples of materials within the scope of soft or poorly consolidated geologic materials. The table demonstrates the geologic conditions in which each "candidate" sampler was used with reasonable success. The geologic materials are listed under generalized descriptions defined as follows:

a) Moderately Jointed - Tightly Jointed: joints are present but are intact and somewhat resistant to disturbance.
b) Moderately Jointed - Infilled Joints: joints contain material of somewhat softer characteristics which is cohesive or plastic and susceptible to movement and erosion when cored.
c) Weak, Rock, Low Grade Metamorphic: moderately firm, possibly brittle, but resistant to disturbance.
d) Weak Rock - Foliated, Schistose, Slately: brittle and subject to parting or chipping while being cored.
e) Strongly Fractured - Hard: rock is hard but fractures are dense and intersecting; any core would need support since fractured chunks can separate easily.
f) Strongly Fractured - Soft and Friable: rock is not only fractured but is crumbly; being friable, it can be cut with proper bit and technique.

g) Interbedded Hard and Soft Strata: alternating seams of hard and soft material; soft material could be cohesive or plastic and subject to movement when cored.

h) Weakly Cemented Conglomerate or Agglomerate: round or angular variable sized rock or gravel fragments cemented together with material assumed to be weak.

i) Weakly Cemented - Fine-Grained: commonly sandstone, siltstone, or claystone in which a weak cementing material such as calcium carbonate is present.

j) Gravels: predominantly coarse-grained material with little or no cohesion between grains.

k) Sands: predominantly medium-grained material with little or no cohesion between grains.

l) Silts: fine-grained material with slight plasticity between grains.

m) Clays: fine-grained, cohesive or plastic material.

It should be recognized that these descriptions had to be general enough to account for the wide variation in geologic conditions possible and at the same time specific enough for practical correlation with special cases; for example, gouge material along a fault zone might be comparable to b) moderately jointed - infilled joints.

A technique applications matrix was next developed to quantify the information shown in Table 2 and to objectively evaluate how successfully the various sampling techniques have been used over the range of geologic conditions considered. For each generalized geologic condition, each sampling technique was rated on a scale of 1 to 4 based on information extracted from the literature or from in-house experience using the following criteria:

4 = generally successful

3 = reported as successful in many cases but with difficulties due to certain conditions of the soils or rock.

2 = reported as successful only where very special techniques are used or very special soil or rock conditions exist.

1 = usually not applicable or not used.

A separate matrix was then developed to evaluate the sophistication and operating characteristics of the various sampling and coring techniques. It was decided to consider thirteen variables in this matrix, which are defined as follows:

1. State of Development: the state of development of a technique and the availability of equipment from commercial manufacturers.

2. Cost of Sampler: the cost of samplers or core barrels and necessary accessories except for drill rods, coring bits, reaming shells or core lifters.

3. Complexity of Use: the ability and training of personnel required to use technique successfully.

4. Water Table Influence: the difficulty of obtaining samples below the ground water table.

5. Equipment Durability: the degree of sophistication and susceptibility to malfunction based on the amount and complexity of movable parts or fluid passages.

6. Influence on Drilling Rate: based on the assumption that a continuous subsurface profile is required, how much additional time is required to recover core samples relative to the time required to advance the hole by drilling only.

7. Core Diameter: the maximum diameter of a sample which can be obtained with the technique.

8. Friction: qualitative measure of the sliding and rotational friction forces exerted on a sample as it enters a sampler or core barrel.

9. Core Blockage: capability of indicating to the driller if core block has occurred and likelihood of any sample recovery in this situation.

10. Variability of Coring Pressures: capability of sampler to efficiently divide the available cutting force between hole cutting and sample cutting in variable strata hardness, generally by adjusting the position of an inner sampling tube with respect to the outer cutting bit.

11. Core Lifting: effectiveness of mechanisms by which a sample is broken away from the subsoil and retained in the sampler of core barrel when lifted to the surface.

12. In Situ Orientation: capability of coring or sampling technique for supplying information relative to the in situ orientation of a sample.

13. Sample Quality (soil/rock): extent of the information which can be validly obtained from the resulting soil or rock sample.

Using these thirteen variables, a technique-performance characteristics matrix was developed in which, for each performance characteristic, each sampling technique was rated on a scale of 1 to 4 using the criteria shown in Table 3. As before, it must be recognized that these variables and criteria had to be general enough to account for the wide variation in characteristics of coring or sampling techniques, and at the same time specific enough to identify which techniques are most practical for a user's given set of circumstances.

The Technique Application (TA) Matrix and Technique Performance Characteristics (TPC) Matrix are shown side-by-side in Table 4. This format was chosen to best maximize comprehension since the true value of ratings in the TPC matrix can only be appreciated in the context of ratings in the TA matrix. That is, the performance characteristics rating which is given to a particular coring or sampling technique in the TPC matrix are only valid in the geologic conditions for which it is given a capable rating in the TA matrix. Total scores for each candidate sampling technique were purposely omitted for both matrices because the importance of a given geologic condition or performance factor (e.g., cost) is expected to vary from one job to another. The reader is urged to assign his own weighting factor to the variables listed in the matrices, thereby arriving at total scores for final sampling technique selections that are pertinent to his real needs.

By virtue of the practical nature of the TPC matrix and the generalized nature of the TA matrix, this rating method is considered to provide a comprehensive and useful evaluation of the efficiency of the candidate techniques for sampling soft or poorly consolidated materials. Caution should be taken when using these ratings for purposes of comparisons; that is, soil samplers cannot be validly compared to rock samplers. In particular, it would not be appropriate to compare piston drive samplers with rotary rock barrels but it may be appropriate to compare piston drive samplers with rotary soil samplers provided the condition of the soil is considered (i.e., density, plasticity, etc.). The intended purpose of these ratings is to show at a glance which sampling or coring techniques have been reported in the literature reviewed, or through in-house experience, as the most versatile over a range of soft or poorly consolidated materials, as well as having good performance characteristics. Based on these ratings it is possible to make an objective decision in selecting perhaps one or two techniques which can be expected to be used satisfactorily for sampling the soft or poorly consolidated materials of interest at a particular site.

In the interest of clarity, a few comments are required regarding technique description, generalized geologic descriptions and ratings which appear in the matrices. The semi-fixed (stationary) piston sampler represents piston samplers that are only partially fixed and would require auxiliary clamps to be fully effective for high quality soil sampling. The large diameter swivel-type double-tube core barrel meets DCDMA standards for M-design bit and core lifter, and although it can be used for the same applications as the smaller diameter core barrel, it received a lower rating in certain rock categories of the TA matrix because bulkiness makes it less practical. Based on a similar line of reasoning, the rubber-sleeve double tube core barrel received a rating of 1 or 2 in rock categories of the TA matrix for which it would be applicable but not very practical. Finally, it should be noted that the generalized geologic category of clays is restricted to soft or poorly consolidated clay-like materials and does not include firm, stiff or hard clays. From a broad general viewpoint, the descriptions for gravel and sands are intended to include material with small amounts of cohesive binder.

SUMMARY AND CONCLUSIONS

The Technique Application (TA) matric rates each technique for its reported as well as its considered ability to successfully recover core in a variety of idealized soft or poorly consolidated geologic conditions.. While the technique experience bar chart only summarizes the reported use of a technique over a range of geologic conditions, the TA matrix presents a quality rating for each technique in each of the geologic conditions. A rating of 1 indicates that a given technique is not generally suitable for a given geologic condition whereas a rating of 4 indicates that a technique has been reported as generally successful in sampling a given soft or poorly consolidated geologic material. Consequently, the field of candidate techniques might be narrowed at this point.

The Technique Performance Characteristics (TPC) matrix rates each technique against a selected listing of performance factors that include cost, operation, and equipment durability. Rating criteria were carefully formulated to represent the range of possibilities for these factors as described in the literature and in manufacturers' specifications. A numerical rating range of 1 to 4 was established to represent least favorable to most favorable possibilities of a given characteristic. Occasionally, the rating criterion for a 4 in the TPC was knowingly set beyond present capabilities to allow for expected future development in those performance factors. Thus, in the TPC as well as the TA matrix there are performance characteristics or geologic conditions for which few if any sampling techniques were given a rating of 4, and these factors represent areas which merit future attention for research and development (e.g., sampling gravel).

Presently it is the driller's skill and experience which have primary control over the results of any coring program. in view of the adverse operating conditions under which drillers generally work, the tedious and repetitive nature of core drilling, and the high level of mechanical ability required of drillers, there is a limited number of drillers who consistently and reliably use various sampling techniques correctly. It is felt that there is a potential for instrumentation and research to identify optimum core recovery procedures that minimize the driller's influence and maximize automation, or at least improve the engineer or geologist's inspection capability of the core drilling operation, since the driller will always be an integral component of any sampling operation.

Any approach to dealing with driller influence on core drilling in the immediate future must be aimed at increasing driller awareness of the need for quality samples. The training course conducted by Acker Drill Company and films available from Soiltest, Inc., represent efforts made in this direction. However, exposure to this type of training could not be expected to optimize driller competence unless measures are taken to periodically field-check driller performance. A procedure which is used on large construction projects to verify the competence of skilled craftsman is to have each person perform a "hands-on" qualification test. This test basically requires that a skilled craftsman perform a task within his (or her) discipline while being closely observed. For example, an inspector might observe a welder's technique in welding a test coupon in all positions, such as overhead, vertical and horizontal, and the test coupon would also be inspected in the laboratory for gas or slag inclusions and strength. In the case of the drillers, a similar testing might require that they core drill a qualification test hole wherein they would be graded on technique, and perhaps several recovered core samples would be inspected in the lab for consistency of quality. Procedures such as this could serve as site certification tests for drillers without the formality and paper work normally associated with licensing.

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Table 1. Sample requirements.

PHASE OF EXPLOR.		TYPE OF TEST	CONDITION OF SAMPLE	QUANTITY OF SOIL OR WATER OR DIAMETER OF SAMPLE
Reconnais. Explorat.		Visual Classification Occasionally approx. Water Content, Limits	Repres.	Augers, cup, or 1 to 2 in. samples. Preserve at least 1/5 pint and preferably 1/2 pint in case of tests
Detailed Exploration Minor Physical Tests		Liquid and Plastic Limits Mechanical Analysis Specific Gravity	Repres.	Fine-grained soils 1/2 pint minim. Mechan. analysis of coarse-grained to gravelly soils 1 pint to 2 quarts
		Water Content Unit Weight	No vol. change	1-3/4 to 2 in. samples usually adequate; 2-1/8 to 2-7/8 in. samples often used. In test pits 3 to 4 in. samples or field volume tests plus 1 to 2 quarts representative sample of coarse-grained to gravelly soils
		Unconfined Compression Direct Shear, Double, Rd. Slicing, Partial Drying	Undist.	
Special Explorations Major Physical Tests		Permeability Consolidation Triaxial Compression	Undist.	2 in. samples occasionally used but 2-7/8 in. diam. advisable minimum and 4 to 6 in. diam. preferable
		Multiple Compres. Tests Direct Shear, Single, Sq. Torsion Shear, Ring	Undist.	4-3/4 in. diam. advisable minimum 5 to 6 in. diam. often used. In test pits 5 to 8 in. round or 10 in. cubes
Construction Materials	Exploration	Mechanical Analysis Compaction and CBR Tests Triaxial Compression Concrete Aggregate Tests	Repres. or Composite Repres.	From single strata or holes 100 lb to 200 lb. Composite sample for a complete series of tests 500 lb. Samples for aggregates see text
	Control	Dry Density, Water Cont. California Bearing Ratio Triaxial Compression	Undist.	Density 2 to 4 in. diam. samples or field volume tests. Others 5 in. min. diam., CBR mold, or 10 in. cubes
Water		Chemical Analysis Bacteriological Analysis	Repres.	1 quart to 1 gallon depending on laboratory method and equipment
Rock Drilling		Visual Inspection Mineralogical Tests Compression, Shear Porosity, Permeability	Undist.	Minim. 7/8 or 1-1/8 in. (EX, AX) 1-5/8 or 2-1/8 in. (BX, NX) preferred because of better recovery. In soft or broken rock 3 to 6 in. diam.

(after Hvorslev, 1949)

Table 2. Technique experience references.

PAGE IN TEXT	SAMPLING TECHNIQUE	Moderate Jointed Rock: Tightly Jointed	Moderate Jointed Rock: Infilled Joints	Weak Rock: Low Grade Metamorphic	Weak Rock: Foliated, Schistose, Slatey	Strongly Fractured: Hard	Strongly Fractured: Soft or Friable	Interbedded Hard and Soft	Weakly Cemented: Conglomerate/Agglomerate	Weakly Cemented: Fine-grained, Weak	Gravels	Sands	Silts	Clays
	OPEN DRIVE SAMPLERS													
28	Thin-Walled Tube Sampler (ASTM D-1587)				(2,22,23,25,42,51,54,92)/(1,7,38,88,94,96,97,102)									
28	Thick-Walled Sampler (SPT, ASTM D-1586)										(-)/(1,38,88,97,102)			
28	Large Diameter Thick-Walled Sampler										(-)/(1,38,97,102)			
61	Double Tube Continuous Drive Sampler												(*)	
59	Wit Sampler with Membrane Retainer											(103)/(-)		
30	M.I.T. Sampler with Retainer and Piano Wire												(-)/(38)	
61	Square Tube Sampler												(101)/(-)	
	PISTON DRIVE SAMPLERS													
34	Fixed Piston, Thin-Walled Sampler (Hvorslev Type)									(22,23,42,93)/(55,92,94)				
34	Stationary Piston Sampler										(-)/(1,38,77,97)			
61	Hydraulic, Fixed Piston Thin-Walled Sampler (Osterberg Type)								(22,23,28)/(38,71,94,102)					
36	Stationary Piston Sampler with Liner												(-)/(102)	
31	Free Piston Sampler											(-)/(38)		
31	Retractable Plug Sampler											(-)/(38,102)		
61	Delft Mud Sampler											(-)/(10)		
	FOIL SAMPLERS/AUGER SAMPLERS													
36	Swedish Foil Sampler										(28)/(45,88,102)			
36	Delft Foil Sampler											(-)/(9)		
67	Foil Sampler with Rotary Coring Bit											(20)/(29)		
67	Rubber-Sleeved Double-Tube Core Barrel		(44,46)/(4,32,44)											
38	Double-Tube Auger										(2,23,107)/(102)			
38	Shrouded Auger												(*)	

Table 2. (cont.) Technique experience references.

PAGE IN TEXT	SAMPLING TECHNIQUE	References	Moderate Jointed Rock: Tightly Jointed	Moderate Jointed Rock: Infilled Joints	Weak Rock: Low Grade Metamorphic	Weak Rock: Foliated, Schistose, Slatey	Strongly Fractured: Hard	Strongly Fractured: Soft or Friable	Interbedded Hard and Soft	Weakly Cemented: Conglomerate/ Agglomerate	Weakly Cemented: Fine-grained, Weak	Gravels	Sands	Silts	Clays
	DOUBLE-TUBE CORE BARRELS														
40	Denison Type Sampler	(22,23,30,42,81)/(1,38,55,81,88,94,102)						□	□	□	□		■	■	■
71	Pitcher Type Sampler	(23,63)/(88,94,96,102)							■	□	□		■	■	■
42	Large Diameter Swivel Type, core lifter in inner barrel	(25,26,35,48,74,95)/(1,32,55,102)			■	■	■	■	■	■	■	□	■	■	
42	Swivel Type, core lifter in inner barrel (DCDMA Standard M-Design)	(25,48,49,50,65,83)/(1,32,38,94,102)	■	■	■	■	■	■	□	□	■				
42	Swivel Type, core lifter in outer barrel (X-Design)	(-)/(1,38)	□	□	□	□	□		□	□					
74	Swivel Type, Retractable Triple Tube (Australian Design)	(2,64)/(7,11,32,66)			■	■	□	■	■	□	■		□	□	
42	Wireline, Double-Tube	(68,82)/(1,4,102)	■	■	□	□	□	□	□	□	□			□	□
71	Wireline, Double-Tube with Liner	(68)/(32)	■	■	■	■	■	■	■	■	■			□	□
	SPECIAL TECHNIQUES														
71	Open Spindle Hollow Stem Auger (MOSS Technique)	(*)										□	□	□	□
50	Orienting Double-Tube Core Barrel	(98)/(44,60)	■	■	■	■	■	■	■	■	■				
50	Bishop Sand Sampler	(14,106)/(38,78,88)											■	□	
79	Integral Sampling	(75,76)/(12,102)	■	■	■	■	■	■	■	□	□				
47	Reverse Circulation Central Sample Return (CSR Technique)	(33,47)/(99)	□		□	□	□	□			□				□
45	Pressure Core Barrel	(-)/(32,38,44)									□		□	□	

APPLICATIONS - GEOLOGIC CONDITIONS

EXPLANATORY NOTES

(field experience references)/(general references)

(-) no applicable references

(*) based on manufacturers' literature only

■ reported applications

□ inferred applications

Table 3. Technical performance characteristics matrix rating criteria.

EVALUATION CATEGORY \ RATING		1	2	3	4
State of Development		Research and development	Operational but user fabricated	Commercially available on special order	Readily available
Cost of Sampler		More than $2,000	$800 to $2,000	$300 to $800	Less than $300
Complexity of Use		Specialist operator required	Technical field supervision, average driller	Better than average driller capable	Average driller capable
Water Table Influence		Not suitable below water table	Recovery and quality of sample questionable	Satisfactory below with normal care	Relatively trouble-free below
Equipment Durability		Several moving parts including complex valves and latches	Several moving parts including check valves and sliding mechanisms -or- drilled passages for circulating fluids	Few moving parts such as bearings, core retrievers -or- fixed seals	All metal, rigid construction
Influence on Drilling Rate		Continuous sampling not possible, must advance and clean hole between sampling intervals	Continuous sampling possible but must regularly remove sampler; moderate to heavy time requirement to remove and replace sampler	Continuous sampling possible but must regularly remove sampler from hole; minimal time requirement to remove and replace sampler	Continuous sampling possible without removing sampler from hole
Core Diameter		Less than 2.0 inches	2.0 inches to 3.0 inches	3.0 inches to 4.0 inches	More than 4.0 inches
Friction		Rotary samplers without double tube; all drive samplers (except foil sampler)	Double tube rotary samplers in which both barrels rotate	Double tube rotary samplers in which inner barrel does not rotate, core retainer in outer barrel does rotate	Double tube rotary samplers with core retainer in nonrotating inner barrel -or- foil drive samplers
Core Blockage		No warning, recovery unlikely	No warning, some recovery possible	Warning signalled to driller on surface	Sampler advance halts automatically at core blockage
Variability of Coring Pressures		All drive samplers -or- rotary samplers without double tube -or- double tube rotary samplers in which inner barrel cannot protrude from outer barrel	Double-tube swivel-type rotary samplers in which inner barrel can protrude from outer barrel; adjustments possible only when sampler on surface	Double-tube swivel-type rotary samplers in which inner barrel can protrude from outer barrel; down-hole adjustment possible while sampling (springs, etc.)	Double-tube swivel-type rotary samplers in which inner barrel can protrude from outer barrel; adjustment possible by driller while sampling
Core Lifting		Sample retained by side friction only	Sample retained by fluid pressures and side friction only	One way sample entry device, moderate mechanical support of sample (core lifters, retainers, etc.)	Sample mechanically separated from subsoil, complete mechanical support of sample
In Situ Orientation		Not possible	Possible with respect to two horizontal axes if sampler orientation can be monitored on surface while sampling	Possible with respect to two horizontal axes without surface monitoring of sampler orientation while down hole	Fully oriented vertically and horizontally without surface monitoring of sampler orientation while down hole
Core Quality	Soils	Not core sample; Random disturbed material, visual classification only	Not core sample; Visual classification, grain size distribution	"Disturbed" core sample; Visual classification, grain size distribution, dry density	"Undisturbed" core sample; Visual classification, grain size distribution, dry density, water content, shear strength, compression index
	Rock	Chips and pieces; Rock type characteristics, (minerology, petrography)	Core sample; Rock type characteristics, joint distribution (i.e., frequency, Rock Quality Designation)	Core sample; Rock type characteristics, joint distribution, joint characteristics (width, infill material, mineralization)	Core sample; Rock type characteristics, joint distribution, joint characteristics, engineering properties (compressive strength, seismic velocities, modulus, etc.)

Table 4a. TA matrix/TPC matrix: open drive samplers.

TECHNIQUE APPLICATIONS MATRIX

PAGE IN TEXT	SAMPLING TECHNIQUE	APPLICATIONS - GEOLOGIC CONDITIONS												
		Moderate Jointed Rock		Weak Rock		Strongly Fractured			Weakly Cemented					
		Tightly Jointed	Infilled Joints	Low Grade Metamorphic	Foliated, Schistose, Slatey	Hard	Soft or Friable	Interbedded Hard and Soft	Conglomerate/ Agglomerate	Fine-grained, Weak	Gravels	Sands	Silts	Clays
28	Thin-Walled Tube Sampler (ASTM D-1587)	1	1	1	1	1	1	1	1	1	1	2	4	4
28	Thick-Walled Sampler (SPT, ASTM D-1586)	1	1	1	1	1	1	1	1	1	1	4	3	3
28	Large Diameter Thick-Walled Sampler	1	1	1	1	1	1	1	1	1	1	3	3	2
61	Double Tube Continuous Drive Sampler	1	1	1	1	1	1	1	1	1	1	2	2	2
59	Wit Sampler with Membrane Retainer	1	1	1	1	1	1	1	1	1	1	4	3	3
30	M.I.T. Sampler with Retainer and Piano Wire	1	1	1	1	1	1	1	1	1	1	1	1	4
61	Square Tube Sampler	1	1	1	1	1	1	1	1	1	1	1	1	4

RATING SCALE: 4 Best, 1 Worst.
For elaboration, see Section 5.1

TECHNIQUE PERFORMANCE CHARACTERISTICS MATRIX

PERFORMANCE CHARACTERISTICS													
State of Development	Cost of Sampler	Complexity of Use	Water Table Influence	Equipment Durability	Drilling Impact	Core Diameter	Friction	Core Blockage	Variability of Coring Pressures	Core Lifting	In Situ Orientation	Core Quality	
												Soil	Rock
4	4	4	3	4	1	4	1	2	1	2	2	4	NA
4	4	4	2	4	1	1	1	2	1	1	1	2	NA
4	4	4	2	3	1	4	1	2	1	3	2	2	NA
3	1	4	2	3	3	2	1	2	1	1	2	2	NA
1	2	3	4	2	1	2	1	2	1	4	2	4	NA
3	3	4	3	3	1	4	1	2	1	2	2	4	NA
2	3	4	3	4	1	2	1	2	1	1	2	4	NA

RATING SCALE: 4 Best, 1 Worst.
For elaboration, see Table 5.2

Table 4b. TA matrix/TPC matrix: piston drive samplers.

TECHNIQUE APPLICATIONS MATRIX

PAGE IN TEXT	SAMPLING TECHNIQUE	APPLICATIONS - GEOLOGIC CONDITIONS												
		Moderate Jointed Rock		Weak Rock		Strongly Fractured			Weakly Cemented					
		Tightly Jointed	Infilled Joints	Low Grade Metamorphic	Foliated, Schistose, Slatey	Hard	Soft or Friable	Interbedded Hard and Soft	Conglomerate/Agglomerate	Fine-grained, Weak	Gravels	Sands	Silts	Clays
34	Fixed Piston, Thin-Walled Sampler (Hvorslev Type)	1	1	1	1	1	1	1	1	1	1	4	4	4
34	Stationary Piston Sampler	1	1	1	1	1	1	1	1	1	1	3	3	3
61	Hydraulic, Fixed Piston Thin-Walled Sampler (Osterberg Type)	1	1	1	1	1	1	1	1	1	1	4	4	4
36	Stationary Piston Sampler with Liner	1	1	1	1	1	1	1	1	1	1	1	4	4
31	Free Piston Sampler	1	1	1	1	1	1	1	1	1	1	2	3	4
31	Retractable Plug Sampler	1	1	1	1	1	1	1	1	1	1	4	4	4
61	Delft Mud Sampler	1	1	1	1	1	1	1	1	1	1	4	4	4

RATING SCALE: 4 Best, 1 Worst.
For elaboration, see Section 5.1

TECHNIQUE PERFORMANCE CHARACTERISTICS MATRIX

SAMPLING TECHNIQUE	PERFORMANCE CHARACTERISTICS												Core Quality	
	State of Development	Cost of Sampler	Complexity of Use	Water Table Influence	Equipment Durability	Drilling Impact	Core Diameter	Friction	Core Blockage	Variability of Coring Pressures	Core Lifting	In Situ Orientation	Soil	Rock
Fixed Piston, Thin-Walled Sampler (Hvorslev Type)	3	2	3	4	2	1	4	1	2	1	2	2	4	NA
Stationary Piston Sampler	4	3	3	4	2	1	4	1	2	1	2	2	4	NA
Hydraulic, Fixed Piston Thin-Walled Sampler (Osterberg Type)	4	2	3	4	2	1	4	1	2	1	2	2	4	NA
Stationary Piston Sampler with Liner	3	3	3	4	2	1	2	1	2	1	2	2	4	NA
Free Piston Sampler	3	3	3	4	2	1	2	1	2	1	2	2	3	NA
Retractable Plug Sampler	4	3	4	4	3	1	1	1	2	1	2	2	2	NA
Delft Mud Sampler	1	3	2	4	1	4	1	1	2	1	3	1	3	NA

RATING SCALE: 4 Best, 1 Worst.
For elaboration, see Table 5.2

Table 4c. TA matrix/TPC matrix: fail samplers/auger samplers.

TECHNIQUE APPLICATIONS MATRIX

PAGE IN TEXT	SAMPLING TECHNIQUE	APPLICATIONS - GEOLOGIC CONDITIONS: Moderate Jointed Rock: Tightly Jointed	Moderate Jointed Rock: Infilled Joints	Weak Rock: Low Grade Metamorphic	Weak Rock: Foliated, Schistose, Slatey	Strongly Fractured: Hard	Strongly Fractured: Soft or Friable	Interbedded Hard and Soft	Weakly Cemented: Conglomerate/Agglomerate	Weakly Cemented: Fine-grained, Weak	Gravels	Sands	Silts	Clays
36	Swedish Foil Sampler	1	1	1	1	1	1	1	1	1	1	3	3	4
36	Delft Foil Sampler	1	1	1	1	1	1	1	1	1	1	3	2	4
67	Foil Sampler with Rotary Coring Bit	1	1	1	1	1	1	1	1	1	1	3	3	4
67	Rubber-Sleeved Double-Tube Core Barrel	1	2	3	3	4	4	4	4	4	1	1	1	1
38	Double-Tube Auger	1	1	1	1	1	1	1	1	1	1	2	4	3
38	Shrouded Auger	1	1	1	1	1	1	1	1	1	1	3	3	3

RATING SCALE: 4 Best, 1 Worst.
For elaboration, see Section 5.1

TECHNIQUE PERFORMANCE CHARACTERISTICS MATRIX

SAMPLING TECHNIQUE	PERFORMANCE CHARACTERISTICS: State of Development	Cost of Sampler	Complexity of Use	Water Table Influence	Equipment Durability	Drilling Impact	Core Diameter	Friction	Core Blockage	Variability of Coring Pressures	Core Lifting	In Situ Orientation	Core Quality: Soil	Core Quality: Rock
Swedish Foil Sampler	3	1	1	4	2	4	2	4	2	1	1	2	4	NA
Delft Foil Sampler	1	1	1	4	2	2	2	4	2	1	4	1	4	NA
Foil Sampler with Rotary Coring Bit	1	1	1	3	1	2	3	4	2	2	1	1	4	NA
Rubber-Sleeved Double-Tube Core Barrel	3	1	1	4	1	2	1	4	2	1	4	1	NA	4
Double-Tube Auger	4	3	3	1	3	2	4	4	2	2	2	1	4	NA
Shrouded Auger	4	3	3	3	2	1	NA	NA	NA	NA	4	1	2	NA

RATING SCALE: 4 Best, 1 Worst.
For elaboration, see Table 5.2

Table 4d. TA matrix/TPC matrix: double tube core barrels.

TECHNIQUE APPLICATIONS MATRIX

PAGE IN TEXT	SAMPLING TECHNIQUE	APPLICATIONS - GEOLOGIC CONDITIONS: Moderate Jointed Rock: Tightly Jointed	Moderate Jointed Rock: Infilled Joints	Weak Rock: Low Grade Metamorphic	Weak Rock: Foliated, Schistose, Slatey	Strongly Fractured: Hard	Strongly Fractured: Soft or Friable	Interbedded Hard and Soft	Weakly Cemented: Conglomerate/Agglomerate	Weakly Cemented: Fine-grained, Weak	Gravels	Sands	Silts	Clays
40	Denison Type Sampler	1	1	1	1	1	2	2	2	3	1	3	3	3
71	Pitcher Type Sampler	1	1	1	1	1	1	3	2	3	1	3	3	3
42	Large Diameter Swivel Type, core lifter in inner barrel	1	1	2	2	3	4	3	3	4	2	2	2	1
42	Swivel Type, core lifter in inner barrel (DCDMA Standard M-Design)	4	3	3	3	2	2	3	2	2	1	1	1	1
42	Swivel Type, core lifter in outer barrel (X-Design)	4	2	2	2	2	1	2	2	1	1	1	1	1
74	Swivel Type, Retractable Triple Tube (Australian Design)	1	1	2	2	2	4	4	3	4	1	2	2	1
42	Wireline, Double-Tube	4	3	3	2	2	2	2	2	2	1	1	2	2
71	Wireline, Double-Tube with Liner	4	3	3	2	4	2	3	3	3	1	1	2	2

RATING SCALE: 4 Best, 1 Worst.
For elaboration, see Section 5.1

TECHNIQUE PERFORMANCE CHARACTERISTICS MATRIX

PERFORMANCE CHARACTERISTICS: State of Development	Cost of Sampler	Complexity of Use	Water Table Influence	Equipment Durability	Drilling Impact	Core Diameter	Friction	Core Blockage	Variability of Coring Pressures	Core Lifting	In Situ Orientation	Core Quality: Soil	Core Quality: Rock
4	2	3	3	3	2	4	4	2	2	3	1	4	2
4	2	3	3	3	2	4	4	2	3	2	1	4	2
4	2	3	3	3	2	4	4	2	2	3	1	3	4
4	2	3	3	3	2	2	4	2	1	3	1	NA	4
4	3	3	3	3	2	2	3	2	1	3	1	NA	3
4	1	3	3	2	2	3	4	2	3	3	1	3	4
4	1	2	3	1	3	3	4	3	1	3	1	2	4
4	1	2	3	1	3	3	4	3	1	3	1	3	4

RATING SCALE: 4 Best, 1 Worst.
For elaboration, see Table 5.2

Table 4e. TA matrix/TPC matrix: special techniques.

TECHNIQUE APPLICATIONS MATRIX

PAGE IN TEXT	SAMPLING TECHNIQUE	APPLICATIONS - GEOLOGIC CONDITIONS												
		Moderate Jointed Rock		Weak Rock		Strongly Fractured			Weakly Cemented					
		Tightly Jointed	Infilled Joints	Low Grade Metamorphic	Foliated, Schistose, Slatey	Hard	Soft or Friable	Interbedded Hard and Soft	Conglomerate/ Agglomerate	Fine-grained, Weak	Gravels	Sands	Silts	Clays
71	Open Spindle Hollow Stem Auger (MOSS Technique)	1	1	1	1	1	1	1	1	1	2	3	4	4
50	Orienting Double-Tube Core Barrel	4	3	3	3	2	2	3	2	2	1	1	1	1
50	Bishop Sand Sampler	1	1	1	1	1	1	1	1	1	1	3	2	1
79	Integral Sampling	3	4	4	4	4	4	4	3	3	1	1	1	1
47	Reverse Circulation Central Sample Return (CSR Technique)	2	1	2	2	2	2	1	1	2	1	1	1	2
45	Pressure Core Barrel	1	1	1	1	1	1	1	1	2	1	2	2	1

RATING SCALE: 4 Best, 1 Worst.
For elaboration, see Section 5.1

TECHNIQUE PERFORMANCE CHARACTERISTICS MATRIX

PERFORMANCE CHARACTERISTICS													
State of Development	Cost of Sampler	Complexity of Use	Water Table Influence	Equipment Durability	Drilling Impact	Core Diameter	Friction	Core Blockage	Variability of Coring Pressures	Core Lifting	In Situ Orientation	Core Quality	
												Soil	Rock
4	1	3	3	4	3	4	1	2	1	2	2	3	NA
4	1	1	3	1	2	4	4	3	1	3	4	NA	4
2	2	1	4	1	1	2	1	2	1	2	1	4	NA
2	2	2	3	NA	1	3	NA	NA	NA	4	4	NA	3
2	1	1	4	2	4	2	1	3	1	2	1	1	1
3	1	1	4	1	2	1	4	2	1	4	1	4	NA

RATING SCALE: 4 Best, 1 Worst.
For elaboration, see Table 5.2

UTILIZATION OF GEOPHYSICAL LOGS IN THE EVALUATION OF SUBSURFACE CONDITIONS FOR MINE SUBSIDENCE STUDIES

David R. Hinrichs

Dames & Moore

ABSTRACT

Conventional rotary drilling in combination with lithologic and down-hole geophysical logging has proven to be the most cost-effective method for investigating abandoned mine conditions and coal seam geometries along the Colorado Front Range. The geophysical log is many times the single most important piece of data obtained as it represents an unbiased record of down-hole conditions present at the completion of drilling. At a minimum, the geophysical suite of tools should contain natural gamma, caliper, and resistivity tools assembled together on a single sonde. The natural gamma and resistivity instruments provide detailed lithologic information while the caliper detects voids, rubble and fractured zones within the mining horizon(s).

INTRODUCTION

Because of the relatively high costs of core-drilling, less expensive rotary drilling in combination with geophysical and lithologic logs is now commonly used as the main technique for subsurface investigations of abandoned coal mines along the Colorado Front Range. The geophysical log is many times the single most important piece of data obtained from conventional rotary drill holes as it represents a reproducible, unbiased record of down-hole conditions.

PLANNING THE GEOPHYSICAL PROGRAM

The geophysical program and the on-site lithologic logging of the drill holes should be coordinated to provide the maximum amount of data possible. During drilling, all test holes, both core and rotary, should be lithologically logged by an experienced geologist with careful attention paid to the extent and condition of rubblized areas, voids, and lost-circulation zones. The lithologic details substantiate and add to the data obtained via the geophysical program.

The drilling program should be set up so as to maximize the quality of geophysical information obtained and minimize exposure of the geophysical equipment to poor hole conditions. If surficial gravels or caving sands are encountered they should be carefully cased as problems with these zones are the chief reasons for abandoning a drill hole without a geophysical log. In rubble zones, the driller should determine if the interval is squeezing or caving badly. Good drilling practices will usually prevent most incidents of stuck or lost geophysical instruments. A certain amount of test holes usually prove impossible to geophysically log and, if for this reason only, all holes should be carefully logged lithologically.

When planning the geophysical program, a minimum of three tools should be requested. Natural gamma, caliper, and resistivity tools arranged on a single sonde (assembled logging instrument) are the most common and versatile. Many geophysical logging companies will have these tools arranged on two separate sondes and will propose to make two logging runs on a test hole. This doubles the exposure of the equipment to a caving hole and doubles the time taken to log the hole (i.e., standby time for drilling contractor). Always request a single combination sonde, if possible, that contains at least the three tools mentioned and make a single pass on test holes to be logged.

The overall cost of the geophysical program is usually set up on a daily, call-out or footage basis or a combination thereof. Projects lasting longer than four weeks are typically priced on a standard monthly rate with a small fee for accumulated logged footage. Naturally, the cost of logging varies with the size, efficiency, and location of the investigation, among other factors, but $0.75 to $1.00 per logged foot can be expected in the Front Range area.

Insurance against loss of the geophysical tools should also be considered when planning the geophysical program. Coal mine subsidence investigations inherently require one to explore for fractured and rubblized zones that may contain wooden beams, iron, abandoned mining equipment, etc. Lost circulation is the rule and near-surface caving gravel zones are very common along the Front Range. The combination of these factors makes for fearful subsurface conditions. Responsibility for loss of the sonde should be discussed with the logging and drilling contractor before the project commences. On large investigations, the geophysical contractor may be able to charge a small fee per hole or per foot to carry the cost of insuring the tool against loss or damage.

TOOL DESCRIPTION AND LIMITATIONS

The following is intended to be an introduction to the types of logging tools commonly used in subsidence investigations. For further discussion of the workings of the instruments and other tools available, consult the better log interpretation manuals (i.e., Schlumberger, Century, or Gearhart-Owens handbooks).

Single-Point Resistivity

Resistivity measuring devices work by applying a constant current to the wall of borehole, via an electrode, measuring the resulting voltage drop. Since the pore spaces of the enclosing rocks are usual filled with water, the resistance can be used to determine the amount of pore space within the rock (i.e., porosity). The resistivity tool is an excellent lithology indicator and it can be used to detect highly fractured areas (high porosity) that may go unnoticed during the drilling of the hole. Both the resistivity and natural gamma logs are used for picking coals and both will show poor quality coal seams and the thicker interburden layers within the coal seams. The major drawback with the resistivity tool is that it only performs in water; dry holes cannot be logged. In partially water-filled holes, the resistivity tool will give the water level.

The single-point resistivity tool is the simplest and most common. Other tools are available, usually at a higher cost, that lessen hole effects and give better bed definition. On certain subsidence investigations, it may be advantageous to investigate the use of alternate resistivity tools such as the 16-inch or 64-inch normal or the Laterolog.

Natural Gamma

The natural gamma ray tool employs a fluorescent crystal, usually thallium-doped sodium iodide, as a detector. This crystal will fluoresce very briefly when struck by a gamma photon. A photo-multiplier picks up and amplifies the light pulse and the number of pulses in a given amount of time is counted.

The gamma tools main use lies in its ability to shown subsurface lithologies. Coal seams and sandstones are shown as low-gamma lithologies while claystones and shales are represented as high-gamma lithologies. The tool works both in and out of water and is only affected to a slight degree by the presence of plastic or steel casing. With the natural gamma log, the characteristic signatures of representative formations, rock units, and coal seams are identified and subsurface correlations can be made. The natural gamma tool is also useful in that the gamma log gives the thickness and relative quality of the coal seams.

Caliper

The single-arm or three-arm caliper mechanically measures the diameter of the borehole. The arm(s) is deployed at the bottom of the hole (electrically) and the tool measures the size of the hole as it is pulled to the surface. Wash-outs and fractured mining zones are identified by their rough and erratic signature on the caliper log. Where the caliper arm opens to near-maximum or maximum extent, voids can be documented. A variety of arm lengths are available on caliper tools and the longer arms will be required to measure the width of large voids.

Gamma-Gamma Density

The gamma-gamma instrument is the most common density tool used for subsidence work. This type of system employs a low-radioactivity gamma emitter to send gamma photons into the formation. The photons from the source are scattered by collisions with electrons from formation atoms. Most of the scattered photons are lost but a few are scattered back to the detector and as the density of electrons in a material is very nearly proportional to the bulk density, the counting rate of returned electrons is a function of mass or bulk density.

Both omnidirectional and unidirectional tools are available. The unidirectional density tools are run with a decentralizer which presses the source and detector against the borehole wall to minimize borehole effects. The omnidirectional tool is sensitive in all directions but is affected to a certain degree by borehole conditions.

The gamma-gamma tool is an important addition to a subsidence investigation as it responds to minor changes in lithology and works well in and out of water. It can be used to obtain a close approximation to bulk density and porosity of the materials encountered in the borehole but because it requires a radioactive source, the tool should only be used in unpopulated areas and in reasonably stable boreholes. The Nuclear Regulatory Commission keeps close watch over all radioactive sources used in geophysical tools and to lose one in a caving borehole can be a very expensive proposition.

Applications

Probably the most obvious use of geophysical logs is in geologic correlations. Geophysical logs, mainly natural gamma and resistivity, will show correlatable strata that may not be apparent from on-site lithology logs. Correlated geophysical logs can be hung on a datum and presented as cross-sections or used to target depths of planned boreholes. Additionally, updated correlations can be used to verify the accuracy of previous subsidence work. In many instances, the correct use of geophysical logs will shown that test holes in previous investigations have not reached the level of the abandoned mines, as indicated, or have only reached the upper seam of multi-level mining.

When subsidence investigations are conducted in areas where historical coal mine maps have either proved inaccurate or are unavailable, geophysical logs become invaluable. Properly run geophysical logs will show the thickness, depth, and quality of the coal seams drilled. As thin, extremely deep, or poor quality coal seams are not commonly mined, the geophysical information will support conclusions drawn as to the mineability of the coal seams encountered.

Figure 1 illustrates a reproduced geophysical log where caliper, natural gamma, gamma-gamma density and single-point resistivity logs were run simultaneously in a rotary drill hole. The hole was drilled into the abandoned Hi-Way Mine, south of Lafayette, Colorado, encountering a 6-foot-thick coal pillar at a depth of 324 feet. Notice the low gamma count, low density, and high resistivity of the coal seams present. The resistivity and density logs shown thin bands of inferior quality coal in the top and bottom of the mineable seam, appearing as lower resistivity-higher density layers in the coal. The top of the Fox Hills Sandstone, commonly used as a datum in this coal field, lies directly below the thin Laramie Formation coal seam present at 335 feet; the sandstone is represented

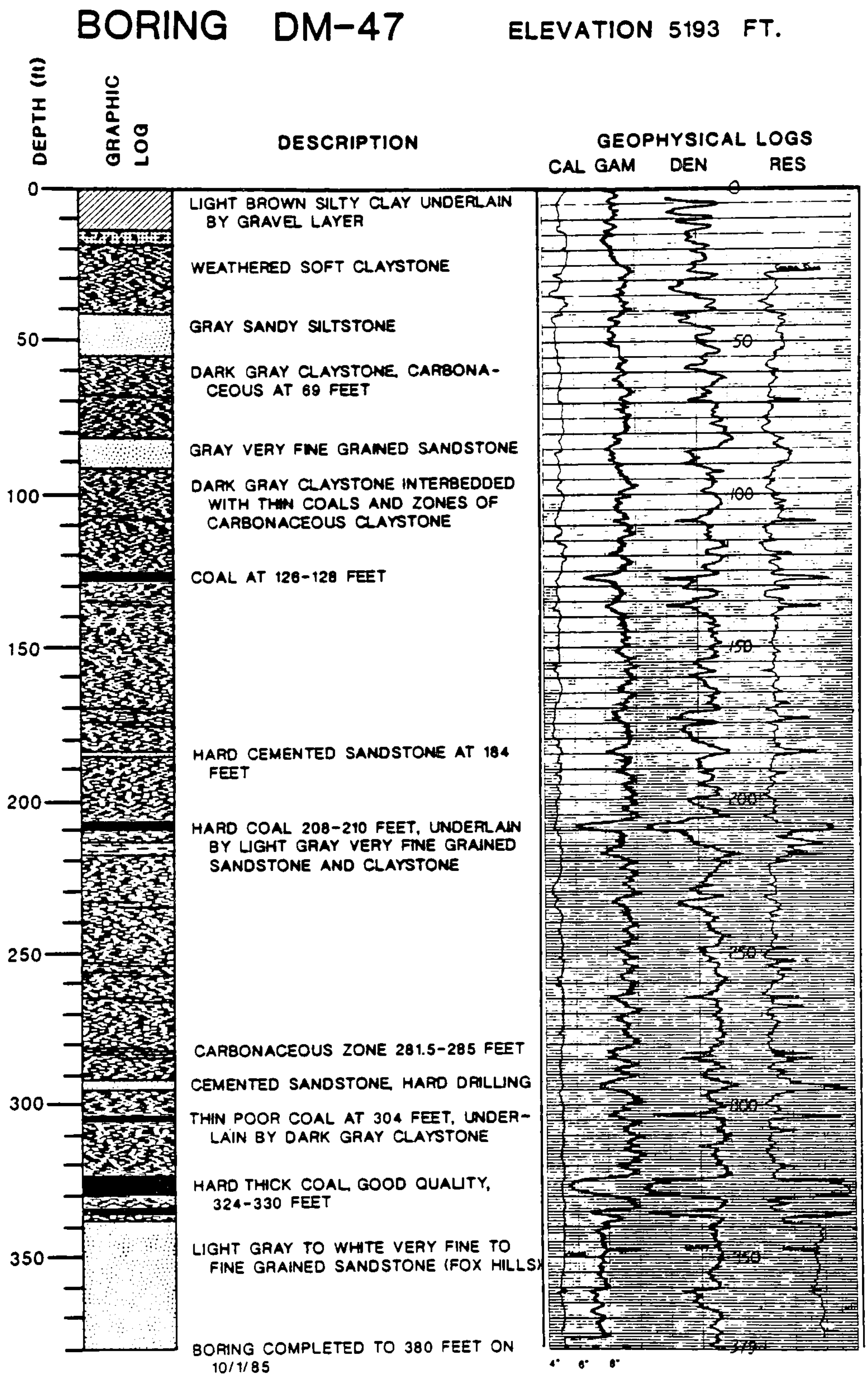

BORING DM-47
ELEVATION 5193 FT.
DEPTH (ft)
GRAPHIC LOG
DESCRIPTION
GEOPHYSICAL LOGS
CAL GAM DEN RES
0
50
100
150
200
250
300
350
LIGHT BROWN SILTY CLAY UNDERLAIN BY GRAVEL LAYER
WEATHERED SOFT CLAYSTONE
GRAY SANDY SILTSTONE
DARK GRAY CLAYSTONE, CARBONACEOUS AT 69 FEET
GRAY VERY FINE GRAINED SANDSTONE
DARK GRAY CLAYSTONE INTERBEDDED WITH THIN COALS AND ZONES OF CARBONACEOUS CLAYSTONE
COAL AT 126-128 FEET
HARD CEMENTED SANDSTONE AT 184 FEET
HARD COAL 208-210 FEET, UNDERLAIN BY LIGHT GRAY VERY FINE GRAINED SANDSTONE AND CLAYSTONE
CARBONACEOUS ZONE 281.5-285 FEET
CEMENTED SANDSTONE, HARD DRILLING
THIN POOR COAL AT 304 FEET, UNDERLAIN BY DARK GRAY CLAYSTONE
HARD THICK COAL, GOOD QUALITY, 324-330 FEET
LIGHT GRAY TO WHITE VERY FINE TO FINE GRAINED SANDSTONE (FOX HILLS)
BORING COMPLETED TO 380 FEET ON 10/1/85

Figure 1.

by relatively low gamma count and high resistivity. The lithologic log presented was constructed using visual, on-site logging of samples in conjunction with information from the geophysical logs.

Figure 2 depicts the natural gamma and caliper logs of a 6-1/2 inch diameter rotary hole CRH-83, drilled into an abandoned slope mine in Colorado Springs, Colorado. The hole encountered an upper unmined coal seam at a depth of about 55 to 60 feet but lost circulation in fractured and rubblized ground soon thereafter. The caliper log, run after the completion of the hole to 120 feet, indicated a 4-foot high void at 80 feet underlain by a rubble and small void interval to the approximate depth of the old mine floor, 111 feet. Note the difference in the appearance of the caliper signature above the void and in the fractured/rubble zone below the void. An estimate of the original mine floor depth is made by using the caliper log in conjunction with penetration rate information from drilling records. Often times the natural gamma log will show a thin layer of unmined coal left at the floor of the mine; the mine floor elevation estimate can be made at the top of the "floor coal".

Rotary drill hole CRH-27 (Figure 3) was drilled into the abandoned Curtis Mine in Colorado Springs. The field lithologic log of this hole indicated that 2 to 3 feet of hard coal was drilled just before the drill bit fell through mushy and rubble-like material at the mining level. The caliper log indicates a clean hole until a depth of about 185 feet, where caving and squeezing conditions are illustrated by the small hole size (note hole diameter in inches at bottom of figure). The natural gamma log offers no indications whatsoever that the coal seam was mined, but instead indicates the very low gamma ray count typical of a thick, good quality coal seam with a thin interburden layer or parting towards the middle. Although the hole was drilled into rubble, the logging tool passed very close to a coal pillar; the natural gamma instrument picked up the natural radiation of the adjacent unmined coal. The original thickness of the mined coal seam, along with an estimated height of mining can be obtained from the logs. The resistivity log shows an indistinct, jumbled lithology in the rubble zone with floor coal or coal rubble at the bottom of the mine.

If the rubble encountered in the mining horizons is very tight and circulation is maintained, indications of an old mine may not be apparent during the drilling of

CRH - 83

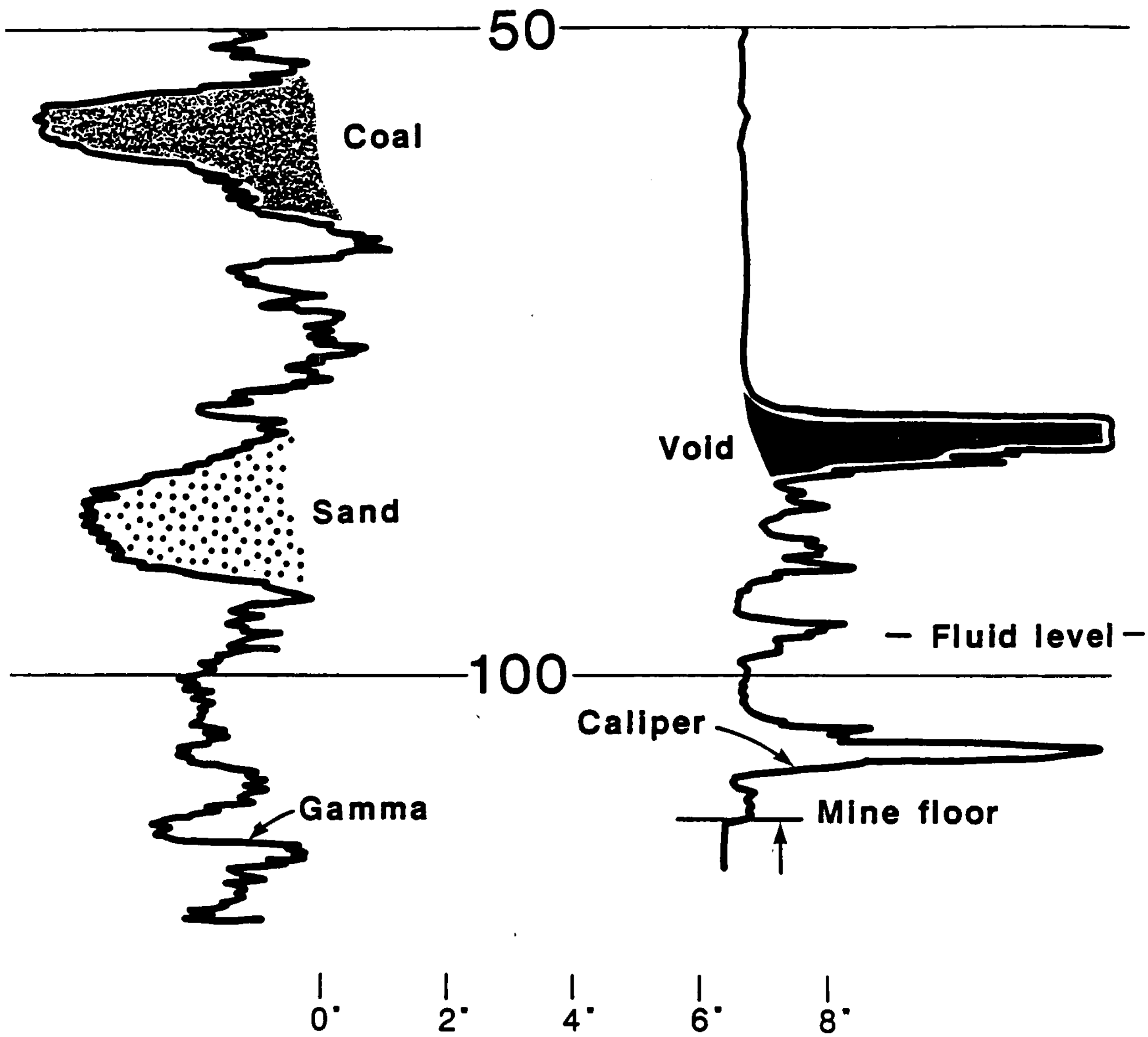


Figure 2.

CRH - 27

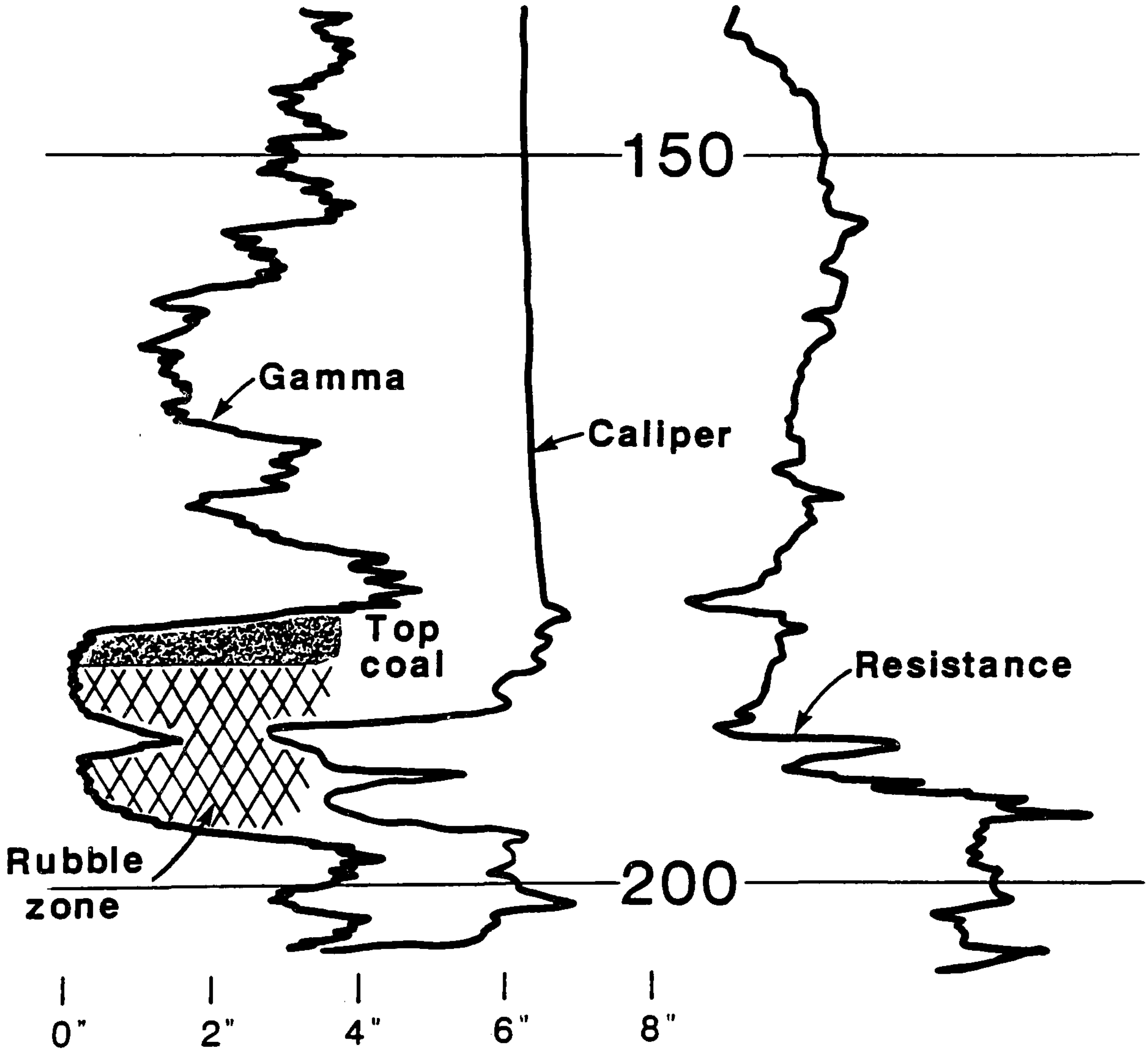


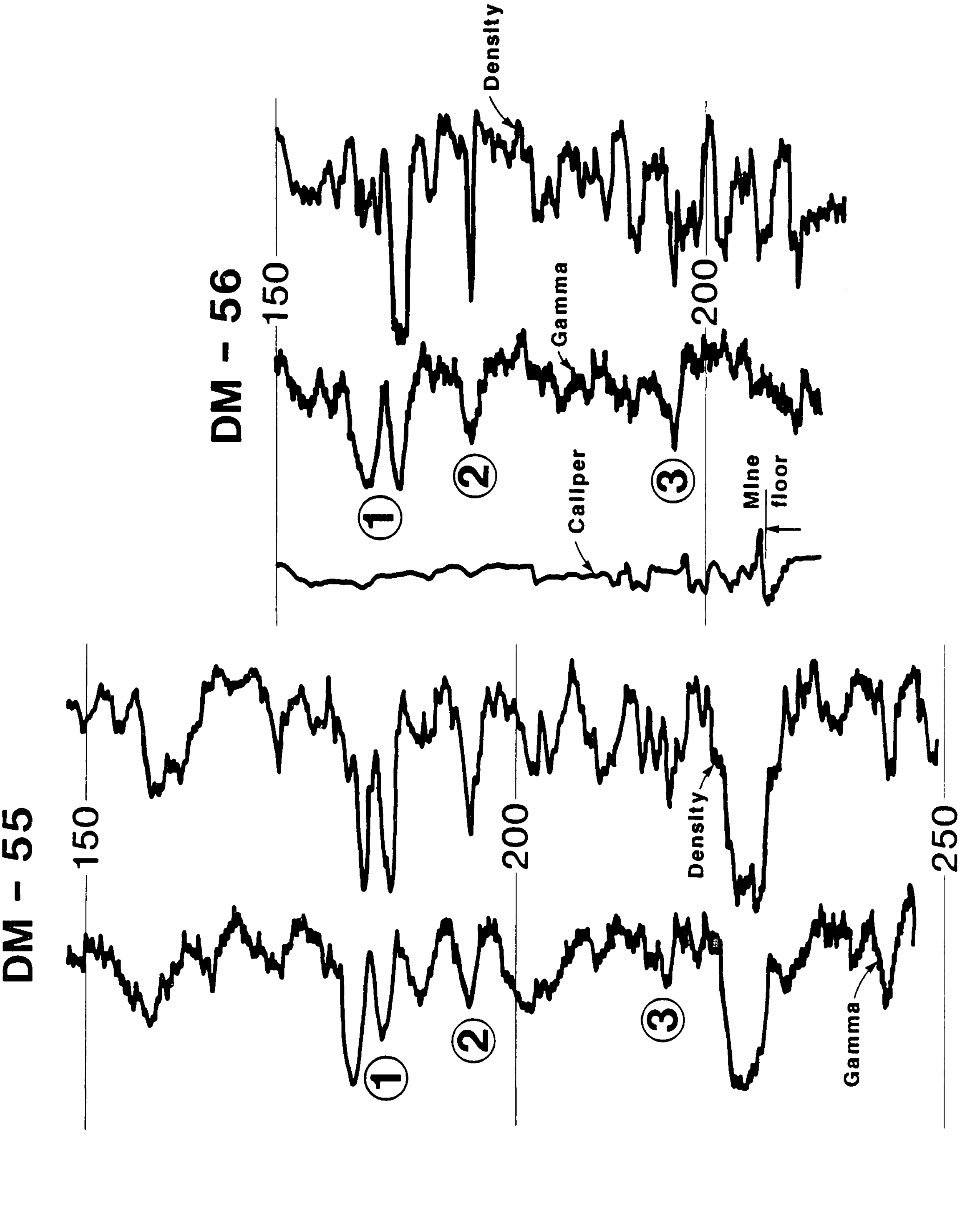
Figure 3.

a test hole. Establishing correlations with geophysical logs from surrounding holes can illustrate the location of the old mine floor as shown in Figure 4.

Rotary holes DM-55 and DM-56 were drilled into the old Matchless Mine near Louisville, Colorado. DM-55 encountered two thin unmineable coal seams at a depth of 180 feet (correlation point 1) and a 4-foot coal pillar in the mine at 225 feet. A second hole, DM-56, was drilled nearby and did not encounter the thicker seam at the level suspected. Circulation was not lost during the drilling operations and no indications were obtained as to the level of mining. Correlation was established between the two holes by comparing the geophysical logs; the gamma log showed that both test holes cut similar thin coal seams at correlation points 1, 2, and 3. Using these correlation, the mine floor elevation in DM-56 was estimated to be 50 feet below the top of the double, thin coal seam or at about 210 feet in DM-56. Careful inspection of the caliper log in DM-56 shows an irregular signature in the interval from 190 to 210 feet. This was taken to be firm, 'rehealed' rubble and fractured material associated with caving of the old mine.

CONCLUSIONS

A properly planned and executed geophysical program, in conjunction with detailed lithologic logging, will greatly enhance the quality and quantity of subsurface information obtained in subsidence investigations. The data can be acquired economically and in a timely fashion if a few important considerations are taken into account prior to commencement of drilling operations: (1) plan drilling operations so as to maximize the total footage logged by utilizing good drilling practices and casing to improve downhole conditions, (2) utilize single-pass geophysical logging to cut down on exposure of geophysical equipment to the borehole environment, and (3) contract for natural gamma, resistivity, and caliper instruments, at a minimum, to obtain a usable and reproducible log of subsurface lithologies and conditions.



DM - 55
150
200
250
Density
Gamma
1
2
3
DM - 56
150
200
Density
Gamma
Caliper
Mine
floor

Figure 4.

REMOTE VIDEO INSPECTION OF ABANDONED COAL MINES: INVESTIGATION AND BACKFILL MONITORING

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ABSTRACT

The use of remote video for abandoned mine investigations and backfill monitoring is a relatively new concept. The factors affecting interpretation of video images are derived from experimentation and field use of the Remote Video Inspection System (RVIS), designed around a modified Westinghouse ETV-1252 video camera and control unit; however, with adjustments, they can be applied to any video camera system. These factors include: depth of field, viewing angles, light intensity, and viewing medium. The physical and visual limitations placed on the camera by the abandoned mine environment when drill holes enter the mine next to timbers or piles of mine trash, or when suspended solids are present in mine water, can present difficult viewing to the video interpreter. Distances of up to 50 feet in dry mine passages have been observed; 15 feet in water-filled mines. Information obtained from the video recordings has been useful for determining the location and concentration of drilling necessary for reclamation measures, orientation and condition of pillars and mine passages, extraction ratios, shaft closure design, the type of backfilling method to be employed, and the progress and success of the backfilling process. Remote video investigations and monitoring have proven to be cost-effective tools for backfilling projects.

INTRODUCTION

From the beginning of the abandoned underground mine reclamation program, geologists and engineers have attempted to directly view conditions in the mines to better assess the factors relating to the design of the reclamation project, drilling densities necessary to accomplish the job, and the behavior and effectiveness of backfill materials. Sundry still cameras and video systems have been employed to obtain views in underground abandoned mines with varying degrees of success.

Remote video systems have distinct advantages over still cameras. They present the opportunity for the observer to view the images live onsite and tape-recorded for further study, to have control of the light intensity and focus while the camera is in the mine, and to observe motions of objects or materials. Some systems offer right angle viewing, as well as the axial views of traditional borehole video cameras. To derive the greatest benefit from the use of remote video systems and to examine abandoned mine conditions or monitor reclamation activities, techniques must be developed for using the video image to measure dimensions of particular objects in the mine, determine how far from the point of observation the objects are, judge how far can be seen in an open void, and assess how effective the reclamation efforts are in both air-filled and flooded mine environments.

This paper presents field observations and surface verification of responses from the Westinghouse ETV-1252 video camera to the abandoned mine environment. The information is presented to provide reclamation professionals with guidelines for interpretation of remote video imagery in underground mines and how to best utilize the video system for monitoring the techniques used in subsidence abatement projects. With proper modifications, the principles contained herein can be applied to any video system used in such endeavors. To the knowledge of the authors, the research involved to obtain the following interpretative procedures is original and no other information of its kind has been published.

The Remote Video Inspection System (RVIS), designed by Goodson & Associates, Inc., is a fully self-contained mobile/portable video studio equipped to view, label, and record video surveys on almost any project location. It is composed of an ETV-1252 camera and control unit connected to a 10 inch black and white monitor, a 3/4 inch format commercial quality VCR, and a computer for video tape labeling and distance estimations. Other support equipment includes; a variable speed electric winch with 500 feet of camera cable, a modified surveyors' tripod for directional control of the camera, an aluminum "quadrapod" with pulley for supporting the camera when used in deep holes and shafts, and drop-lights with extension cords for hole-to-hole communication determinations. Power for the RVIS is supplied by a 5 KW portable generator or standard house power, when practical.

The ETV-1252 camera system is comprised of a fixed aperture, black and white video camera connected, via cable, to a camera control unit (CCU). The CCU contains both the focus and light intensity controls and can be coupled to any video cassette recorder and/or video monitor. Various viewing attachments are available which provide light sources and allow either axial or right angle viewing of subjects. One style of right angle viewing attachment contains a built-in compass to provide direction determinations of objects in the video image. The System operates on standard 115 volts AC, 60 Hz power supplied from commercial utilities or portable generators and can be converted for use with 220 volts AC, 50 Hz power in other countries.

For abandoned underground mine applications, the camera and light attachments can be lowered down drillhole casings as small as 3 inches inside diameter. The depth capability of the system is up to 500 feet in dry or flooded mines. Directional control is accomplished by steering the camera cable at the surface. Being totally portable, the RVIS can be used where vehicular access is restricted.

Camera Specifications

The following specifications for the ETV-1252 video camera are supplied by the manufacturer and are the most important ones used for interpretations of the video images:

Lens	16mm, f/2.8 fixed aperture
Diagonal Field of View	38 degrees in air; 28 degrees in water
Remote Focus Range	From edge of viewing attachment to infinity
Gray Scale	10 shades of gray, minimum
Light Sources	12 watt on axial and closeup right angle attachments; 85 watt on extended range right angle attachments

Although the light sources seem to be low power, the camera is an extremely light sensitive instrument. More powerful light sources may harm the video camera tube.

VIDEO INTERPRETATION PRINCIPLES

The principles involved with interpreting video images in abandoned underground mines are derived from calculated angles and observed responses of the ETV-1252 video camera to a variety of contrived surficial environments to approximate abandoned mine conditions. The accuracy of interpretations depends largely on the operator's manipulation of the video camera's adjustable parameters; focus, light intensity, and vertical position within the mine void. Fixed parameters, such as depth of field and viewing angles in air and water, can then be used to provide a concise picture of the void from the point of observation.

Focus and Depth of Field

Focus and depth of field properties of the ETV-1252 camera are presented together because of their direct relationship. The camera is equipped with a fixed aperture lens which maintains a constant depth of field, regardless of the environment in which the video image is produced. In abandoned mine investigations, large voids are most important to the observer and the camera should be focused to the point at which objects an infinite distance away are clear in the view. This point is reached by adjusting the focus on an object greater than 2 feet from the camera prior to lowering the camera into the mine. When the camera enters the mine, any object greater than 2 feet in distance will be in focus. If the focus needs adjustment to view something else, that object is closer than 2 feet and a distinct range of in-focus images will be observed. As objects occur closer to the camera, the in-focus range will narrow in a seemingly logarithmic relationship. Figure 1 is a graphic representation of the approximate depth of field ranges for the ETV-1252 video camera.

```
||-|--|---|-----|--------|---------------------------->
0 ft        1 ft         2 ft                  infinity
```

Figure 1. ETV-125 Depth of Field

Manufacturers of video equipment always refer to diagonal measurements for their system specifications; 10 inch monitor, 38 degree viewing angle, etc. Standard monitors and televisions are subrectangular in nature. The horizontal and vertical components of these instruments retain the same proportional relation to the diagonal, regardless of the magnitude of the measurement (see Figure 2). Assuming the video image to be rectangular, the horizontal and vertical viewing angles of the video camera, for air and water media, can be calculated.

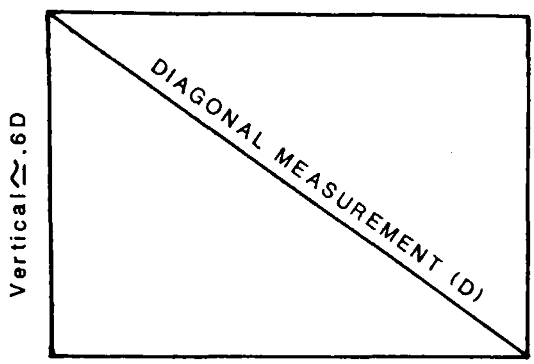

Figure 2. Rectangular Proportions of Video Monitors

The calculations are made as follows (refer to Figure 3):

For Air-filled Voids

Given	38 degree diagonal angle of view	
Then	A = 19	(diagonal angle/2)
Assume	b = 1	(distance from object)

Solving for a

$$a = b \tan A$$
$$a = 1 \tan 19$$
$$a = .344 \quad \text{(diagonal measurement)}$$

With the diagonal measurement now known, the horizontal and vertical angles may be calculated using the proportions from Figure 2 and the triangle in Figure 3

Horizontal Viewing Angle

Given $a - .8\ (.344) = .28$ and $b = 1$

Solving for A tan A - a / b

tan A = .28 / 1

tan A = .28

A = 15.6 degrees

The horizontal viewing angle = 2 A = 31.2 degrees

Vertical Viewing Angle

Given a= .6 (.344 = .21 and b = 1

Solving for A tan A = a / b

tan A = .21 / 1

tan A = .21

A = 11.9 degrees

The vertical viewing angle = 2 A = 23.8 degrees

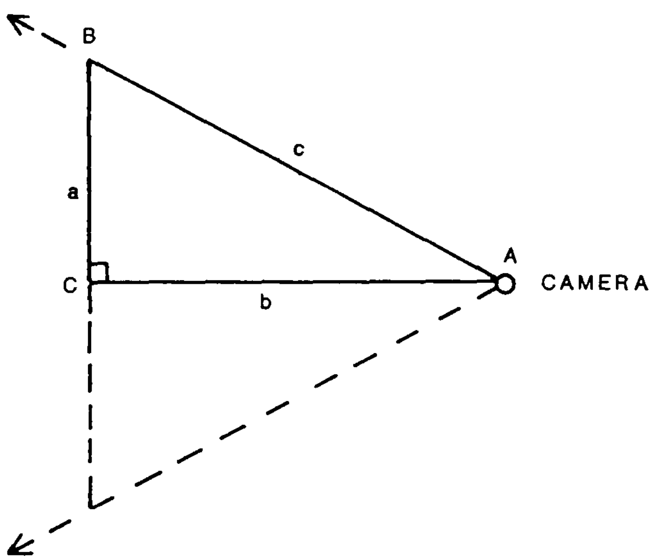

Figure 3. Triangle Used For Solving Horizontal and Vertical Angles

The calculations of the horizontal and vertical viewing angles for water-filled voids are the same as above, except A = 14 degrees and the diagonal measurement a = .249 in the initial calculation. This gives a horizontal viewing angle, in water, equal to 22.6 degrees and a vertical viewing angle equal to 17.0 degrees.

Once the viewing angles in the horizontal and vertical directions are known, a table of dimensions of the view on the monitor at given distances, valid for any units of measurement, can be produced (Table 1).

Table 1.

DISTANCE FROM CAMERA	DIMENSIONS IN AIR HORIZONTAL	DIMENSIONS IN AIR VERTICAL	DIMENSIONS IN WATER HORIZONTAL	DIMENSIONS IN WATER VERTICAL
0.5	0.3	0.2	0.2	0.1
1.0	0.6	0.4	0.4	0.3
2.0	1.1	0.8	0.8	0.6
3.0	1.7	1.3	1.2	0.9
4.0	2.2	1.7	1.6	1.2
5.0	2.8	2.1	2.0	1.5
10.0	5.6	4.2	4.0	3.0
15.0	8.4	6.3	6.0	4.5
20.0	11.2	8.5	8.0	6.0
25.0	14.0	10.6	10.0	7.5
30.0	16.8	12.7	12.0	9.0
35.0	19.6	14.8	14.0	10.5
40.0	22.4	16.9	16.0	12.0
45.0	25.2	19.0	18.0	13.5
50.0	28.0	21.1	20.0	15.0

An object of known, or assumed, size can be assigned a distance from the camera by measuring the portion of the monitor which the object occupies and comparing the measurement to the table of dimensions. Conversely, the dimensions of an object at a known, or assumed, distance can be determined from the table.

Light Intensity

The discussion of light intensity as a video interpretation tool is based upon responses of the 85 watt, right angle viewing attachments to experimental surface environments with the light set at maximum intensity.

It has been determined that the spot produced by the 85 watt bulb will begin to "wash out" the video image in dry bituminous and anthracite mines at a distance of approximately 10 feet from the camera. In a less reflective environment such as a lignite mine, the light begins to wash out the image at a distance of about 8 feet.

Water in mines presents a more difficult setting for interpretations, due largely to suspended solids in the mine water after disturbance from drilling or other activites. The distance at which the light will begin to wash out on features in flooded mines has been estimated to be 3-5 feet in clear water; less distant in murky water. When possible, solids in mine water should be given time to settle before the remote video system is used.

Features up to 50 feet from the camera have been observed in dry, open mines. In flooded mines, objects approximately 15 feet from the camera have been viewed. In order to be able to view features and objects at such distances, the video image should be observed in an extremely dark viewing area. Many of the subtle differences in shades of gray will be more discernible.

ABANDONED MINE FIELD APPLICATIONS

The Remote Video Inspection System can be configured for many applications. With the proper light attachments, geologic examinations of boreholes, inspections of well casings, pipes and other conduits, as well as viewing of other environments inaccessible to humans can be conducted with the RVIS.

When investigating underground abandoned mine conditions or monitoring the reclamation of an abandoned mine, the system should be equipped to provide the greatest amount of light available for viewing objects and activities at considerable distances from the camera. The 85 watt spotlight, compass equipped right angle and 12 watt, dual bulb axial viewing attachments have proven to be very effective tools for abandoned mine applications.

Investigations

Remote video has been very useful in abandoned mine investigations when used in conjunction with drilling programs. Position within the mine, roof conditions beyond the drillhole, mine passage trends, pillar conditions, and ventilation control patterns can be observed and analyzed from a well-conducted video survey.

When mine maps are available, or surface features cannot be correlated with mine maps and drilling locations are uncertain with respect to the mine, the remote video can be used to direct the drilling locations and intersect the mine after initial holes have penetrated the mine void. Thus, using remote video can reduce the number of drillholes which miss the void and increase the efficiency of the drilling program.

Reclamation Design

The design of underground mine reclamation and subsidence abatement projects, as well as mine shaft closures, can be greatly influenced by using remote video inspection surveys.

For areal reclamation projects, the reclamation method to be employed and drilling density for more effective backfilling of the mine can be planned from an understanding of actual observed conditions in the mine. The estimation of backfill material volumes will be more accurate when the video is analyzed for pillar robbing and roof fall material deposited in worked-out rooms; features which may not be portrayed on the mine maps. Project areas with definite boundaries can be investigated for the location of backfill containment structures, if required. Water wells drilled into the mine and used for backfilling projects may be viewed for possible placement of barriers to protect the pumping equipment from damage by backfill materials flowing to the well.

Areas of active subsidence can be investigated for lateral and vertical continuity of roof rock fractures. A more efficient and effective subsidence abatement project can then be designed and implemented; providing better stability for structures over the collapsing mine.

Mine shaft closure designs can also be affected by the use of remote video investigations. When analyzed for intersecting drifts, shaft wall conditions, and other features not readily visible by direct inspection, the video will be invaluable for the design of the most effective and permanent shaft closure.

Backfill Monitoring

Monitoring the behavior and movement of backfill materials by remote video is the most positive method for verifying an underground mine reclamation project's progress and success. Recording the filling of mine passages from strategically placed monitor holes has been very useful for confirmation of filling of mine passages and, when required, verification that the backfill materials have been contained within project boundaries.

The remote video has been used to monitor construction of barrier structures. Images have indicated the need for more closely spaced drillholes to fill gaps in the structures which, if not closed, could have allowed material to flow away from the project area and increased the volume of backfill by a significant amount over the original estimation.

Videos have also shown backfill material flowing several hundred feet from the point of injection and filling into areas not originally anticipated to have been backfilled from such a great distance. The necessity of further drilling was subsequently eliminated by the evidence provided by remote video evaluation.

SUMMARY

The ability to visualize abandoned underground mine conditions and monitor reclamation efforts in an environment which prohibits human access is an essential asset to the AML program today. The use of remote video cameras for investigating mine conditions and monitoring the reclamation of underground mines has been extremely helpful for planning projects of this type.

The principles and procedures for interpreting the video imagery from underground mines have been derived from extensive use and experimentation with just one type of video system. Other systems may be available which, with the proper adjustments for specific parameters, will be equally valuable for providing the information necessary for successful reclamation of an abandoned underground mine. With proper use, remote video can provide time and cost savings to agencies concerned with the reclamation program.

MULTI-PHASED SUBSIDENCE STUDY AND USE OF PROGRESSIVE FAILURE MODEL FOR SUBSIDENCE PREDICTION ABOVE ROOM AND PILLAR MINES

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ABSTRACT

A multi-phased subsidence study was performed for a site in Colorado Springs located above a series of abandoned room and pillar coal mines last worked in the 1920's and 1940's. The three phases involved: 1) an initial review of available published data on the mines to assess project feasibility; 2) a limited subsurface investigation to characterize the site and assign a subsidence risk to various parts of the site; 3) a very detailed evaluation of the eastern portion of the site resulting in a prediction of final subsidence profile and ground strains. The final analysis utilized a progressive failure model to predict the final failed configuration of the mine. The model considered pillar, roof and punching failures. The resultant maps of subsidence and ground strain have been used for project planning and site selection.

INTRODUCTION

The project site is located in the northeast portion of the city of Colorado Springs, Colorado in an area commonly known as Cragmoor (Figure 1). At the time of the investigation the site contained only a small farmhouse and the majority of the property was being used as pasture land. Immediately to the north of the site is an area which had already been developed with high density single-family residential construction. The site itself is zoned R-5, for high-density multi-family residential development.

The site is undermined by portions of three separate underground coal mines (Figure 2). The Busy Bee Mine is located in the west half of the property which was a room and pillar mine operated between 1905 and 1924. In the midsection of

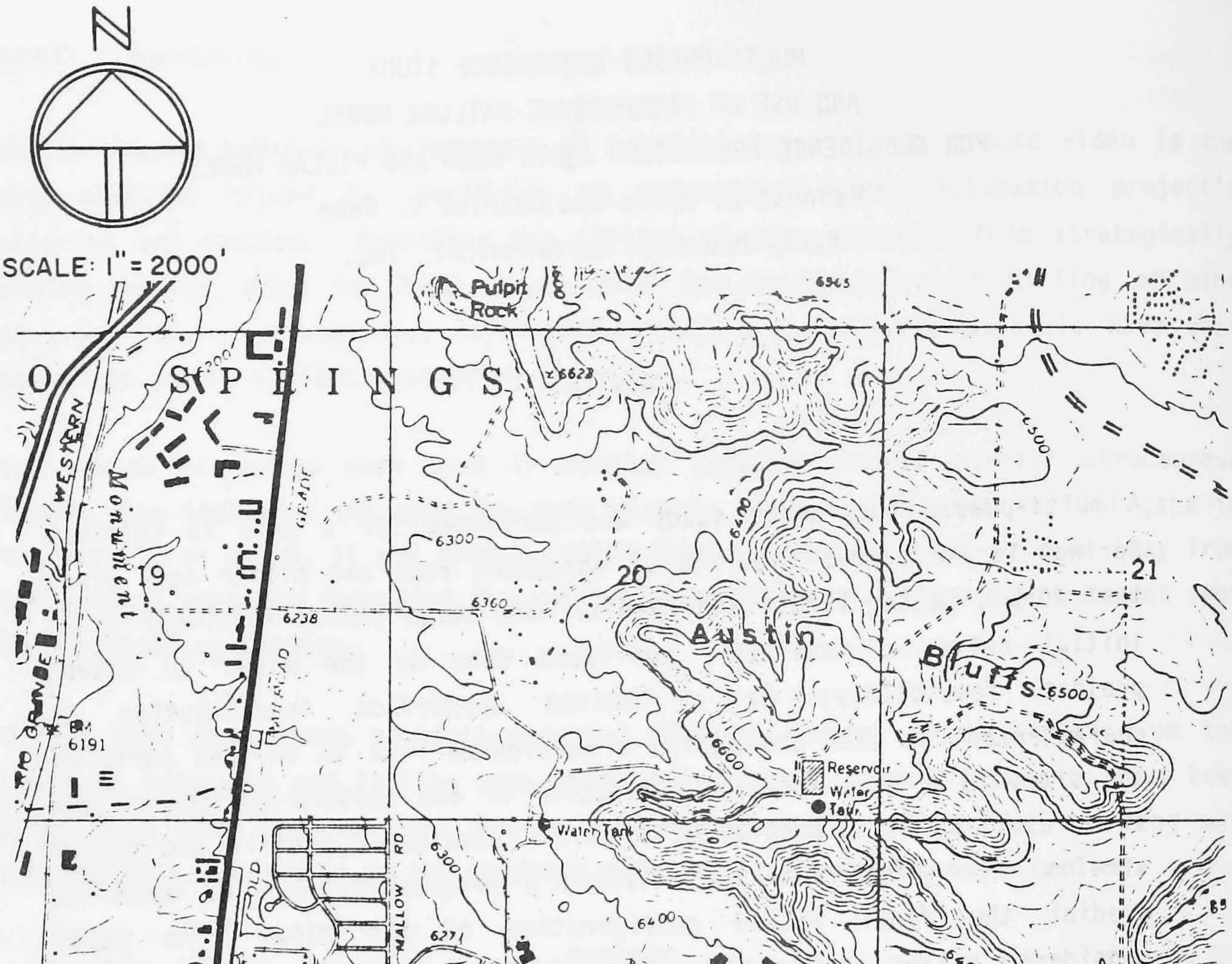

Figure 1. Site location diagram.

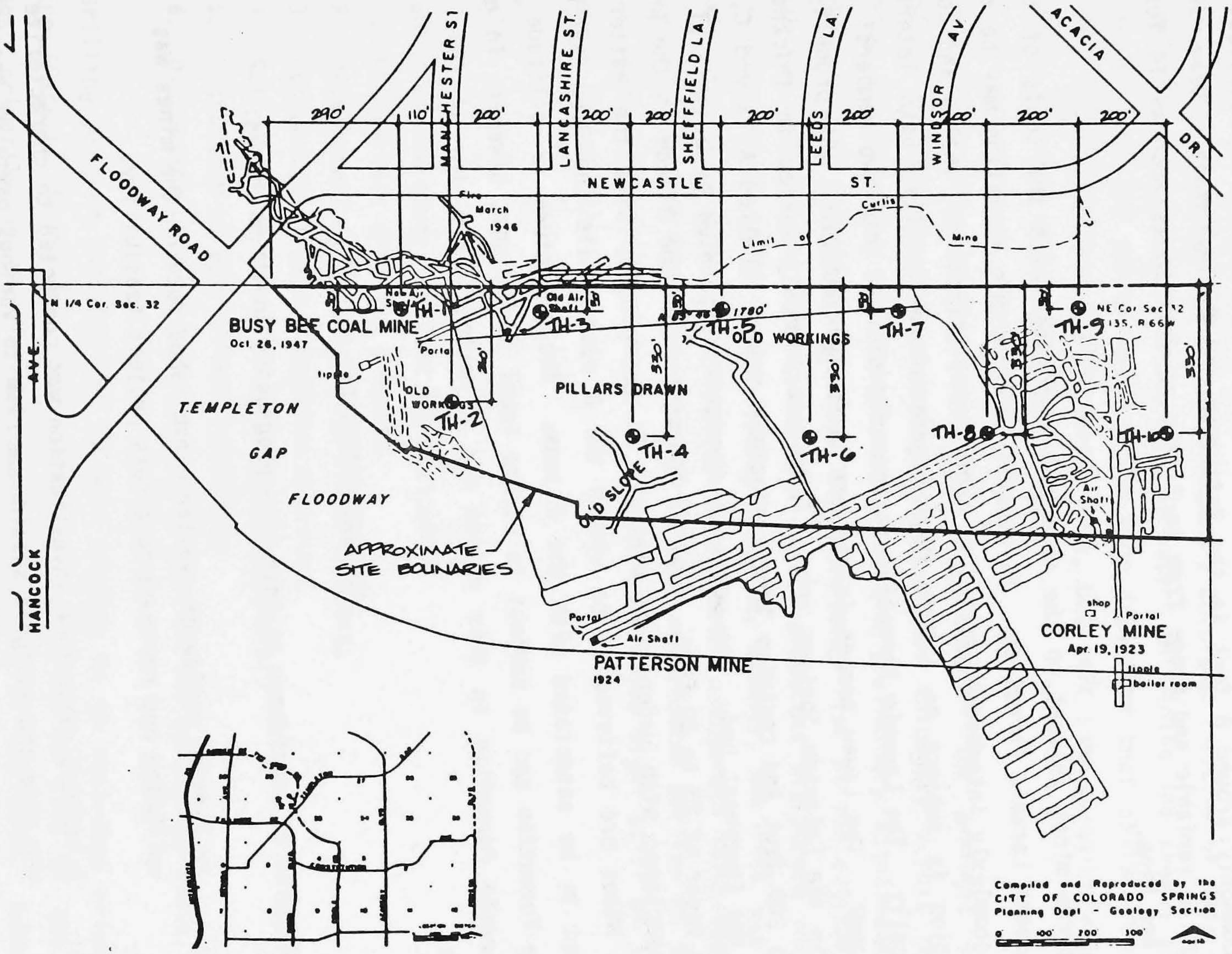

Figure 2. Mine map and test boring location diagram.

the property is the Patterson Mine, a room and pillar mine operated between 1933 and 1940. The extreme eastern half of the site contains the Corley Mine, again, a room and pillar mine operated between 1921 and 1924. Seam thicknesses vary, but are commonly around 8 feet in the Patterson and Corley Mines. Seam thicknesses are quite variable and range from as little as four to as much as 14 feet in the Busy Bee Mine.

The three mines present on the site are associated with the coals of the Upper Cretaceous Laramie Formation. In general, the Laramie Formation may be described as a complexly interbedded series of sandstones, siltstones, shales and coal. The formation is subject to a very high degree of variability, both laterally and vertically. The Laramie Formation is commonly divided into two members: an Upper and Lower. The Lower member is the one commonly containing the productive coal beds in the Colorado Springs area. This zone commonly varies in thickness from 100 to 200 feet and contains three principal seams, labelled A, B and C, with A being the lowermost bed. The seams are typically separated by a vertical spacing on the order of 25 to 50 feet. East of Monument Creek the A seam is the principal bed associated with underground mining. On the project site the Patterson and Corley Mines are believed to be within the A seam, while the Busy Bee Mine is believed to be associated with the B seam. The structure or attitude of the Laramie Formation can be subject to strong local variations, however, in general, the Laramie Formation in this region has a northeasterly dip of four to six degrees.

THE INVESTIGATION

The evaluation of subsidence on this site progressed in three phases:

Phase I: An initial review of available published data on the mines was collected and reviewed to assess project feasibility.

Phase II: A limited subsurface investigation was conducted to characterize the site and assign a subsidence risk to various parts of the site.

Phase III: A very detailed evaluation of the eastern portion of the site was conducted resulting in a prediction of final subsidence profile and ground strains.

Phase I

Mine maps and production records were available for all three mines from the U.S. Bureau of Mines Mine Map Depository in Denver, Colorado. Review of this material provided better information on the lateral extent of mining and showed all three mines to be room and pillar mines. The maps indicated that pillar robbing had definitely occurred within the Patterson Mine, but left some question with regard to both the Busy Bee and the Corley Mines.

Available topographic information and a projection of the geologic structure allowed us to estimate the variation in overburden thickness across the site. Utilizing all the data collected to this point a preliminary assessment of the subsidence hazard potential was made. The subsidence risk at the extreme western edge of the property was felt to be high due to projected overburden thicknesses in the range of 20 to 40 feet. Moving eastward, however, the risk was felt to gradually drop into a moderate range where projected overburden thicknesses could reach as high as 160 feet. Even in the extreme westernmost portion of the site, however, mine maps disclosed areas of unmined coal which might still be safe from subsidence (Figure 3).

Phase II

This phase of the study involved the following:

1. Preliminary drilling program;
2. Development of stratigraphic cross-sections;
3. Evaluation of past subsidence activity;
4. Refinement of the subsidence hazard potential;
5. Discussion of appropriate land uses;
6. Discussion of available forms of mitigation and associated costs.

The drilling program consisted of 10 test borings in an east-west oriented grid pattern (Figures 3 and 4). Open voids were observed in five of the 10 test borings, primarily on the extreme eastern portions of the site. Rubble zones indicating past roof fall and subsidence activity were observed in three test borings in the central most portion of the site. Two of the 10 test borings indicated no voids or rubble, but solid coal. At the time of the investigation

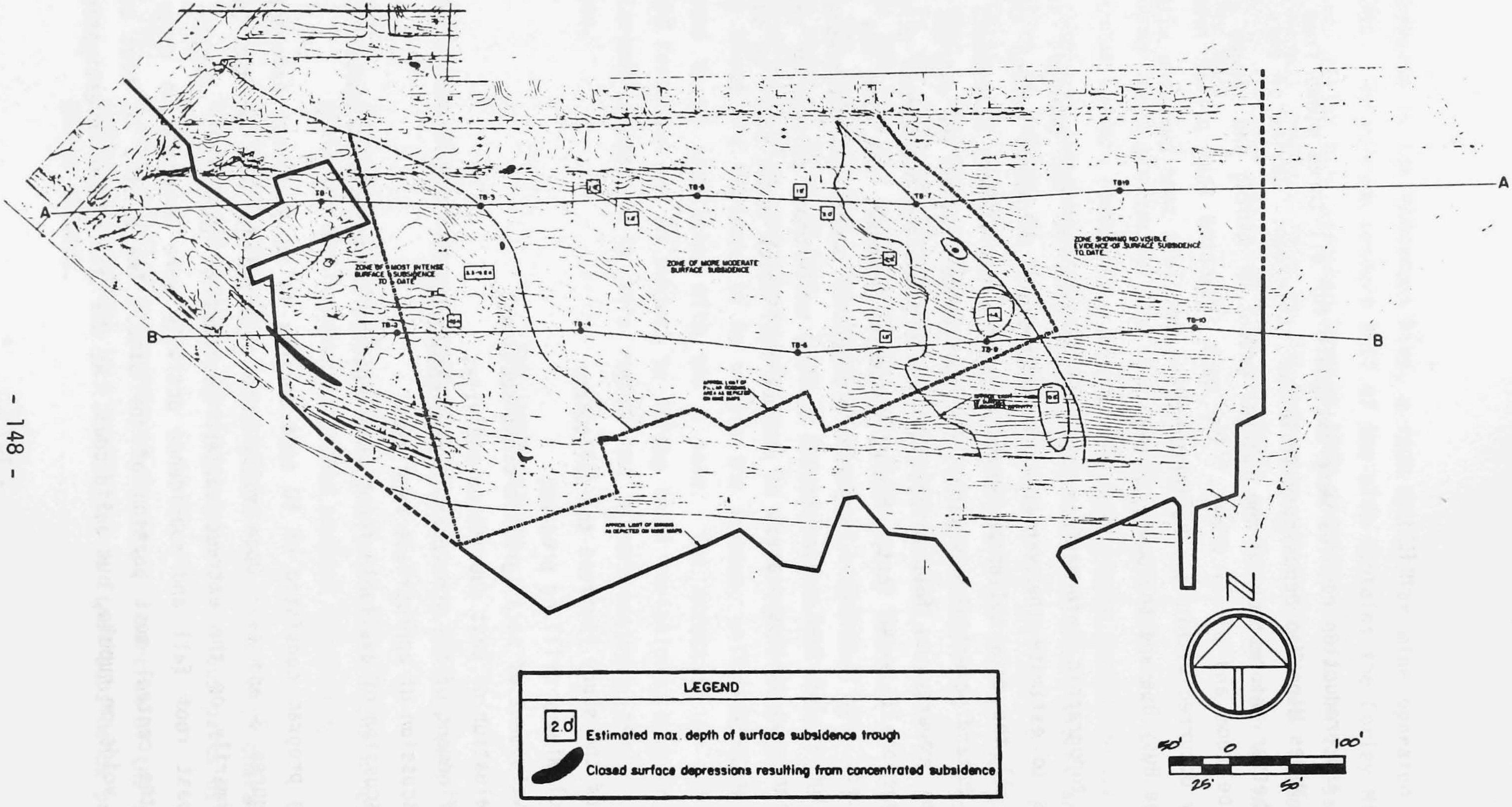

Figure 3. Topographic map with existing surface subsidence features.

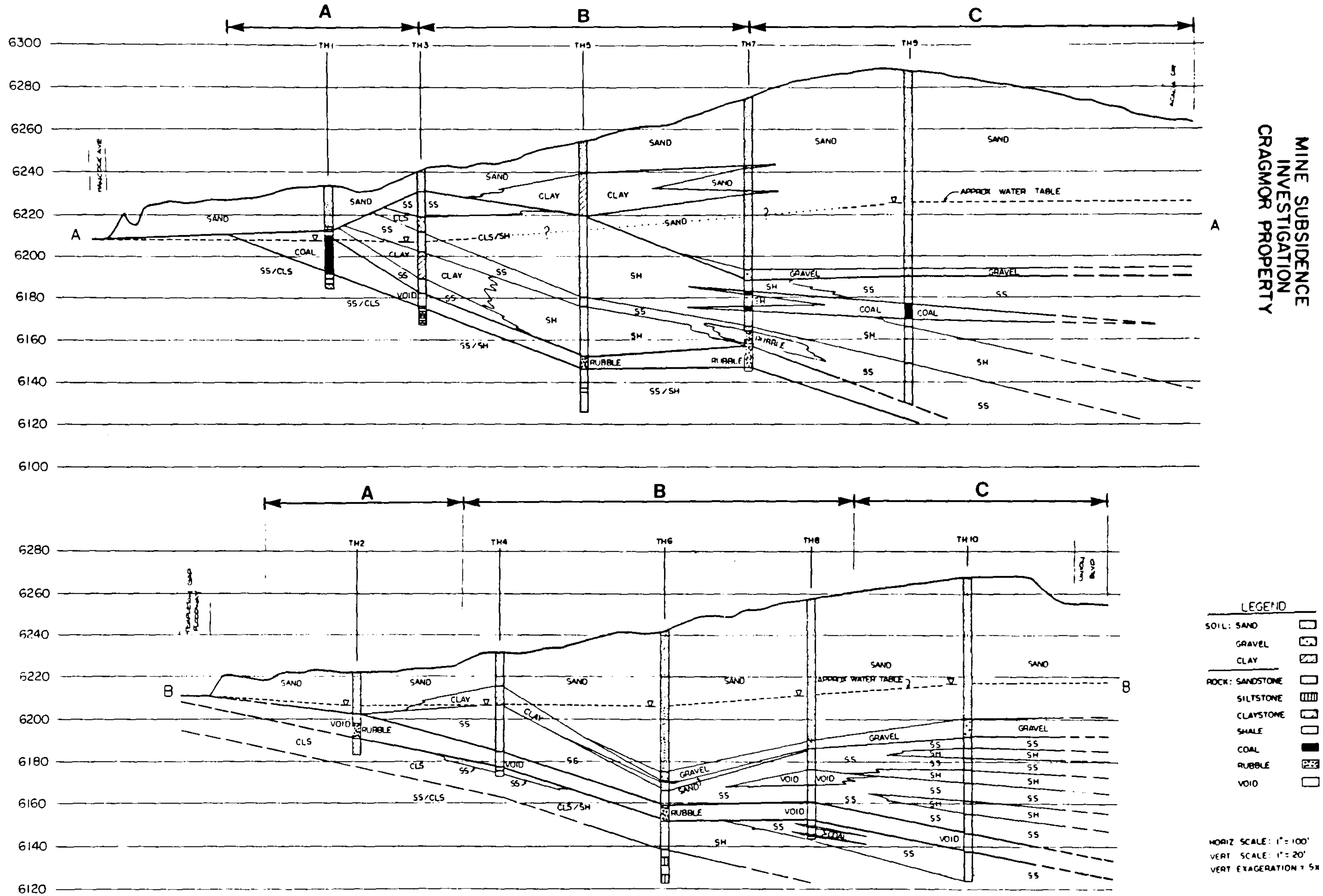

Figure 4. Typical subsidence profiles through site. (A) Zone of most intense subsidence to date (B) Zone of more moderate subsidence (C) Zone showing no invisible indication of surface subsidence to date.

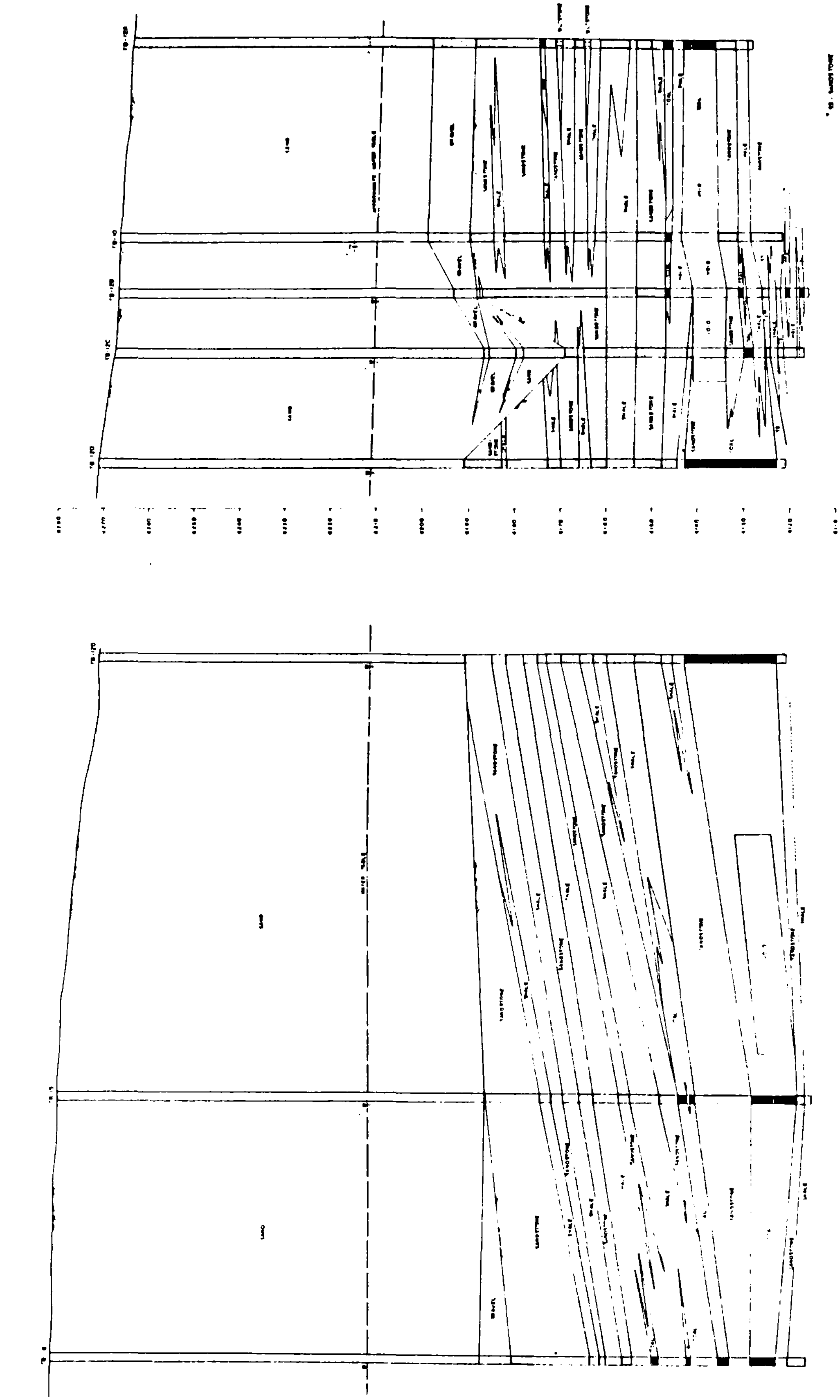

Figure 5. Profile.

the groundwater levels were in all cases above the level of the roof, with the exception of the extreme westernmost portion of the site where the mine roof rises to within 20 feet of the ground surface.

Rock materials in the roof of the mine consist of a complexly interbedded series of sandstones and shales (Figure 5). The sandstone layers can vary in thickness from one foot to over 40 feet. Similarly, shale layers may vary in thickness from one foot to 20 feet. A very dominant feature in the stratigraphic column on this site is an exceptionally thick deposit of soil. This material appears to be primarily Eolian, or windblown sand, over at least a thin layer of water-deposited alluvial sand and gravel which is present immediately above the rock. Due to the presence of this soil material, the total thickness of rock in the roof area can become extremely thin in places despite overburden thicknesses in excess of 140 feet. This could be very detrimental to stability conditions in the roof of the mine as it adds considerable weight to the mine roof, but offers little support with respect to the ability of the roof to span between pillars.

The pillars on site consist of unmined areas of largely subbituminous coals of the Laramie Formation and associated carbonaceous shales. Pillars left by the mining operation are commonly on the order of seven feet in height.

The floor materials are most commonly either shale or sandstone. Across the majority of the mine sandstone materials predominate in the floor. In some areas, however, weathered claystone is encountered immediately beneath the pillars. This material would commonly be termed an "underclay". These extremely weathered materials possess shear strength characteristics more commonly associated with clay soils than with shale bedrock materials. The presence of these lower density clays can create a potential for pillar punching or a bearing capacity failure of the pillars into the floor materials.

Groundwater was observed in all test borings on the site at depths ranging from 40 to 75 feet below the ground surface. The groundwater has an extremely important effect on stability conditions within the mine. The presence of groundwater actually reduces the effective weight of the overburden acting in the roof since in those areas below the water table, the buoyant unit weight of the materials present may be considered, which is substantially less than the total unit weight in an unsaturated environment. On the other hand, the groundwater is largely responsible for the softening of the clay shale materials producing the weak underclays in the floor as mentioned above. Therefore, the presence and position of the groundwater table on this site is critical to the overall stability conditions.

In order to evaluate past subsidence activity, a photogrammetric map of the site was prepared at a scale of one inch equals 50 feet with a contour interval of one foot. Interpretation of this map showed evidence of extensive surface subsidence in the westernmost portion of the property with maximum surface ground movements estimated to be approximately three to four feet. The central portion of the property also showed evidence of subsidence with maximum ground movements estimated to be approximately 2 to 2.5 feet. Further to the east evidence of existing surface movement due to subsidence becomes much more sparse with those areas indicating subsidence showing maximum ground movements on the order of ± one foot. The extreme eastern portion of the property showed no significant evidence of subsidence movement at the time of the investigation. This data obtained from interpretation of the surface topography was consistent with the conclusions and predictions in the original Phase I investigation.

Extensive evidence of past subsidence activity in the extreme westernmost portion of the site, coupled with confirmation of open voids remaining in the area from available test boring information, confirmed the high subsidence risk earlier assigned to the area. In the centralmost portion of the site, however, some of the test borings showed the presence of rubble instead of an actual void at the mine level. This can be an indication of subsidence already having occurred diminishing the potential for future subsidence. Analysis of surface topographic information, however, indicates that only 2 to 2.5 feet of surface subsidence has occurred in the area. Estimates of maximum potential subsidence utilizing the National Coal Board procedures indicated a maximum potential on the order of 5 to 6 feet. This would imply that a potential for additional surface movement (on the order of 2.5 to 4 feet) remains.

The extreme easternmost portion of the site showed evidence of little or no subsidence movement. Also, as mentioned previously, it was suspected that pillar robbing has not occurred within the Corley Mine in the extreme eastern portion of the property. Correlation between the limit of the area on the surface showing no evidence of subsidence and the limit of the area not subjected to pillar robbing was very strong. These limits were within 50 feet of one another and perfectly parallel. It appeared quite possible, therefore, that the post-mining roof, pillar and floor conditions in that area were conducive to long-term stability which would equate to a minimal risk of future surface subsidence. However, in order to verify that such conditions did exist, additional subsurface exploration would be required. These investigations would have to accomplish, as a minimum, the following:

1. Confirm the accuracy and reliability of available mine maps;
2. Provide samples of rock materials in roof, pillar and floor areas for shear strength testing;
3. Yield sufficient information to perform an analysis of the factors of safety associated with roof and pillar failure.

Phase III

This study was a more detailed evaluation of the eastern portion of the site, resulting in a prediction of final subsidence profile and ground strains, involving:

1. Transfer of mine map information onto available topographic maps and verification of the mine map through drilling;
2. Sampling of the overburden, pillar and floor materials through the drilling process;
3. Laboratory testing;
4. Analysis of the anticipated surface subsidence and ground strains utilizing a progressive failure model.

As part of this more detailed investigation, we were able to interview a former mine worker who had worked both within the Busy Bee and the Patterson Mine through 1938. Many of his general comments can be summarized as follows:

> The entrance to many of the mines in the area were through slopes having typical inclinations on the order of 20 to 25 degrees. Entries during the development stages of mining were typically on the order of 9 to 10 feet in width, with a mined height on the order of 7 feet being most common. Rooms

were commonly developed with widths on the order of 20 to 24 feet, but in some cases could reach up to 30 feet. A layer of "top coal" typically of two feet in thickness, was commonly left to improve roof stability. This top coal layer could, however, reach thicknesses of up to four feet in the thicker seams. Both the Busy Bee and Patterson Mines were extensively pillar robbed on retreat, which commonly included removing top coal and slashing the walls of entries and haulageways. Coal was most commonly excavated using a Sullivan or Jeffrey Coal Cutting Machine which would undercut the face up to six feet with a six-inch thick cut at the base. The face was then advanced six feet by drilling and shooting with black powder. Most of the larger rooms were heavily timbered. He specifically remembered a very large room within the Busy Bee Mine immediately north of the existing structure on-site which was described as 30 to 40 feet in width, of unknown length, seven feet in height with four feet of top coal left in place, and heavily timbered. All of the mines were wet mines requiring dewatering through pumped wells.

The drilling program on this site consisted of 13 test borings utilizing both continuous flight auger and water-cooled rotary coring techniques. Those holes which were cored produced a continuous column of NX size core.

The location of room and pillar features for the Corley Mine were plotted on the site topographic map based on information available on the original maps. The drilling program was then designed to verify the location of mine features by confirming an anticipated pattern of pillars and voids in not less than two separate lines of test borings at different locations within the mine. Initial drilling efforts did not verify the anticipated pattern of pillars and voids, indicating either the mine maps to be inaccurate or the mine features shown on the mine map to be misoriented. As drilling progressed, a schematic of the Corley Mine was moved around on the base map in order to identify a locus of points representing various locations and orientations of the available mine map information which would satisfy the patterns of alternating voids and pillars observed in the test drilling program. The location of subsequent test borings were selected on the basis of narrowing down and eliminating all of the various locus of points identified except one. This being accomplished, it was determined that, in our judgement, the basic representation of the room and pillar features showed on the Corley Mine map were accurate, however, it appeared that the mine was not in the position as indicated on the original mine map. Based on the test drilling program, we felt the mine to actually be located some distance to the south of the map location shown and to be rotated approximately 14 to 15 degrees to the east. The most likely scenario for why such a condition may have developed would appear to be that a pin marking an existing property corner was mistaken for the Section corner and that the magnetic declination was not accounted for in the recorded map orientation. The property corner exists approximately 125 feet south of the Section corner. If the mine features are laid out using this point as the Section corner and neglecting the magnetic declination (12.5 degrees on this particular quadrangle) the information recorded on the mine map very closely approximates what we believe to actually exist on the site underground.

Comparison of available mine map information and production records show a considerable discrepancy. This discrepancy created some concern with respect to whether pillar robbing had occurred and was simply never reflected on the final map. An important consideration, however, is that in this particular phase of the mine subsidence investigation, focusing on the area above the Corley Mine a total of 13 test borings were drilled, only four of which produced voids. With 9 of the 13 test borings drilled in the area revealing pillars we felt it was highly unlikely that the area had been pillar robbed and tended to believe the available mine map information.

Laboratory testing for this investigation consisted of rock mechanics tests performed on selected samples of the roof, pillars and floor of the mine obtained from the rock coring portion of the drilling operation. Twelve Brazilian Tensile Strength tests were performed on samples of coal removed from the pillars and from the various lithologies involved in the floor of the mine. Specific results of testing can be found in Table 1.

FAILURE MECHANISMS INVESTIGATED

Three different types of failures were investigated at this site (Figure 6). These included:

1. Pillar failure;
2. Roof failure;
3. Pillar punching failure.

Table 1. Summary of Laboratory test results.

Sample No.	Hole No.	Depth (feet)	Rock Type	Location	Compressive Strength (psi)	L/D Ratio	Brazilian Tensile Strength (psi)	Modulus of Rupture (psi)	Unit Weight (pcf)
S-1A	1A	23.9 - 25.0	Coal	Pillar	11	2.0	---	---	75
S-2A	11A	118.7 - 119.1	Coal	Pillar	2260	1.1	---	---	61
S-3A	11A	126.0 - 126.6	Shale	Floor	30	1.4	---	---	124
S-4A	11A	115.4 - 115.9	Shale	Roof	---	---	11	---	126
S-4B	11A	115.4 - 115.9	Shale	Roof	---	---	18	---	126
S-5A	12A	127.2 - 128.2	Sandstone	Floor	1090	2.5	---	---	139
S-6A	12A	122.5 - 123.4	Coal	Pillar	1220	2.0	---	---	84
S-6B	12A	122.5 - 123.4	Coal	Pillar	2000	1.5	---	---	93
S-7A	12A	123.4 - 123.7	Coal	Pillar	1470	1.0	---	---	73
S-8A	12A	124.2 - 124.5	Coal	Pillar	1670	1.5	---	---	76
S-9A	12A	117.0 - 117.5	Coal	Pillar	1402	2.5	---	---	---
S-10A	12A	114.2 - 114.6	Shale	Roof	---	---	70	---	132
S-10B	12A	114.2 - 114.6	Shale	Roof	---	---	60	---	133
S-11A	12A	105.7 - 106.3	Shale	Roof	---	---	---	10	---
S-12A	12A	104.4 - 105.0	Shale	Roof	---	---	---	---	---
S-13A	12A	103.0 - 104.1	Shale	Roof	---	---	---	12	139
S-14A	12A	96.4 - 97.0	Sandstone	Roof	---	---	---	4	---
S-15A	12A	96.0 - 96.4	Sandstone	Roof	---	---	92	---	135
S-15B	12A	96.0 - 96.4	Sandstone	Roof	---	---	45	---	136
S-16A	13A	94.7 - 95.2	Sandstone	Roof	---	---	152	---	127
S-16B	13A	94.7 - 95.2	Sandstone	Roof	---	---	127	---	128
S-17A	13A	91.7 - 93.6	Sandstone	Roof	---	---	---	27	140
S-17B	13A	91.7 - 93.6	Sandstone	Roof	---	---	---	27	139
S-18A	13A	90.0 - 91.7	Sandstone	Roof	---	---	153	---	138
S-18B	13A	90.0 - 91.7	Sandstone	Roof	---	---	153	---	138
S-18C	13A	90.0 - 91.7	Sandstone	Roof	1280	2.5	---	---	138

Pillar Failure

This type of failure involves the crushing of the individual pillars due to excessive overburden loads. Pillar failure analysis was based upon procedures described by Goodman in a paper entitled "The Evaluation of Collapse Potential Over Abandoned Room and Pillar Mines". These equations utilized are based upon the work of Hustrulid (1976) in his review of size and shape corrections used by many investigators. To analyze the worst case pillar failure scenario on this project we decided to utilize an iterative approach to the project.

The first step in this analysis is the determination of the overburden stresses on each individual pillar. The stress in each pillar is calculated by assuming each pillar supports an area of roof spanning half the distance to the next pillar. Our particular analysis assumed the average weight of the overburden to be 145 pcf and that there had been approximately one foot of loosening and weathering around each pillar which could not be counted on for support. The strength of the pillar materials was based upon unconfined compression tests of samples obtained of pillar material during the exploration boring work. After the pillar strength had been determined, a factor of safety was determined for each pillar by dividing the pillar stress by the pillar strength. If the factor of safety fell below the minimum acceptable factor of safety, it was assumed that the individual pillar had collapsed and that the roof load was then transferred to the surrounding uncollapsed pillars. This analysis involved performing a series of iteration until all pillars remaining showed a factor of safety above the minimum requirement.

Roof Failure

After the pillar failure analysis was completed, the spans between the remaining individual pillars were analyzed to determine if roof failure could occur. This analysis was based upon beam theory equations (Obert and Duvall, 1967) assuming that the roof acts like a wide, clamped beam and neglecting horizontal stresses. The maximum tensile stress was determined based upon equations for beam theory. Maximum tensile strengths computed for a particular roof thickness were then compared to the laboratory flexural strength. A maximum span length for specific locations was then determined assuming an appropriate factor of safety. The roof

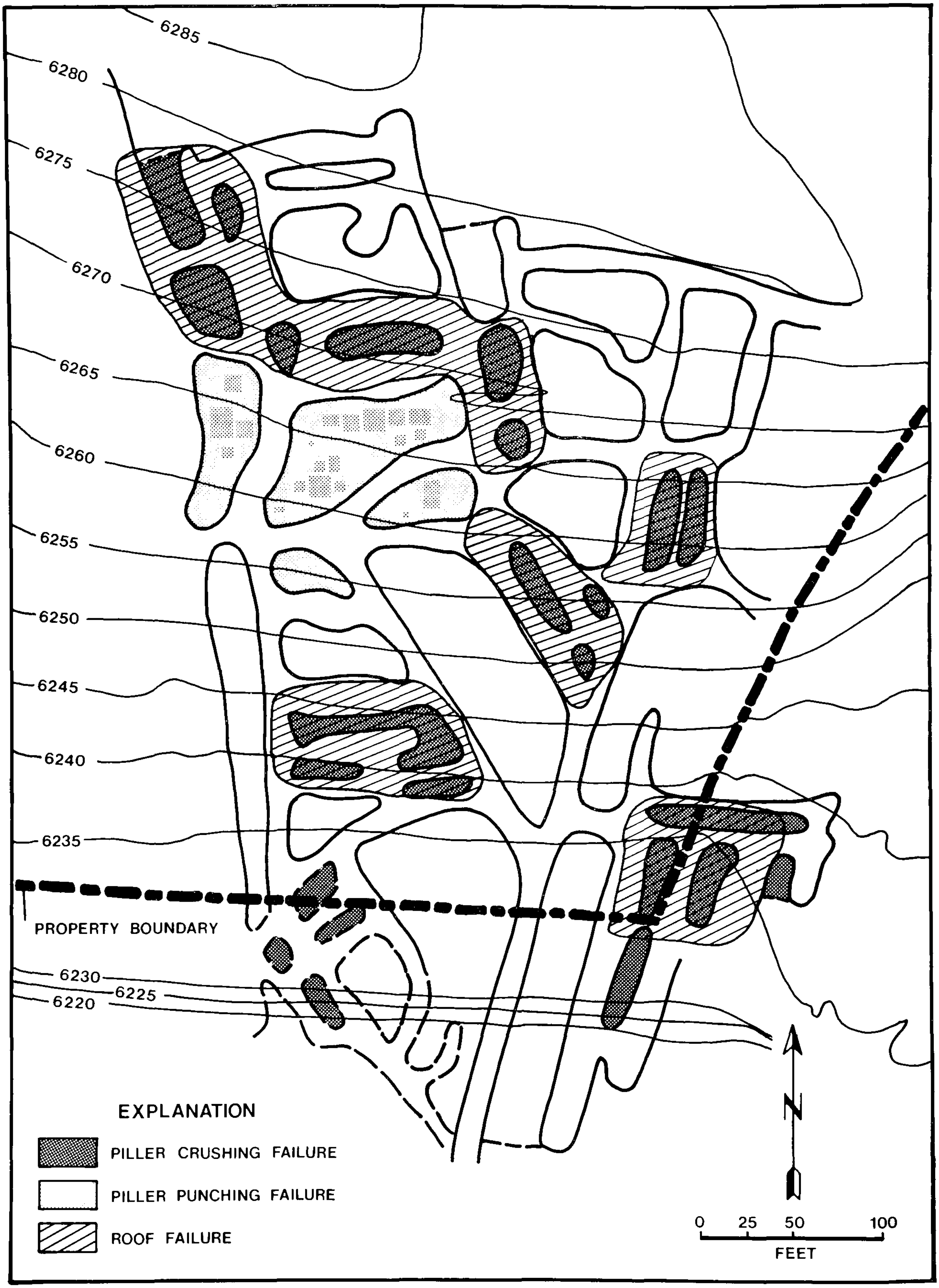

Figure 6. Modes of failure/factor of safety = 2 with water table.

was assumed to fail in areas if the existing span length exceeded the calculated maximum allowable span for the particular roof material.

Pillar Punching Failure

The last failure mechanism analyzed involved pillar punching or the bearing capacity failure of the floor material at each individual pillar. The exploratory work indicated that the floor primarily consisted of sandstone materials. However, there were a few isolated cases where there was a thin layer of softened shale (underclay) beneath individual pillars. The floor material strengths were based upon unconfined compression tests performed on samples of floor materials retrieved during the exploratory boring work. A shallow bearing capacity failure analysis was used and the pillar was assumed to fail when the calculated factor of safety was below the minimum requirement. The bearing capacity factor of safety was determined for each individual pillar by dividing the individual pillar stress by the calculated bearing capacity of the underlying floor material.

Typically, a factor of safety of 2.0 is recommended for pillar crushing analysis (Figures 7 and 8). However, it has been documented that pillars having a design factor of safety greater than 1.5 have an extremely low probability of pillar failure (Solomon and Munro, 1967). The roof failure and pillar punching analysis normally utilizes a factor of safety of 2.0.

Three different cases were analyzed for the pillar failure analysis (Figure 7 through 11). These cases assumed that the groundwater elevation was lowered to the current mine level which is the absolute worst case condition. The second case assumes that the groundwater stays at its current elevation and assumes a minimum required factor of safety of 2.0. The third case involved assuming a minimum required factor of safety of 1.5. After these analyses were completed, a surface subsidence and strain analysis was performed using the predicted final failed configuration of the mine for each case analyzed. The surface subsidence and horizontal strain amounts were calculated based upon procedures in the "Subsidence Engineer's Handbook" by the National Coal Board. These values would be considered conservative for the site conditions and assumes a trough rather than a sinkhole type of subsidence. Intermediate stages of subsidence development are not considered predictable by current state-of-the-art engineering procedures.

The overburden materials in the United Kingdom, where the National Coal Board procedures were developed, tend to be highly fractured and relatively incompetent, while roof materials in the U.S. are typically more competent sandstones, siltstones, shales, etc. These materials have a tendency toward elastic behavior. This is contradictory to the National Coal Board data which is based upon clastic failures. The elastic subsidence involves sagging in the rock materials over mine openings, mobilizing a considerable amount of strength within the rock materials, which has a tendency to reduce subsidence. Past subsidence observed on-site has been estimated to be only one-half to one-third of that predicted by the National Coal Board's equations. However, at this site the roof contains only a thin zone of competent rock with a considerable thickness of unconsolidated soil materials. Therefore, the profile is more likely to behave as clastic materials involving movement of broken rubble and debris, making the National Coal Board equations more representative.

MITIGATIVE MEASURES

Based on the results of all investigations, potential land use options were evaluated. Independent of the economics associated with marketing of the development and looking solely at controlling the risk of damage to man-made structures and other improvements, we ranked the proposed land uses in the following order of priority:

1. Open space;
2. Low density office, industrial or commercial development;
3. Mobile home park;
4. Multi-family residential.

The multi-family residential use carried the highest risk of detrimental impact from subsidence due to the large number of permanent structures which would be scattered more or less at random across the site. This use also required a rather intense system of utilities and other improvements, all of which would be associated with significantly higher design and construction costs. An office, industrial or commercial use will similarly involve permanent structures; however, planning can be such that they are fewer in number and concentrated in the less risky portions of the site. It would also be feasible to spend more per structure

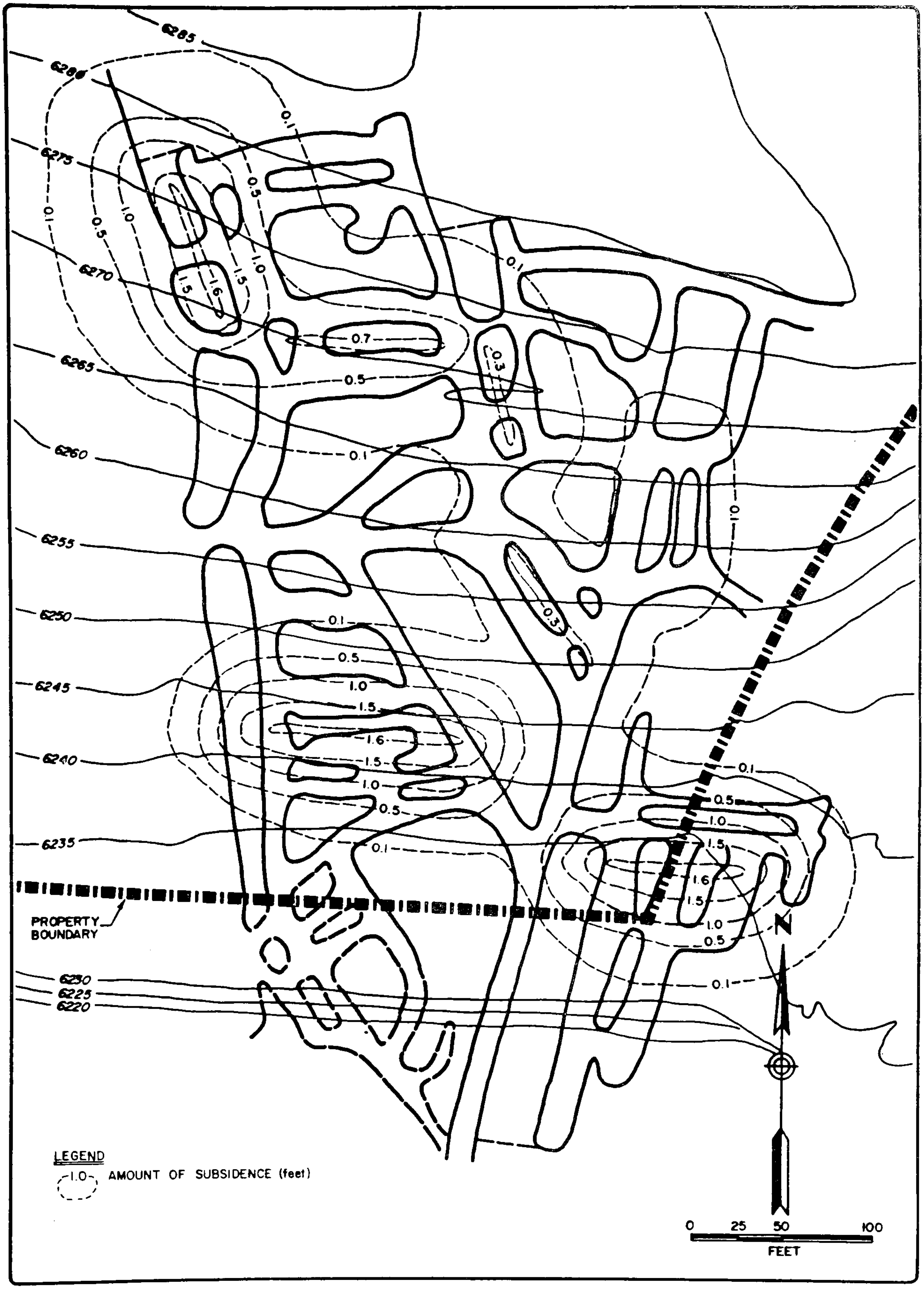

Figure 7. Subsidence contours/factor of safety = 2 with water table.

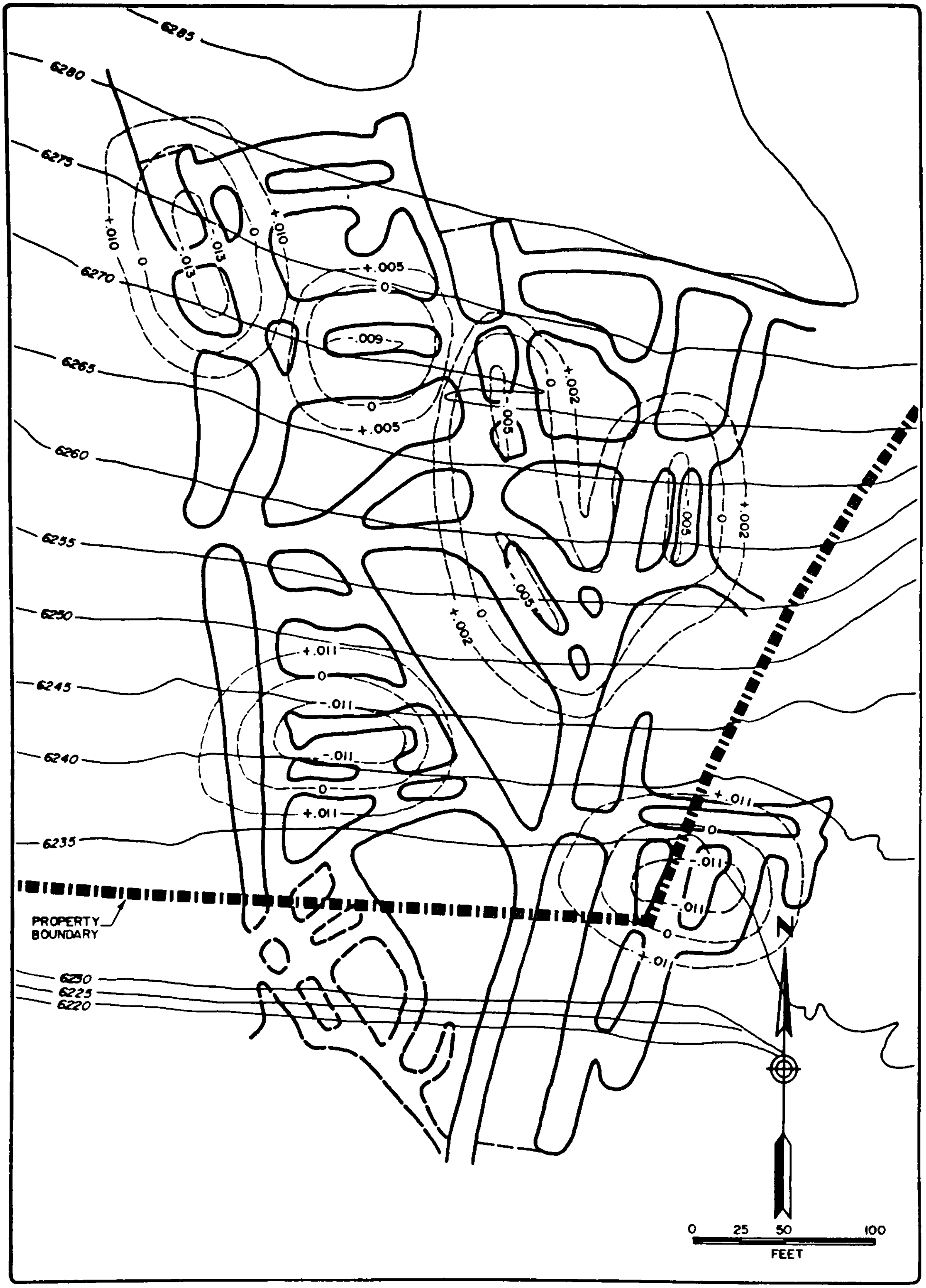

Figure 8. Maximum compression and tensile strain contours/factor of safety = 2.

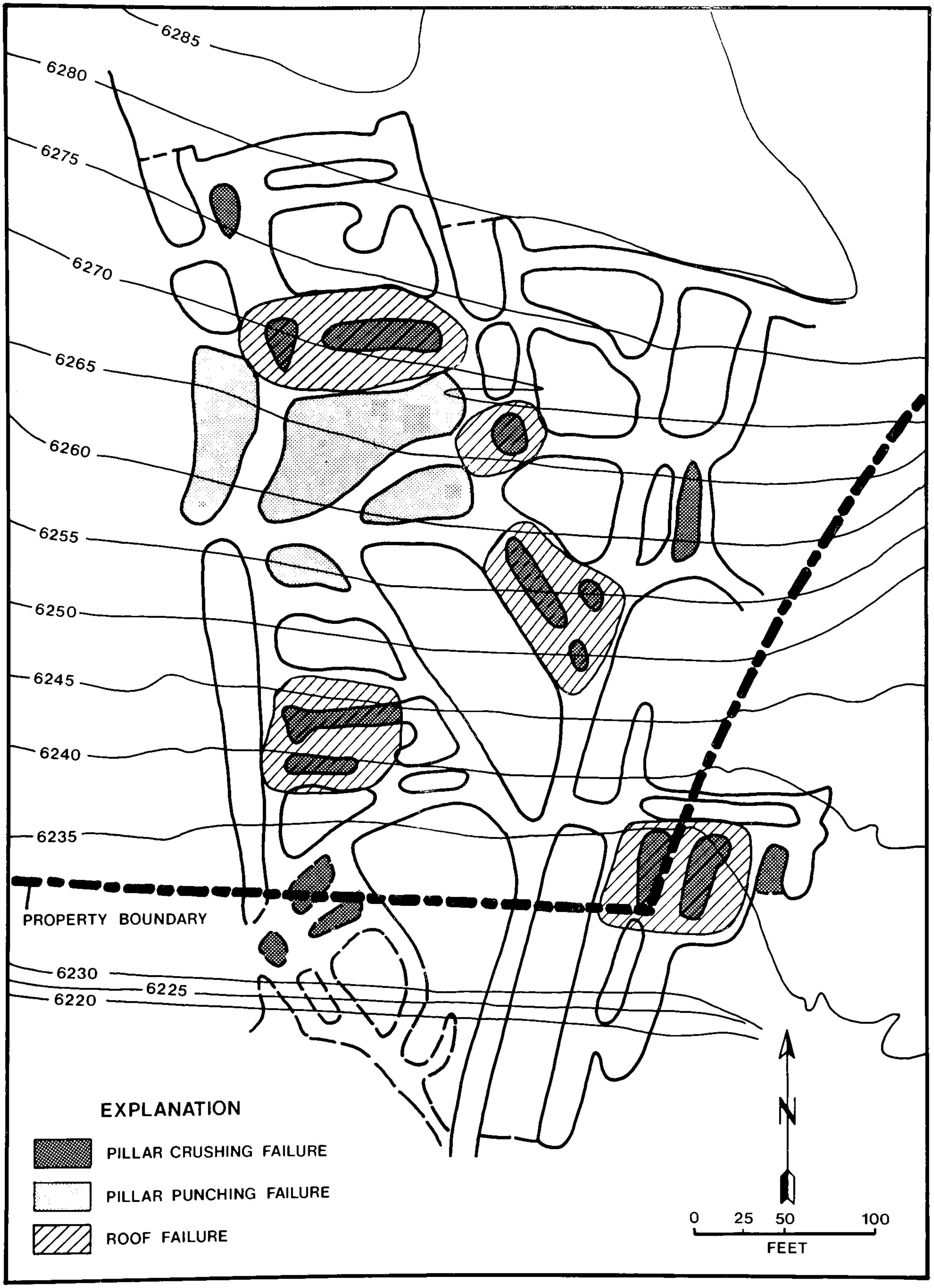

Figure 9. Modes of failure/factor of safety = 1.5 with water table.

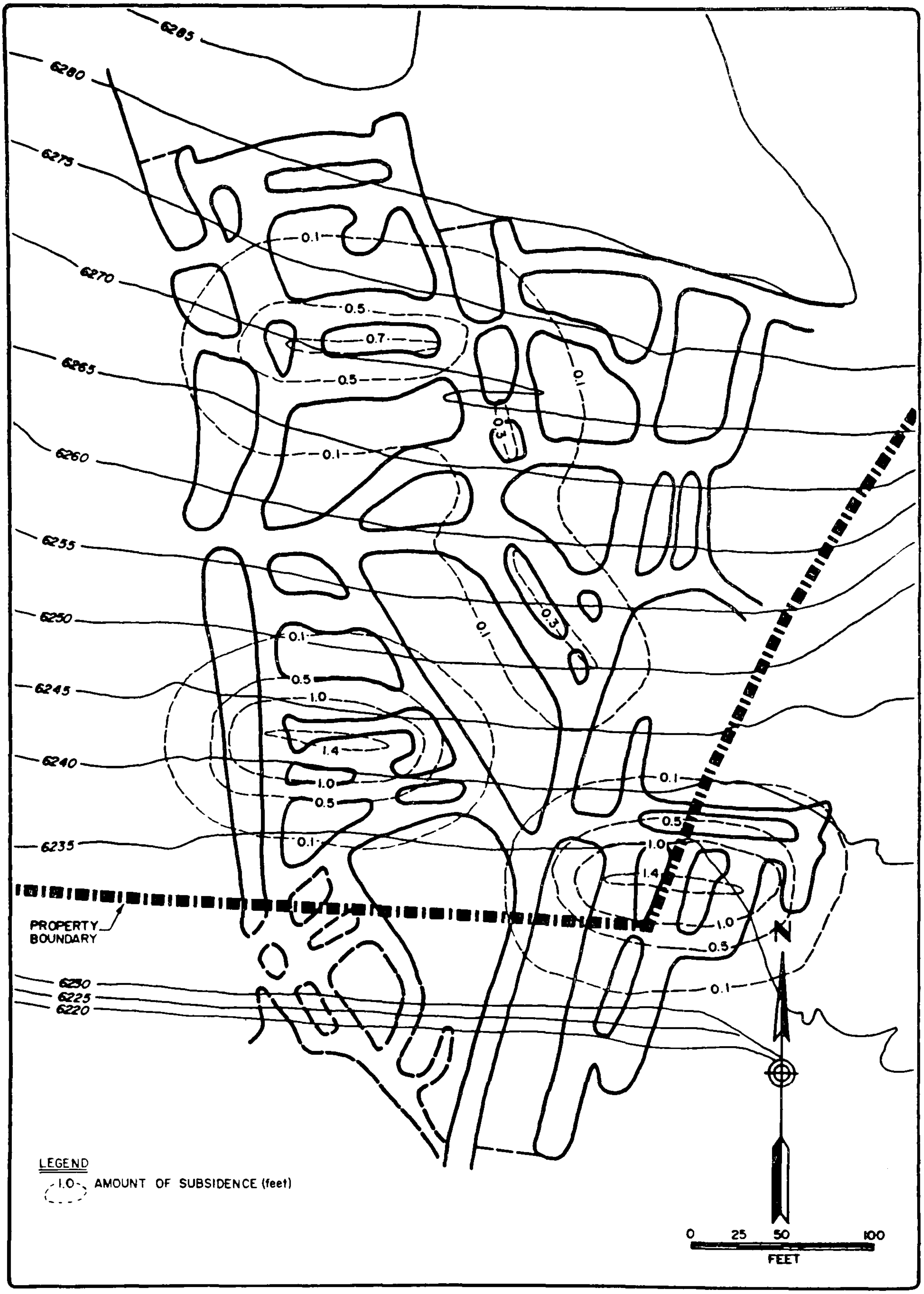

Figure 10. Subsidence contours/factor of safety = 1.5 with water table.

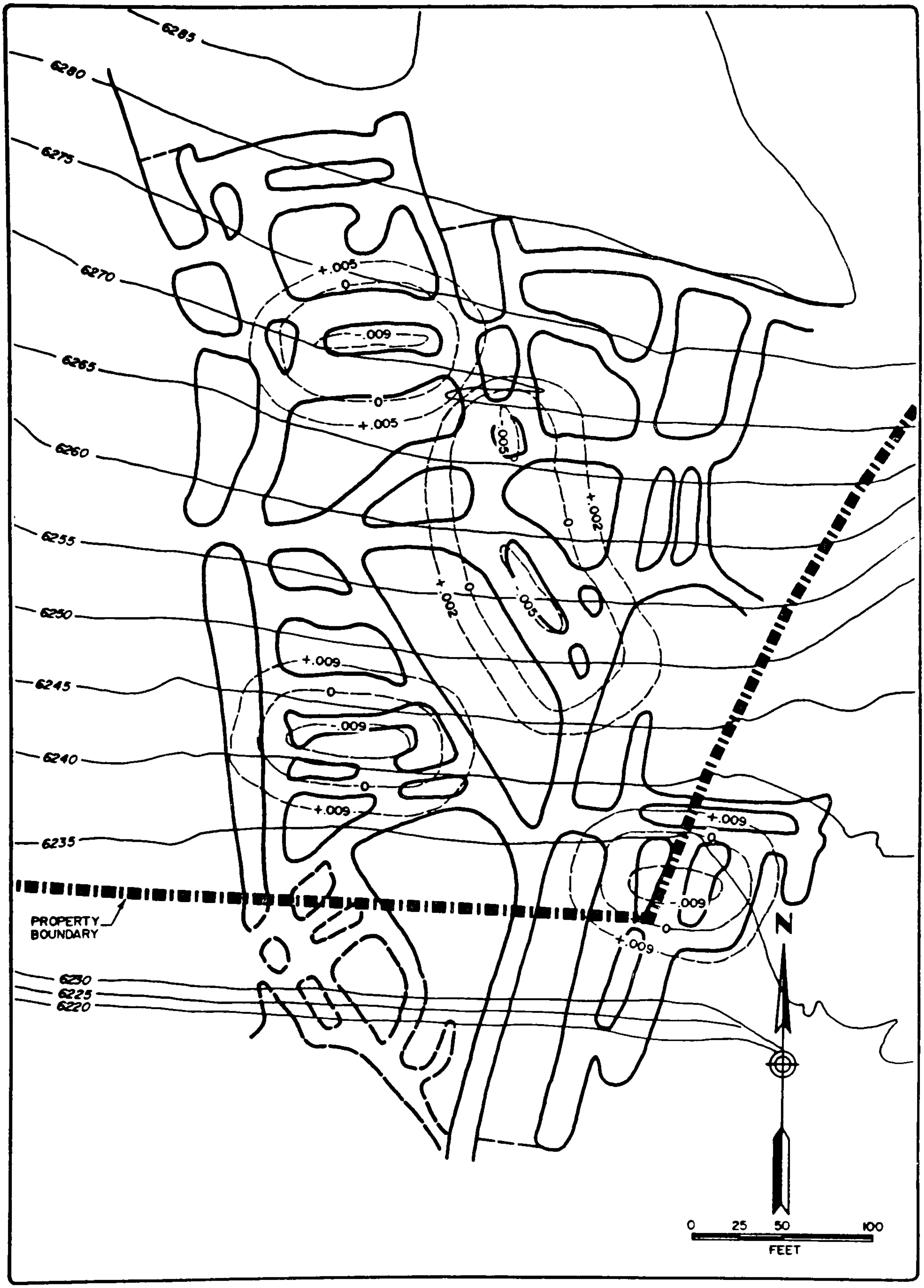

Figure 11. Maximum compressive and tensile strain contours/factor of safety = 1.5.

on mitigation of the subsidence effects. Utility requirements for this land use would also be less intensive. The mobile home park concept involves structures which might not be considered permanent and, which by their nature, will be considerably more tolerant to the surface effects of subsidence. This use may still, however, require an extensive network of utilities. An open space or recreational use can involve few, if any, permanent structures and few, if any, utilities, therefore, resulting in a considerable reduction in the risk of damage to man-made improvements resulting from subsidence. However, the economics associated with this type of land use could make it less desirable or unfeasible.

The following design techniques were considered to help mitigate surface effects due to underground mine subsidence. Permanent structures could be designed to be either extremely flexible (so that they may tolerate significant movement without structural damage) or extremely compact and rigid (so that they may move independently of one another and act as a single compact unit without experiencing structural damage). In the case of rigid structures, provision must be made for the releveling of the units as may be required following subsidence. Roadways could be designed with flexible pavement systems capable of undergoing movement with less visible damage. Gradients critical to drainage of roadway areas could be steepened to account for changes in grades after subsidence, permitting continued positive drainage. Utilities involving pipelines could contain flexible joints, and in the case of pressurized lines, telescoping joints. If possible, flexible, ductile material should be utilized in lieu of brittle materials. Lines could be designed with shorter rigid sections accommodating greater strains across the full length of the line.

The following techniques were discussed for preventing, arresting or retarding on-site subsidence. The approaches fall into two general categories:

1. Selective support to supplement existing subsurface support and prevent or minimize subsidence movements;
2. Filling methods which prevent or minimize future subsidence by eliminating subsurface voids.

Specifically, the techniques considered included:

1. Blind flushing;
2. Pumped slurry injection (Dowel process);

3. Grouting;
4. Overexcavation and backfill;
5. Dynamic compaction;
6. Blasting;
7. Grout columns;
8. Groutcase;
9. Deep foundations.

Conclusions regarding the practicability of these techniques on-site were as follow. For all portions of the site having future subsidence potential, the use of one of the hydraulic backfill techniques could be considered. We preferred the use of the pumped slurry injection (Dowell process) over blind flushing, but considered either acceptable. the use of grout columns could be considered for any portions of the site where a need is identified for additional intermediate support. The procedure would be considered to have greatest application in the easternmost portion of the site where the pillar robbing had not occurred. Within the pillar-robbed zone, considering the scarcity of information available on the mine plan, it is anticipated to have limited or no utility. Use of other techniques, such as dynamic compaction and deep foundations could have limited utility in the extreme westernmost portion of the project only where overburden thicknesses were low. We would anticipate, however, that conditions justifying the use of these procedures would be the exception rather than the rule. All other procedures were rejected on the basis of unproven effectiveness or cost.

OBSERVATIONS ON THE LOCATION OF CHIMNEY SUBSIDENCE SINKHOLE DEVELOPMENT ALONG THE COLORADO FRONT RANGE

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ABSTRACT

Chimney subsidence sinkhole development from collapse of abandoned coal mines is one of the major subsidence hazards along the Colorado Front Range. This paper reviews the mechanism of chimney subsidence sinkhole development in soft rocks and presents empirical data on the maximum height chimney subsidence sinkholes may develop over horizontal and dipping coal seams. Generalizations are drawn which can be useful in the prediction of potential chimney subsidence sinkhole development throughout the Front Range.

INTRODUCTION

Subsidence due to underground coal mining can take three general forms. These are: 1) trough subsidence, 2) chimney subsidence and 3) localized trough subsidence. Trough subsidence is a broad dish shaped lowering of the ground surface normally resulting from high extraction mining (i.e., where more than 90 percent of coal has been removed in one area). This type of subsidence occurs over relatively large areas, typically hundreds to thousands of feet in breadth. Chimney subsidence is typified by the development of sinkholes at the ground surface. The sinkholes are generally several feet to several tens of feet in breadth, circular or elliptical in shape and range in depth from less than a foot to greater than 10 feet. localized trough subsidence is transitional between chimney and trough subsidence and is characterized by an erratic (with respect to location, magnitude and timing) lowering of the ground surface. This form of subsidence can occur in both low extraction and high extraction areas. In addition, localized trough subsidence may occur as a result of long-term adjustment of the ground surface to previous subsidence or the response of undermined areas to significant changes in the normal subsurface hydrologic

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The development of chimney subsidence sinkholes is by far the most common subsidence problem which has been reported along the Colorado Front Range. To the authors' knowledge, few cases of recent trough or localized trough subsidence have been satisfactorily documented. Although it is likely that localized trough subsidence has occurred, data on the severity of subsidence damage and surface evidence of subsidence has been insufficient to definitely identify this subsidence phenomenon. Identification of subsidence problems is further complicated by the impact of swelling and collapsing soil conditions along the Colorado Front Range. As a result, the development of chimney subsidence sinkholes is likely to remain the single most visible type of subsidence and the most frequent cause of identifiable subsidence related damage. The purpose of this paper is to examine the mechanics and characteristics of chimney subsidence sinkhole development and to identify the factors which effect its development along the Colorado Front Range.

COAL GEOLOGY/MINING HISTORY

The coal mines developed along the Colorado Front Range were mined in coal seams from the lower Laramie Formation of Cretaceous Age. The minable coal is generally present within 150 feet of the contact between the Laramie Formation and Fox Hills Formation. The coal was deposited in numerous, laterally extensive seams which thicken and thin depending on the paleo-geologic depositional environment. In most areas the presence of several seams has allowed for multiple seam mining. Double seam mining is present in most of the major Front Range coal fields with triple seam mining present in limited areas of the Boulder coal field.

Coal was mined along the Colorado Front Range from the 1860s to the 1970s. The vast majority of coal was mined from seams which are relatively flat lying (i.e., dip less than 15 degrees). However, some mining of steeply dipping coal seams was performed in parts of Littleton and Jefferson County. These mines were developed on coal beds which dip approximately 50 to 90 degrees from the horizontal. The coal mining in both relatively flat lying and steeply dipping seams was performed at depths ranging from less than 50 feet to greater than 900 feet below the ground surface.

In flat lying coal seams, room and pillar and retreat mining was most common. Extraction ratios for the room and pillar mining areas ranged from 25 to 75 percent with an average of about 50 to 60 percent. In most areas, retreat mining (i.e., pillar extraction) was performed when room and pillar development was complete. The retreat mining did not completely remove all the pillars. A completed retreat mining section generally had an extraction ratio of between 70 to 95 percent with about 80 to 85 percent being most common. After the mines were abandoned the support in the haulageways was left in place (unless haulageway barrier pillars were extracted). As a result, the haulageways and other supported areas could remain stable for an extended period of time.

In any particular mine, the retreat mining pillar extraction was completed on a generally regular sequence. The extraction method utilized was the so called "pocket and stump" method. Figure 1 shows the typical configuration of "pocket and stump mining" in two mines as reported by U.S. Bureau of Mines (1933).

Steeply dipping coal seams were mined utilizing either a variation of room and pillar mining or open stoping. In general, haulageways were driven parallel to the strike of the coal seam. Stopes, which varied from about 30 to 100 feet high and 50 to 100 feet wide, were developed above the haulageways. Each stope had a barrier pillar between it and the adjacent stope. The barrier pillar was normally left in place after mining was complete. In general, multiple stope levels were developed in the steeply dipping seams. The vertical dimension between stope levels varied, but was usually between 75 to 150 feet. When the mines were abandoned, the support was probably left in most of the main haulageways and some stopes. A more detailed description of this mining method is presented by Hart (1986) in this volume.

MECHANICS OF CHIMNEY SUBSIDENCE DEVELOPMENT

Failure of abandoned underground coal mine openings in areas of roughly geostatic in situ horizontal stress can occur in three ways. These are: 1) roof collapse, 2) pillar failure, and 3) floor heave (i.e., pillar punching into the floor). In order to understand why chimney subsidence is so common along the Colorado Front Range one must examine and identify the most critical failure mode(s) for the underground mine openings. For instance, if it is found that pillar failure or floor heave is a critical failure mode then one would expect to see trough or localized trough subsidence. However, if roof collapse is found to be the most

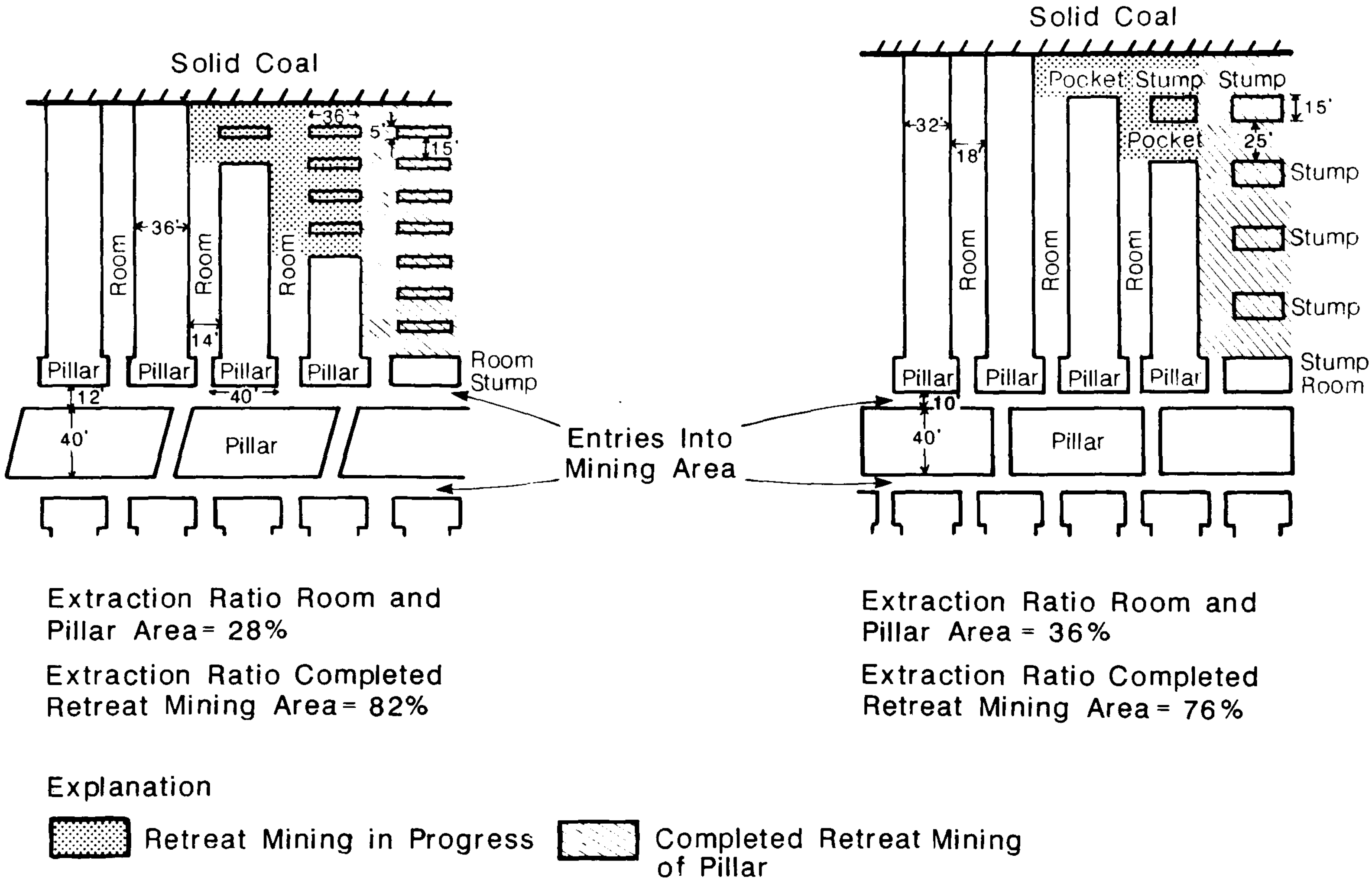

Figure 1. Pillar extraction method for two mines in Boulder Coal Field (after Tomlinson, 1933.)

critical failure mode then one would expect extensive chimney development and rubblization. Therefore, in order to identify the critical failure mode, the relative strength of the pillars, roof and floor must be examined under various extraction ratios and overburden depths. In order to perform these analyses a quantification of the strength of the mine and overburden materials is required.

Material Properties

The majority of rock materials pertinent to mine stability along the Colorado Front Range can be classified as either 1) coal, 2) sandstone, or 3) claystone. Given the large areal extent of the coal fields, the mechanical properties of these materials may vary considerably. However, in general, the sandstone and claystone which make up the majority of the rock overburden, roof and floor materials, are weak and have mean strengths which fall within relatively narrow ranges. As part of mine subsidence investigations the laboratory strengths of the various materials have been measured. Tables 1, 2 and 3 present a compilation of available laboratory strength data from various Front Range coal fields.

The strength of laboratory size test samples does not normally provide a good estimate of in situ rock mass properties. This has been demonstrated for numerous materials including coal (Bienawski, 1968; Pratt et al, 1972). The rock mass strength/laboratory strength ratio depends on many factors. These include 1) the homogeneity of the rock mass, 2) the presence, orientation and frequency of fractures in the rock mass, 3) the quality of the rock core recovered (i.e., was only the strongest most durable core recovered of sufficient size for testing), and 4) the size of the area over which the stress is being applied.

Various researchers (cited above) have studied the relationship between the rock mass and laboratory strength. The best documented data involves coal. The results of these studies suggest that the compressive strength of coal is reduced until a certain "critical size" is obtained. This critical size has been estimated to be a cube with a side length of between 36 to 60 inches (Hustrulid, 1978). A relationship which is widely utilized to convert laboratory coal strength into rock mass coal strength, assuming a 60 inch critical size, is as follows:

$$m = \frac{L^{D}}{}$$

Table 1. Lower Laramie Formation sandstone material property data along Colorado Front Range.

Location	Average Moisture Content (%)	Average Moist Unit Weight (pcf)	Average Compressive Strength (psi)	Average Elastic Modulus (psi)	Comments
Central Springs Area Colorado Springs	11	142	775	103,500	Dip Less Than 5°
Rockrimmon Area Colorado Springs	10	136	805	63,800	Dip Less Than 5°
Economy Mine Littleton	12	138	705	86,000	Residual Friction Angle - 31° Dip About 52°
New White Ash/ Loveland Mines Golden	10	143	770	91,900	Triaxial Strength Ø = 48 C = 140 psi Dip From 70° to 90°
Boulder County East of Marshall	8	144	1450	178,750	Dip From 5° to 30°

Table 2. Lower Laramie Formation claystone material property data along Colorado Front Range.

Location	Average Moisture Content (%)	Average Moist Unit Weight (pcf)	Average Compressive Strength (psi)	Average Elastic Modulus (psi)	Comments
Central Springs Area Colorado Springs	14	134	410	29,600	Dip Less Than 5°
Rockrimmon Area Colorado Springs	12	141	954	40,000	Dip Less Than 5°
Economy Mine Littleton	14	139	206	30,000	Residual Friction Angle - 31° Dip About 52°
New White Ash/Loveland Mines Golden	17	137	86	72,000	Dip From 70° to 90°
Boulder County East of Marshall	10	141	775	87,515	Dip From 5° to 30°

Table 3. Lower Laramie Formation coal material property data along Colorado Front Range.

Location	Average Moisture Content (%)	Average Moist Unit Weight (pcf)	Average Compressive Strength (psi)	Average Elastic Modulus (psi)	Comments
Central Springs Area Colorado Springs	26	87	1500	129,500	Residual Friction Angle - 16° Dip Less Than 5°
Rockrimmon Area Colorado Springs	34	109	3190	NA	Residual Friction Angle - 21° Dip Less Than 5%
Economy Mine Littleton	39	81	1620	122,000	Dip About 52%
New White Ash/ Loveland Mines Golden	27	84	1380	135,000	Dip From 70° to 90°
Boulder County East of Marshall	24	83	2640	193,000*	Dip From 5° to 30°

Note: All Sample Compressive Strengths Were Corrected to a 1:1 Height to Diameter Ratio

* Based On One Sample Only

where: m = rock mass coal strength

D = side length of 1:1 cubical coal specimens

L = laboratory strength of 1:1 cubical coal specimens

Note that cubical specimens are often unavailable and that cylindrical specimens are often utilized. This introduces an error into the calculation, and will underestimate the strength of the coal approximately 5 to 10 percent. Also, a single specimen of coal is insufficient to estimate _m. This calculation should involve at least 10 coal specimens and preferably 10 coal specimens from each of several locations.

The estimation of the rock mass strength of claystone and sandstone is less straight forward. The best method available is to back calculate a range of rock mass strengths from an area of known rock floor failures. Areas of floor failure in claystone are often shown on old mine maps, however, little or no data is normally available for areas of mine roof failure in either sandstone or claystone. As a result, back calculation of claystone strength can often be performed. This back calculation involves utilizing bearing capacity equations to estimate the range of minimum shear strength required for a pillar to have a factor of safety of 1.0 When doing this calculation, one must consider both the bearing capacity, assuming a range of claystone layer thickness below the pillar, relative to the width of the pillar. The methods for back calculation of these strength parameters are presented by Terzaghi and Peck, 1948 and Vesic, 1970.

The estimation of sandstone strength relies heavily on judgment. In general, the sandstone appears to have a higher strength than the claystone since few, if any, cases of pillar punching occur in sandstone. Table 4 presents estimates of the range of the rock mass strength of various materials encountered in coal fields along the Colorado Front Range.

Critical Failure Modes

The rock mass material property data provides the necessary input to calculate the relative strength of the mine roof, pillars and floor under various combinations of mine geometry, overburden thickness and material strength. Figure 2 presents the results of a calculation of the height of overburden material required to

Table 4. Estimated rock mass strengths.

Material	Moist Unit Weight (pcf)	Friction Angle (degrees)	Cohesion (psi)	Compressive Strength (psi)
Coal	85	37	60 to 120	250 to 500
Sandstone	140	42	90 to 140	400 to 600
Claystone/Shale	135	27	40 to 80	125 to 250 psi

cause pillar or floor failure for theoretical adjacent 40 by 40-foot blocks of coal which were mined to various extraction ratios. The analysis was completed assuming that for each higher extraction ratio (i.e., the percentage of coal mined in the 40 by 40-foot block) square pillars were left in place with constant width mining areas around the pillars. For instance, if 35 by 35-foot pillars were left, the drift between the pillars was assumed to have a roof span of 10 feet and a corresponding extraction ratio of 44 percent. All coal was assumed to have an average mined height of 7.5 feet. Table 5 presents the calculation of the factors of safety for various roof spans and rock tensile strengths assuming that the roof can be treated as a clamped beam.

Examination of Figure 2 and Table 5 suggests the following:

- For the range of extraction ratios shown as typical for room and pillar mining areas, the roof failure is the most critical failure mode followed by floor failure mode. As the mine depth increases, strength of floor material becomes increasingly more critical.

- For the range of extraction ratios shown as typical for retreat mining areas, roof failure is the most critical failure mode. As the extraction ratio increases to over 90 percent, however, both the pillars and floor become unstable at about the same relatively low overburden thickness.

- Figure 2 indicates that floor heave can be expected at relatively thin overburden thicknesses (i.e., less than 200 feet) in some room and pillar mining areas if a thick, low strength claystone is present in the mine floor.

Overall, these calculations show that for the majority of mined areas the mine roof is the least stable followed by the mine floor. This is especially true at relatively shallow overburden depths (i.e., less than 200 feet). The mine pillars, except in high extraction ratio areas (i.e., greater than 90 percent) should be the most stable. It should be noted, however, that shear failure of either the floor or roof could cause the pillar to deform laterally and significantly reduce pillar strength. The results of these calculations are consistent with verbal descriptions provided by miners in both the Colorado Springs and Boulder County coal fields.

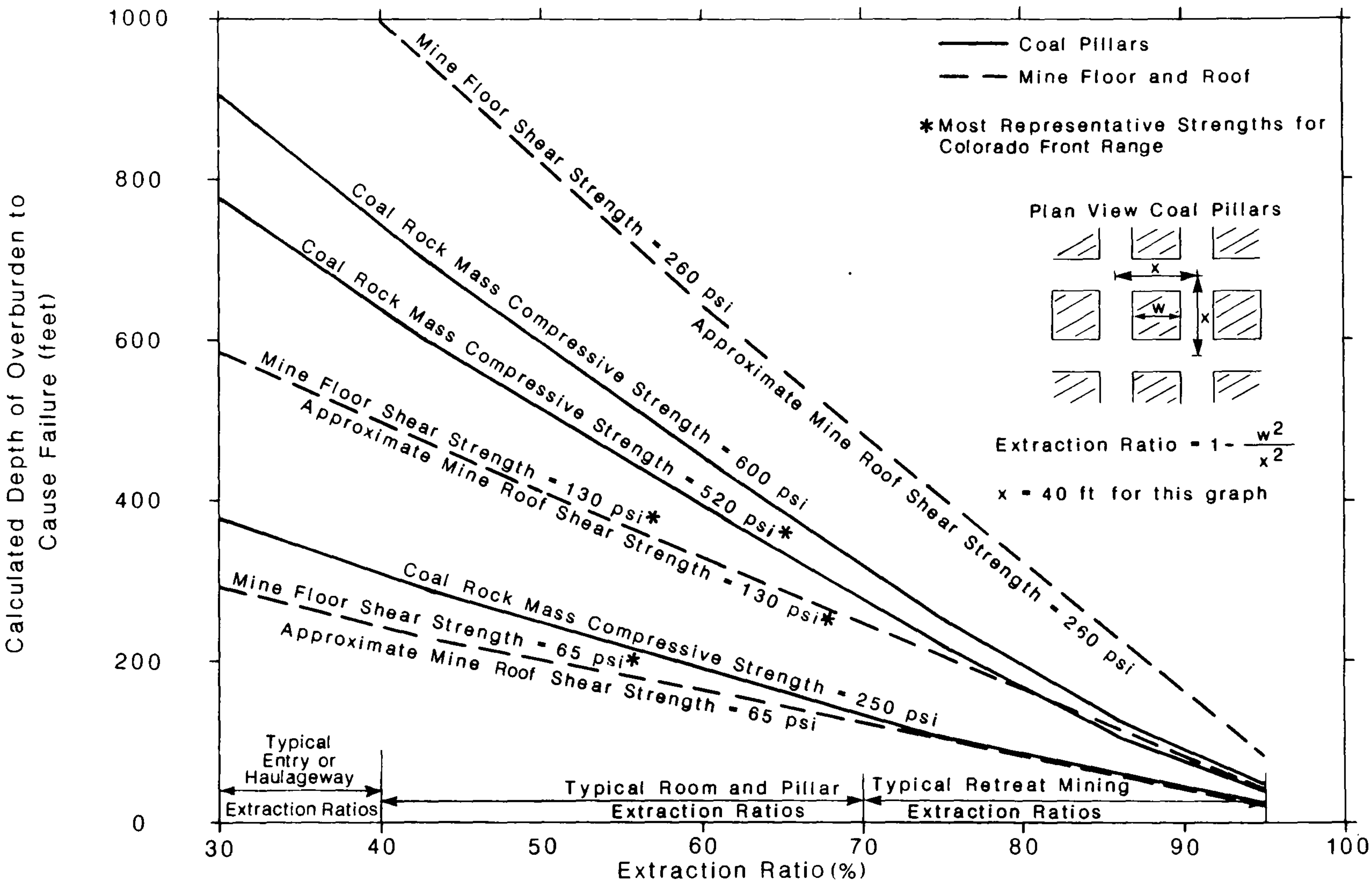

Figure 2. Calculated overburden depth to cause shear failure of mine pillars, roof and floor for various rock moss strengths.

Table 5. Example calculations of factor of safety for roof spans for various roof tensile strengths.

Assumed Tensile Strength Rock (psi)	***Roof Span***			
	8 ft	***10 ft***	***12 ft***	***20 ft***
75 psi	1.01	0.64	0.45	0.15
100 psi	1.34	0.86	0.60	0.21
125*psi	1.67	1.07	0.74	0.27
150 psi	2.01	1.29	0.89	0.32
250 psi	3.35	2.14	1.49	0.54

Note: Roof beam thickness of 5 feet assumed in all cases.

* Estimate of most appropriate strength for study area.

LOCATION OF CHIMNEY SUBSIDENCE

Aerial photography from the 1930's to 1980's, mine maps, and field reconnaissance of the ground surface above mined areas provides an opportunity to locate observed chimney subsidence sinkholes with respect to the underground mining. From this data, observations can be made of the location of chimney subsidence sinkhole features with respect to the depth of mining, type of mining and geologic conditions. This data has been gathered for a number of mines along the Colorado Front Range. The mose common method to present this type of data is to describe the observed sinkhole location as a ratio of the overburden thickness to the mined thickness. The mined thickness is measured perpendicular to the coal seam.

As discussed under mining history, three types of mining are predominant along the Colorado Front Range. These are room and pillar mining, retreat mining and a type of open stope mining. Figure 3 presents a compilation of data from the Colorado Springs coal field which reflects the categorization and compilation of about 2400 sinkholes over both relatively flat lying room and pillar and retreat mining areas. This figure shows a slightly different relationship between the percentage of total sinkholes observed versus the overburden depth for room and pillar and retreat mining areas. In general, it appears that a greater proportion of chimney subsidence sinkholes are observed at greater depths over retreat mining areas. Assuming an average mined thickness of approximately 7.5 feet in the Colorado Springs area, the ratio of overburden thickness to mined thickness below which 95 percent of observed sinkholes occur is approximately 14.5 for retreat mining areas and 10 for room and pillar mining areas.

The Colorado Springs coal field study provides the largest data base of its kind along the Colorado Front Range. Sinkholes are present over many of the other mines present in the area including steeply dipping coal seams. Steeply dipping coal seams represent a major change in geologic conditions above which chimney subsidence sinkholes occur.

Figure 4 presents a plot of observed sinkhole development with respect to the overburden thickness/mined thickness ratio for various coal seam dips. Also shown are the overburden thickness/mined thickness ratios for points in mined coal seams which have not had historical development of sinkholes. From this, an approximate boundary line between the overburden thickness/mined thickness ratio for observed sinkhole development versus no observed sinkhole development has been drawn. This reference line should help in predicting the maximum height above mine workings that sinkholes can be expected to develop. The overburden thickness utilized in the overburden thickness/mined height ratio for steeply dipping coal seams was measured from the top of the stope to the ground surface directly above the stope. In all cases, where the coal seam dip was greater than 50 degrees and less than 80 degrees, the location of the sinkhole was not directly above the stope. Figure 5 presents an example of the relative location of the sinkhole development with respect to the mine workings for the Economy Mine in Littleton. As shown, the sinkhole developed up dip from the uppermost reaches of the stope. It is the authors' opinion that over steeply dipping coal mines (i.e., 50 to 80 degree dip), the roof collapses into the stope and the chimneying process progresses vertically upward until a resistant strata or very weak strata is encountered. Once a resistant or very weak strata is encountered the chimney process deflects up dip and follows the bedding planes until it encounters the near surface weathered rock zone. At this point, the chimneying processes again continues vertically upward. Since the calculation of overburden thickness/mined thickness ratio uses the vertical distance above a stope rather than the oblique distance that the chimney actually takes, the overburden thickness/mines thickness ratio is reduced for dips between 50 to 80 degrees. This is shown on Figure 4. At a dip of 80 to 90 degrees the caving process is filling in a void equivalent to a vertical slot. As a result, the overburden thickness/mined thickness ratio may increase to a value greater than 20. In mined coal seams dipping between 50 to 80 degrees from the horizontal, the most likely place for a chimney to develop is between the surface projection of the top of the uppermost mined stope and the outcrop of the coal seam. In coal seams dipping at greater than 80 degrees chimneys are generally seen to develop within approximately 20 feet of the projected coal seam outcrop. To the authors' knowledge no chimneys have been documented outside these limits in steeply dipping coal seams along the Colorado Front Range. It should also be noted that, with the exception of slopes and shafts, chimney subsidence features have not been observed to develop over isolated mine drifts in steeply dipping coal seams. It appears that in steeply dipping coal seams, chimney subsidence is unlikely unless a stope has been developed.

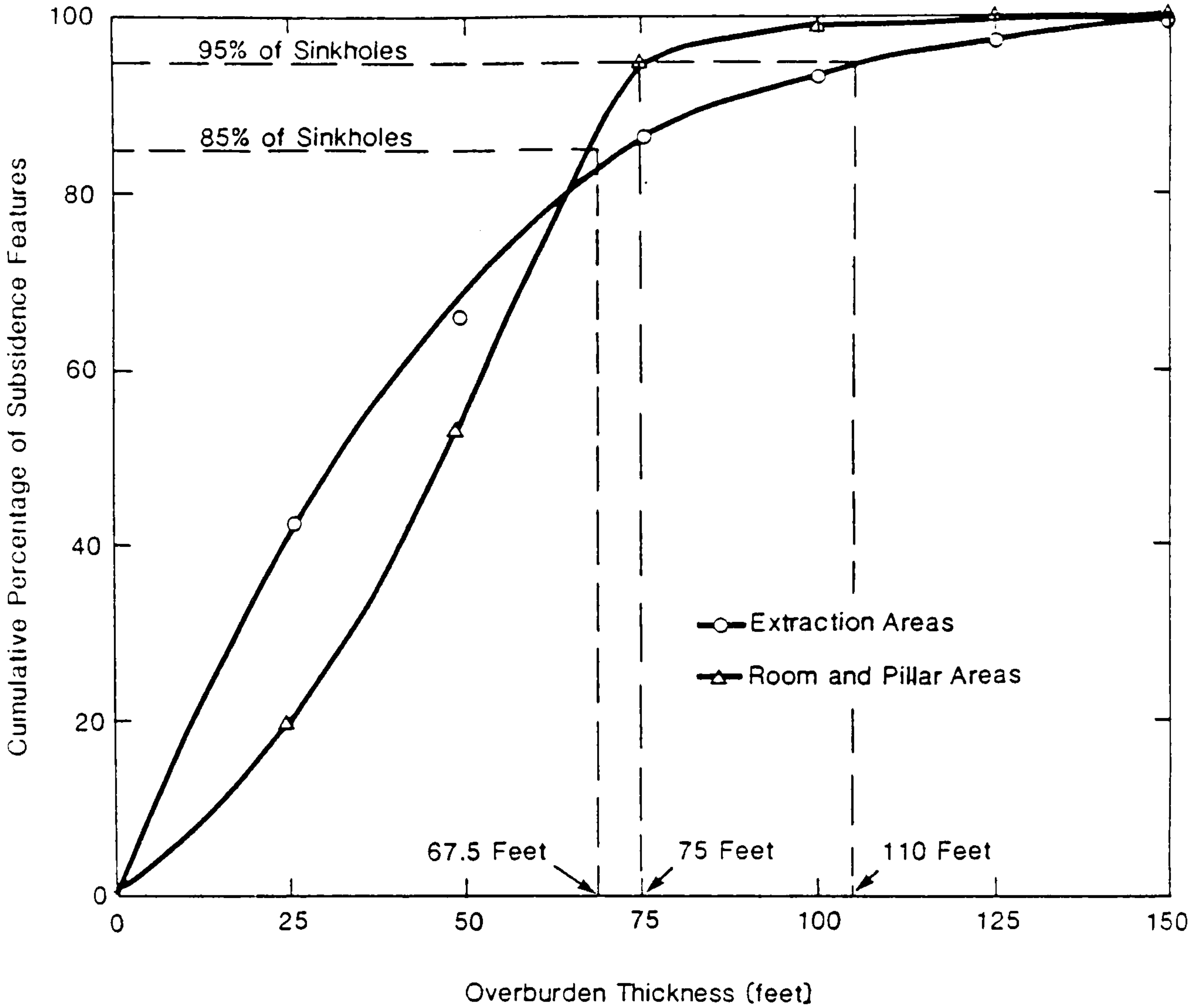

Figure 3. Cumulative percentage distribution of sinkholes with overburden depth.

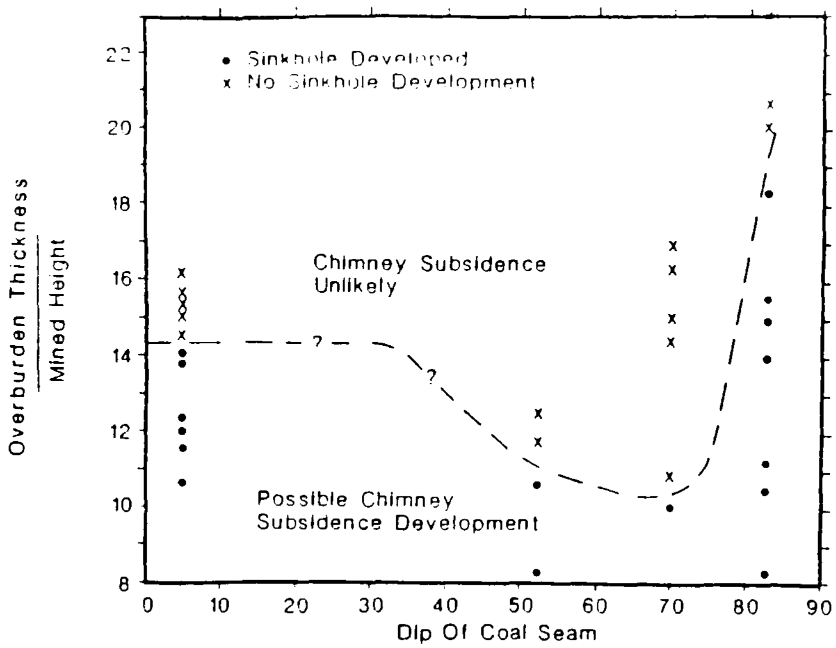

Figure 4. Apparent relationship between overburden thickness/mined height ratio and maximum depth of observed chimney subsidence sinkhole development along Colorado front range.

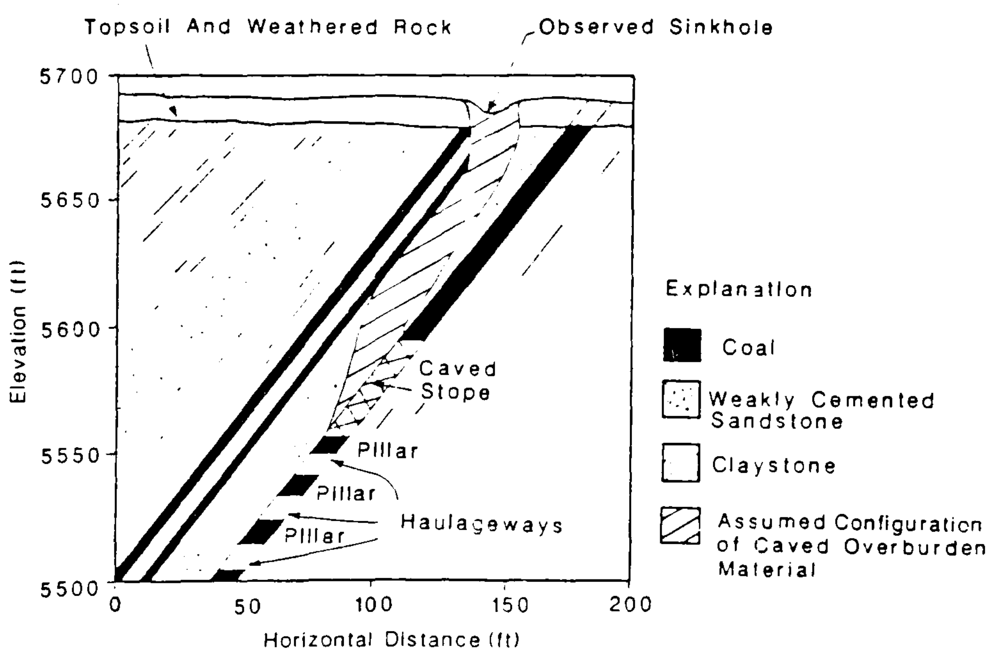

Figure 5. Location of surface sinkhole with respect to mine workings at Economy Mine, Foothills District.

TIME HISTORY OF CHIMNEY SUBSIDENCE DEVELOPMENT

The prediction of timing of future subsidence events over abandoned coal mines is not possible given the current state of predictive technology. Inferences about the time rate of subsidence occurrence can be made by examining the amount of area which has experienced subsidence for various periods of time after undermining. Evaluation of historical aerial photography is the primary tool utilized in this analysis. These photographs can be examined on a periodic basis and a count made of the number of sinkholes which develop for each year examined. Figure 6 shows a plot of the time rate of chimney subsidence sinkhole development for a portion of central Colorado Springs. As shown on this plot, the rate of chimney subsidence sinkhole development reduces rapidly about 30 to 40 years after mining. In addition, the surface expression of the majority of the sinkholes did not begin to appear until about 10 to 20 years after mining. A similar plot for the time history of chimney subsidence sinkhole development can be produced for the remaining mines in Colorado Springs and the Boulder coal field.

Interpretation of these data suggest that a major portion of subsidence development (probably all types of subsidence) occurs within a time span of approximately 30 to 40 years after mining. After that time, chimney subsidence, and other types of subsidence, will continue to occur at a much slower rate. It is possible that after the major period of subsidence, large scale trough type subsidence may occur in certain areas. It is more likely, however, that chimney subsidence sinkholes or localized trough subsidence features, occurring over limited areas (less than 1 acre), will be the most prevalent type of subsidence events. Most chimney subsidence sinkholes will be readily identifiable (except under structures). However, localized trough subsidence may not be identifiable or may be attributed to other soil conditions, depending on the magnitude of the feature. It should be noted that most chimney subsidence features which have developed over abandoned coal mines in the past 10 years have occurred over slopes into mines and shallow haulageways.

CONCLUSIONS

Based on the data collected and reviewed on the development of subsidence along the Colorado Front Range the following conclusions have been drawn:

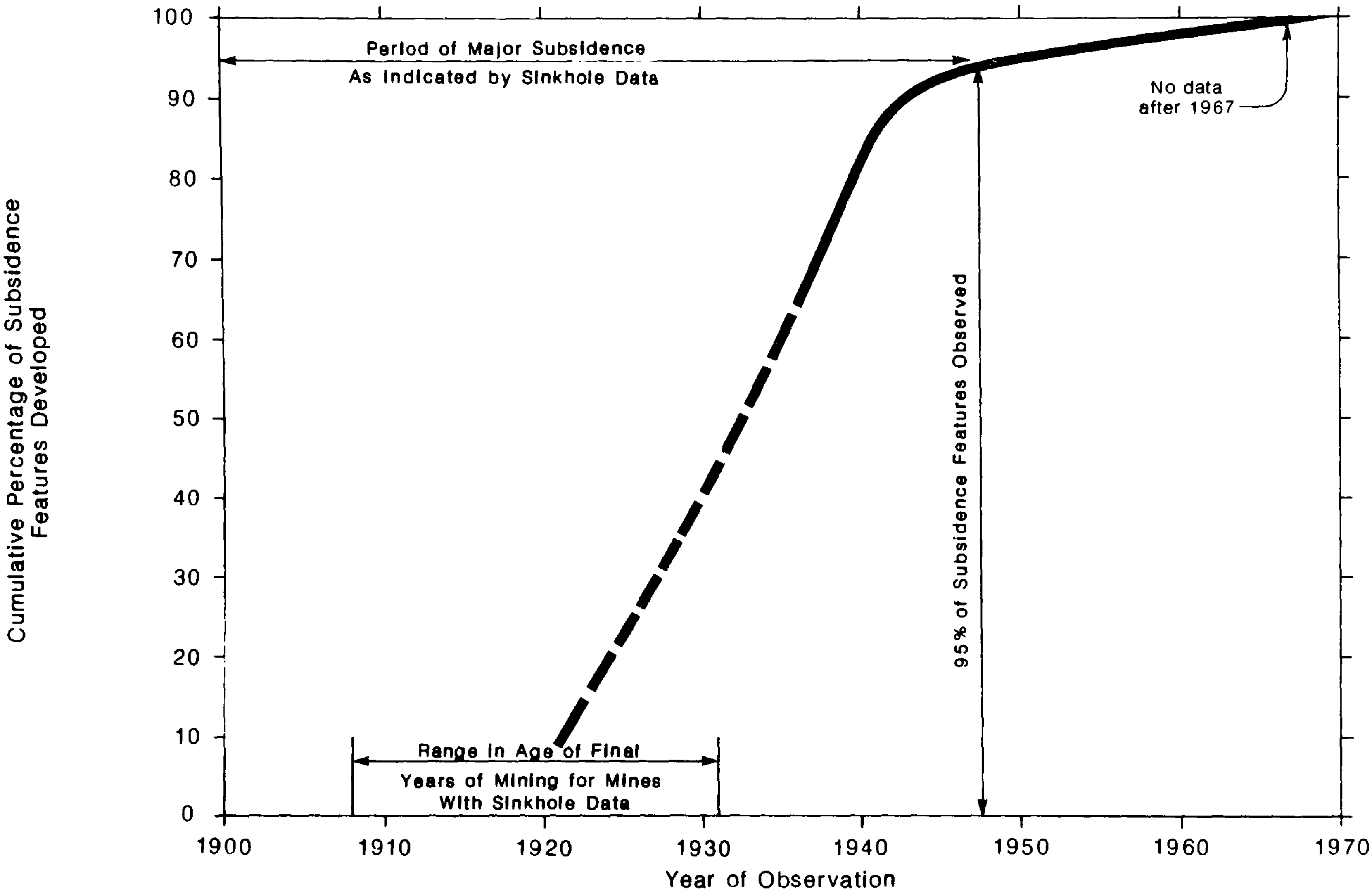

Figure 6. Relationship between time since mining and relative frequency of observed subsidence feature development.

- The strength of various rock materials indicate that roof failure is the most critical failure mode of underground openings followed by floor failure and pillar failure.

- Chimney subsidence sinkholes can be expected to occur most frequently up to an overburden thickness/mined height ratio of approximately 10 in room and pillar mining areas and approximately 15 in retreat mining areas for flat lying coal seams. Slopes into mined areas appear especially prone to development of chimney subsidence features.

- Chimney subsidence sinkholes can be expected to occur up to an overburden thickness/mined height ratio of 8 to 20 in steeply dipping coal seams over stopes depending on the coal seam dip. The sinkholes will most likely occur between the coal seam outcrop and the vertical projection of the top of the uppermost mine stope to the ground surface.

- The major time period for which all types of subsidence development appear to occur is within approximately 40 years after mining. Subsidence still occurs after 40 years, however, the majority of subsidence features will be expressed as chimney subsidence sinkholes or localized trough subsidence occurring over limited areas. Chimney subsidence will normally occur within the limits of overburden thickness/mined height ratios discussed above. The exact location and magnitude of subsidence cannot be estimated.

- Although chimney subsidence should be fairly easy to identify, localized trough subsidence may be difficult to distinguish from features caused by other near surface soil and rock deposits along the Colorado Front Range.

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ANALYTICAL METHODS OF SUBSIDENCE PREDICTION

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ABSTRACT

Underground coal mining has been practiced in the United States for over 200 years. Much of the early mining was done less efficiently than today resulting in remnant pillars left to support the mine roof. In later years, sequential removal of pillars upon retreat from the mine and continuous longwall mining techniques were introduced resulting in more efficient extractions and providing different analytical problems.

Potential subsidence is a two-fold problem for civil and mining engineers. Urban sprawl has resulted in construction of developments over abandoned mine workings. Also, the need for additional energy resources leads to further mining of coal beneath developed areas.

This discussion of subsidence prediction summarizes: (1) the history of subsidence prediction; (2) current practices in subsidence engineering; and (3) recent developments of predictive subsidence models. The discussions include analytical approaches for longwall and room-and-pillar mining techniques. Methods presented include the Rubble model, NCB techniques, Complementary Influence Functions, the BLOCKS analogy, physical modeling and other less popular techniques.

INTRODUCTION

Subsidence is defined as a movement of the ground surface caused by extraction of a fluid, soil or mineral from beneath the surface. Underground coal mine-related subsidence has long been recognized and addressed as a significant problem in

Europe. Land once thought to be in a rural setting is now being developed due to urban sprawl in major U.S. cities. Engineers must deal with the potential for subsidence, prevention and control of subsidence, and abatement construction techniques. This paper describes several historical methods of subsidence prediction and discusses currently used and potentially useful analytical techniques which appear appropriate for room-and-pillar operations found in the west.

HISTORY OF MINE SUBSIDENCE PREDICTION

Early Investigators and 19th Century Theories. The earliest subsidence modeling developed in the 19th century included the vertical, normal and dome theories (see Figure 1). The vertical theory stated that breaks and fractures in the strata overlying an underground excavation were vertical about its boundaries and the surface area affected equaled the area extracted. The vertical theory was proposed for both level and inclined seams. The harmless depth theory was developed as a correlary to the vertical theory and states that, if no workings were present within 100 meters (328 feet) of the ground surface, no surface damage would result. This theory was purely conjectural.

The normal theory proposed that fracturing of overlying strata occurred perpendicular to the coal seam and extended to the ground surface regardless of the depth of extraction. This directly opposed the harmless depth theory. The normal theory was highly criticized for application in areas of steeply dipping strata. A further hypothesis was that fracturing would occur between the normal and vertical.

The dome theory was developed through static model testing. The proponents showed the fracture zone over a coal extraction took the shape of a paraboloid or a dome. These investigators supported the harmless depth theory and estimated the harmless depth based on the volume increase or bulking of fallen overburden. The dome theory also introduced the concept of "angle of draw". The angle of draw defines a larger affected surface area than the area of extraction, and opposed the normal theory.

Early 20th Century Theories. Around the turn of the century investigators expanded on principles learned in the late 1800's by developers of the dome

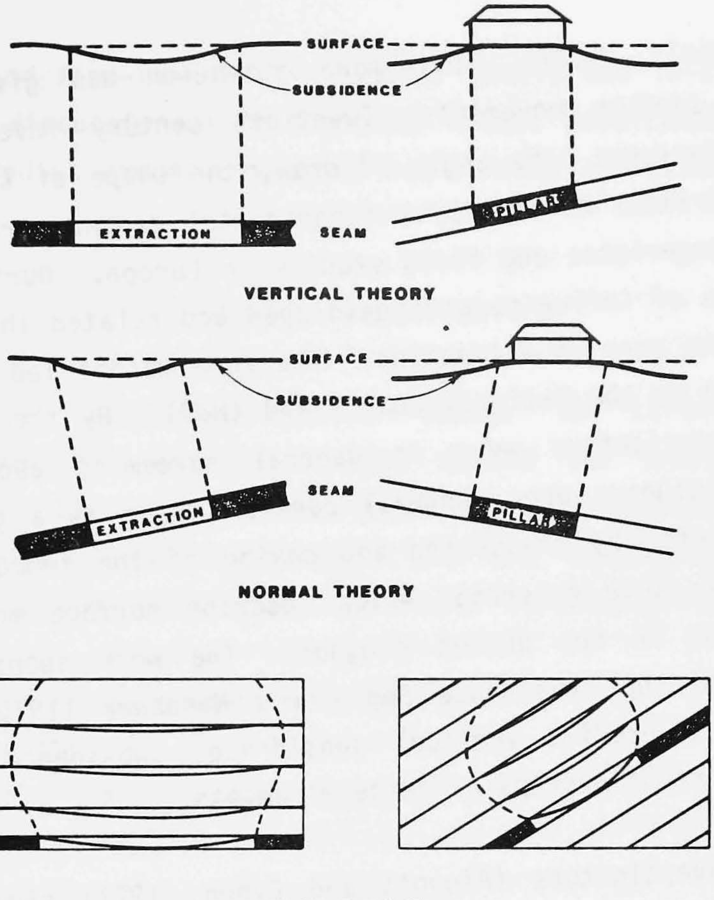

Figure 1. Nineteen century subsidence theories.

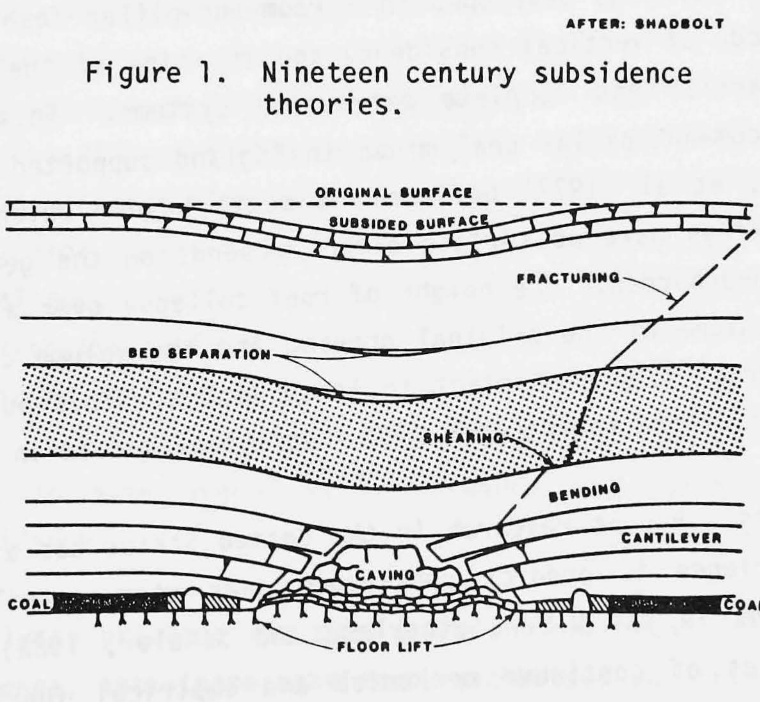

Figure 2. Subsidence over long wall panel.

theories (Shadbolt, 1977). Far more attention was given to measurement and prediction of surface movement. Twentieth century investigators studied roof stresses and pressures, the angle of draw, the shape of subsidence features, the magnitude of vertical movements, and horizontal ground strains. The developments were based on experience and field studies in Europe. During this time, the zone methods for area of influence were developed and related the occurrence of maximum subsidence to the area of extraction. The zone method led to the "critical panel width" developed by the National Coal Board (NCB). By the late 1960's a majority of British investigators were in general agreement about the mechanisms of subsidence. Subsidence over longwall panels occurs as a general sagging of the overburden triggered by fracturing and caving of the immediate roof (Figure 2). Profile functions were generated which describe surface movements over longwall mining operations in the United Kingdom. The work sponsored by the NCB was consolidated into the Subsidence Engineer's Handbook (1975). Profile functions were developed to predict vertical subsidence, subsidence profiles, horizontal strains and time relationships of these movements.

Other English investigators (Piggott and Eynon, 1977) studied ground movements over shallow mine workings developed in a room-and-pillar fashion. This research found the magnitude of vertical subsidence and the size of the affected area were different for partial and complete extraction systems. This survey of ground movements over room-and-pillar coal mines in England supported the harmless depth theory. Piggott, et al (1977) believe the depth beyond which the influence of shallow mine workings have no surface effect depends on the geometry of the mine opening and the overburden. The height of roof collapse over a mine opening is a function of the volume of the original opening and the volume change or "bulking" of collapsed material from the intact to loose states. This bulking mechanism is the basis for much of the recent work with theoretical models in the United States.

Recent Developments. Recent research in the United States has attempted to expand on European experience to predict subsidence over room-and-pillar and longwall mine configurations in the U.S. (Sutherland and Schuler, 1982). Early attempts used the principles of continuum mechanics and empirical functions to describe mathematically the ground movements over an extraction (Voight and Pariseau, 1970). With the advent of the computer theoretical models have been developed to predict movements in the overburden after mining. These empirical and computer models are verified and fine-tuned with physical models and in-situ measurements. The emphasis of this discussion is on the more recent developments, which strive to more accurately predict ground movements over mining operations in the western United States.

SUBSIDENCE PREDICTION

The identification of subsidence-related damage to structures, expanding residential and commercial development, and demand for energy resources has increased awareness to the potential for subsidence. Researchers are currently evaluating factors which affect subsidence and are developing new subsidence prediction techniques. Currently, the significant subsidence-related factors are thought to include:

1. Thickness of the coal seam extracted;
2. Depth to mining;
3. Width of the extraction or panel;
4. Degree of extraction;
5. Sequence of mining;
6. Geometry of the mine workings;
7. Pillar dimensions;
8. Thickness and nature of the overburden;
9. Bulking or caving of fallen strata;
10. Presence or absence of ground water;
11. Method of mine backfill;
12. Artificial support within the mine area;
13. Loading from the surface; and
14. Age of mining activities.

All these factors to some degree will influence the potential for, and the magnitude of, subsidence.

As part of the analysis process, the subsidence engineer must identify the factors controlling subsidence, anticipate subsidence mechanisms and select an appropriate predictive model. The factors controlling subsidence can be grouped into four general categories, which are: (1) the geometry of the mine workings; (2) the mining method used; (3) the nature and thickness of overburden; and (4) the proposed land use above the mine.

Through the 1970's, theories developed for the prediction of subsidence included: (1) profile functions for trough-type subsidence over longwall mines (National Coal Board, 1975); (2) bulking or caving theories for shallow workings, which were based on field observations; and (3) empirical functions, which mathematically modeled movements over underground extractions. Empirical models developed for U.S. mines prior to 1970 have not been largely successful or widely used. They are complex, require input of geometry and geology-related parameters, and should be verified by field observations or measurements.

In the authors' experience, the most widely used subsidence prediction tools are the profile functions developed by the NCB (1975). These profile functions are accurate and reliable for their data base area: coal fields developed by the longwall mining method in the United Kingdom. However, much of the coal mined in the United States, and especially the Colorado area, was by the room-and-pillar method. The vertical subsidence and horizontal ground strains predicted by NCB profile functions are not accurate over partial extractions. In addition, measurements in Illinois longwall coal mines show the geology in the United States is quite variable and affects the predicted movements.

Clearly, additional data acquisition and research is necessary to develop accurate predictive models for application in the United States. Following are discussions of various subsidence analysis techniques, which are currently being used or are being developed for U.S. applications.

ANALYSIS TECHNIQUES

Numerous empirical, theoretical and physical models have been developed to predict subsidence hazard and associated ground movements. The methods vary with respect to the treatment of subsidence mechanisms, mine geometry, geology and mining method.

National Coal Board Experience. For several decades the European coal mining industry has been forced by extensive surface development and underground mining to evaluate and treat subsidence. This need prompted the National Coal Board of the United Kingdom to sponsor a program of field measurements of ground movements over active longwall mines. They accumulated a large data base, which was used to develop descriptive subsidence models for the study area. The Subsidence Engineers' Handbook (NCB, 1975) was the culmination of this effort.

In Europe high extraction ratios are achieved by mining coal with the longwall method. The NCB found that ground movements over English collieries were a gentle sag or trough-type subsidence triggered by fracturing of the roof. From the large data base, investigators were able to extrapolate profile functions for predicting maximum subsidence, subsidence profiles, strain profiles and time relationships. The movements which can occur at the ground surface include vertical subsidence, tilt, curvature, horizontal displacement and strain.

Maximum subsidence produced by longwall mining is a function of the extraction width to mine depth ratio, and is related to the extracted thickness. The surface area affected was found to be greater than the extracted area and is inscribed by the "limit angle" or angle of draw. The NCB found the English geology was an insignificant parameter in evaluating subsidence, and therefore, was not included in the analyses. The critical panel width is that which is required to develop the maximum subsidence at a given mine depth (Figure 3). Narrower panels develop less than the maximum subsidence over a broader width.

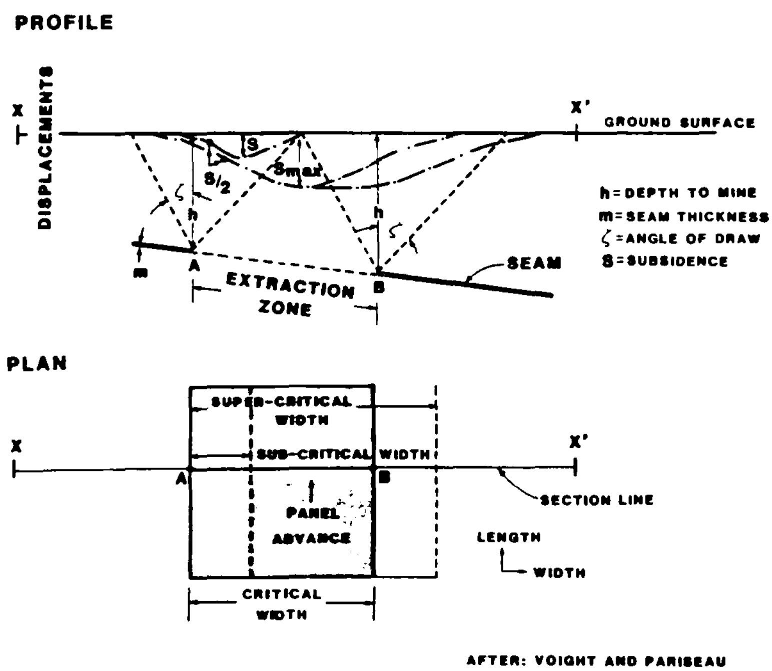

Figure 3. Critical width concept.

As the ground subsides, strains develop in the ground surface. The ground surface over the extraction experiences negative or compressive strains, and the ground over the rib sides elongates and experiences tension. However, for super-critical panel widths a hump may develop in the compressive portion of the strain profile.

The NCB investigators observed that subsidence developed simultaneously with extraction, and that subsidence essentially ceased shortly after mining stopped. Their evaluation techniques allow calculation of a subsidence traveling-wave profile for a surface point as the mining activities pass below and beyond it.

Work by the National Coal Board was exhaustive, and resulting descriptive models accurately predict ground movements over longwall mines in Europe. However, their applicability in the United States is largely limited due to room-and-pillar mine geometries and varying overburden geology. Case studies at U.S.longwall mines have shown fair correlation to NCB predictions in some instances. However, varying geologic conditions controls the accuracy of NCB predictions. The National Coal Board procedures are not suited to room-and-pillar situations, because of different caving mechanisms. Strains predicted by the NCB methods for room-and-pillar configurations are usually underestimated.

Bulking or Caving Theories. For extremely large panel widths, such as are achieved in longwall mining, it is assumed subsidence will propagate to the ground surface regardless of the depth of mining. However, where partial extraction of the coal reserves is achieved and pillars are left to support the mine roof, the mechanics of failure are significantly different. It cannot be assumed that subsidence will propagate to the ground surface. The risk of subsidence over partial extractions can be assessed by: (1) evaluating the ability of pillars to support the overburden; (2) determining the limit of caving due to bulking; (3) evaluating the potential of the roof to span a void; and (4) assessing pillar punch into the roof or floor. The parameters most greatly affecting the potential and magnitude of subsidence over a partial extraction are the width of the extraction, the depth of mining, the height of extraction, weathering effects and the geology of the overburden.

Several investigators (Piggott and Eynon, 1977 and Oravecz, 1977) observed ground movements over room-and-pillar configurations and noted significant differences from the movements predicted over longwall mining (National Coal Board, 1975). Piggott and Eynon support the harmless depth theory first proposed in conjunction with the vertical caving theory. Their theories are based largely on observations of rubble zones above shallow room-and-pillar workings, which were exposed in open pit excavations. They believe the depth beyond which the influence of shallow mine workings have no surface effect depends on the width and height of mine openings, the nature and thickness of the overlying strata, and the nature and thickness of unconsolidated surface deposits. Also, the height of roof collapse observed over the mine extraction is a function of the volume of the original opening and the volume change or bulking of collapsed material from the intact to loose states. Generally, the height of collapse observed was limited to 10 times the thickness of extraction, and commonly 3 to 5 times the mined thickness.

A study of surface and subsurface movements over a room-and-pillar mine was conducted by Oravecz (1977), while pillars were extracted from adjacent panels. The study was designed to measure vertical and horizontal displacements of the ground surface, tilt and vertical displacement of the bedrock strata. The results indicate that the induced displacement field for the zone over the pillar extraction lies between displacements measured for room-and-pillar and those for longwall mining operations. In essence, the mine is physically transformed from a room-and-pillar to a longwall mine. However, there are three major differences between a pillar extraction and longwall mine, which are: (1) the areas of pillar extraction are piecemeal in fashion; (2) the shape of the completed extraction is often complex; and (3) small remnant pillars are often left fully or partially intact. The intact portions were found to significantly influence the extent of caving and surface movements. Oravecz (1977) found that the magnitudes of the displacement components were smaller than would be expected for a complete extraction. The presence of internal barriers and the low panel width to mining depth ratio helped reduce the displacements.

Simple Beam Analysis. In sedimentary rocks, the strata are usually planar. The rock types, the frequency of bedding planes and presence of discontinuities influence the ability of the rock strata forming the roof to span an unsupported distance. The properties of the immediate roof affect the long-term strength and stability of the roof. The thickness of the immediate roof, integrity of the roof, and stratigraphic sequences of the bedrock are the important properties affecting the behavior of the immediate roof (Peng, 1978). Thinly laminated strata tend to fracture and separate leading to roof instability. An immediate roof may contain material, such as clay minerals, which are more susceptible to weathering and deterioration. Massive, well cemented sandstones overlying a mine may be sufficiently strong to span an extraction (see Figure 4).

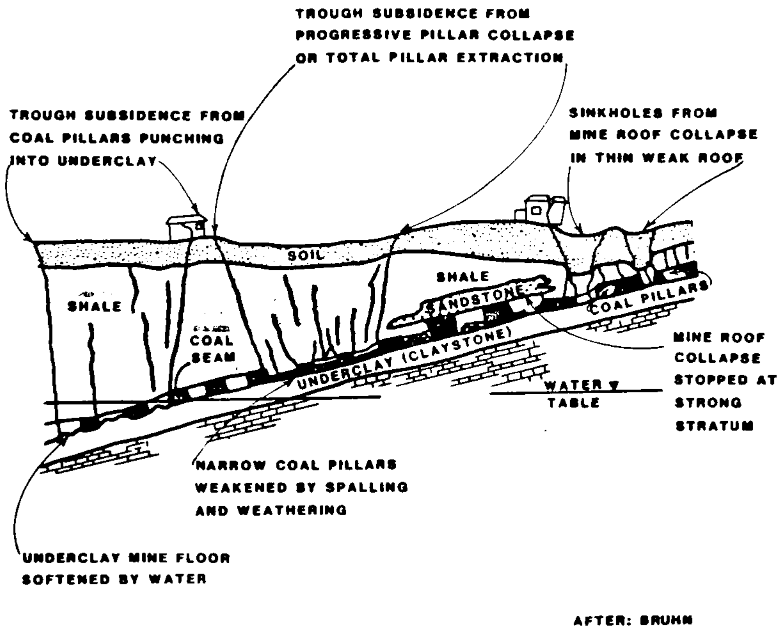

Figure 4. Modes of subsidence.

A special case of the caving theories is a simple beam analogy which assesses the ability of a hard bedrock strata to halt subsidence. Peng (1978) presented simple beam and fixed-ends beam models for calculating maximum tensile stress, shear stress and deflection of a rock mass acting as an unsupported, uniformly loaded beam. The critical span of a simple beam under a uniform load is related to the thickness of the beam, the uniform load on the beam and the modulus of rupture of the material forming the beam. An indirect tensile strength is an appropriate measure of the modulus of rupture. Simple indirect tensile strength tests may be performed on core samples in the laboratory.

Provided the immediate roof is sufficiently strong, massive, lacking discontinuities and will maintain its strength over the long-term, it may bridge a void created by mining. This method is applicable to comparatively narrow workings, such as haulways. The analysis should include a sufficient factor of safety to allow for material variabilities, discontinuities and deterioration.

Continuum Finite Element Approach. Benzley and Basinger (1984) developed a finite element computer program to compute the failure and collapse of geologic materials caused by underground mining. The rubble model (Benzley and Kreig, 1980) was formulated based on the principles of continuum mechanics. The ability to accurately predict ground motion requires models of several processes, such as: 1) the failure of a rock mass above a mined region; (2) the free-fall of elements of this mass into the mined-out area; (3) the bulking of the rock rubble; and (4) the recompaction of this rubble under its own weight and subsequent rubble (Figure 5).

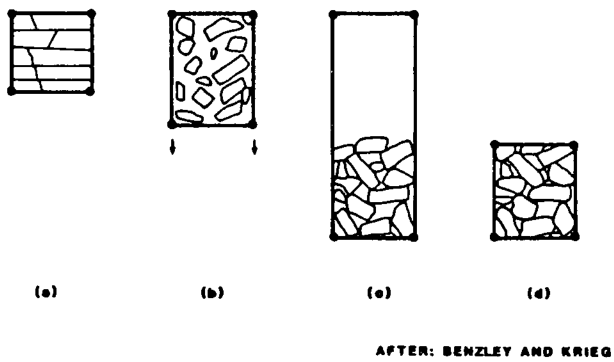

Figure 5. Rubble formation, (a) continuum element under gravity load, (b) rubble element in free fall, (c) unloaded, bulked rubble element, (d) loaded, bulked rubble element.

Rubble formation is activated when a critical tensile stress is reached in the rock mass. At this point, the material loses all stiffness and is allowed to deform freely and fall under the force of gravity within the void created by mining. The material is allowed to bulk during free-fall and recompress upon impact to some predetermined expanded configuration, which is looser than the initial overburden formation.

A dynamic relaxation solution is used in this finite element approach, which allows handling of the zero strength and rubble free-fall mechanisms. The dynamic relaxation solution computes static solutions by critically damping the dynamic equations to an equilibrium state at each time step. In other words, the mass is treated as a series of blocks, springs and dash pots. An advantage of the dynamic relaxation solution is that the inertia terms provide continuity between adjacent load steps. A significant improvement to the solution was the "slip-plane" concept, which allows rotation and translation of falling elements. An example of subsidence simulation by the rubble model and the resulting computer output is shown on Figure 6.

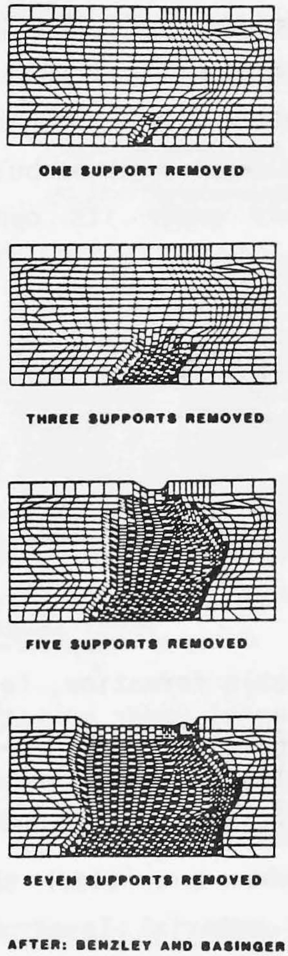

Figure 6. Subsidence simulation by rubble model, discrete slip-plane skewed mesh.

Subsidence predictions using the rubble model have correlated well with field measurements at underground coal mines in the United States. These solutions were developed with the aid of physical simulations of subsidence using centrifuge techniques, which are described later. Although specifically developed for a longwall case, the void-volume mechanics of rubble formation should also apply to room-and-pillar configurations.

Complementary Influence Functions. Complementary influence functions were developed (Sutherland and Munson, 1983) to provide a simple technique for prediction of subsidence over either room-and-pillar or longwall mines. Sutherland and Munson (1983) found both the mined and unmined portions of a seam contribute equally to movements at the ground surface. Therefore, influence functions were formulated based on two elements: the mined element and an unmined element. This concept assigns a surface response function to each of the elements.

The response of the unmined element is based on the elastic response of the strata overlying the extraction. This elastic response can be modified to account for a variable thickness of the elastic beam caused by roof failure and crushing of the unmined element, which is termed the "yield pillar" concept. The response is described by a mathematical function.

The response of the mined element is related to the breaking of the immediate roof and non-uniform distribution of voids in the rubble. The surface response function takes the form of a mathematical error function. The surface movements are calculated by integrating or summing the response of each unit element over all the elements in the area of influence (Figure 7). Both mined and unmined elements are thought to contribute equally to the subsidence prediction.

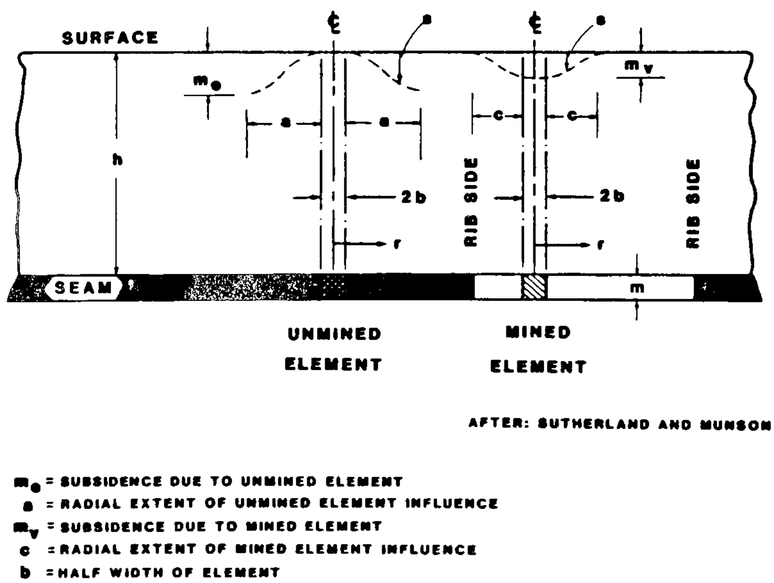

Figure 7. Complementary elements.

This empirical model is believed to be more simple and more accurate than other predictive models for application in the United States. The complementary influence functions are applicable to both longwall and room-and-pillar mine configurations. The influence function technique is especially useful in room-and-pillar applications because of increased accuracy over the rib side, and the ability to handle complex geometries. The comparatively smaller panel widths and closer spacings of rib sides in a room-and-pillar mine necessitates an accuracy across the entire panel. The influence functions have been proven with physical models and field measurements at Illinois, Virginia and Pennsylvania mines. Additional research is needed to refine the parameters used to define the response functions to account for variable geology.

Block Motion Code. Research at Sandia National Laboratories (Taylor, 1983) has developed a theoretical block motion code, which may be used to describe ground movements over underground coal mining activities. This code, known as "BLOCKS" was formulated specifically to develop a rubble model for oil shale projects and subsidence prediction. The block motion code tracks individual elements of a rock mass as they fall under the influence of gravity through the mine opening, collide with other blocks, and deform under impact.

The block motion code models the rock mass as a collection of discrete elements, as opposed to conventional continuum mechanics theory use in the rubble model (Benzley and Krieg, 1980). This discrete element approach allows greater flexibility in modeling details of the geologic formations and geometry. The code is especially useful in highly jointed rock masses, which are difficult to analyze using the finite element techniques. The individual block elements can be treated as rigid elements or can deform upon impact. Also, fracturing of individual elements is permitted. Typical output of the "BLOCKS" simulation is shown on Figure 8.

The block motion code has gone through several generations of development of the storage scheme and coding to facilitate computation on the Cray. This approach is useful in research and in highly complex geologic settings. However, the extremely large computer storage requirements and associated costs make this tool impractical for most consulting applications.

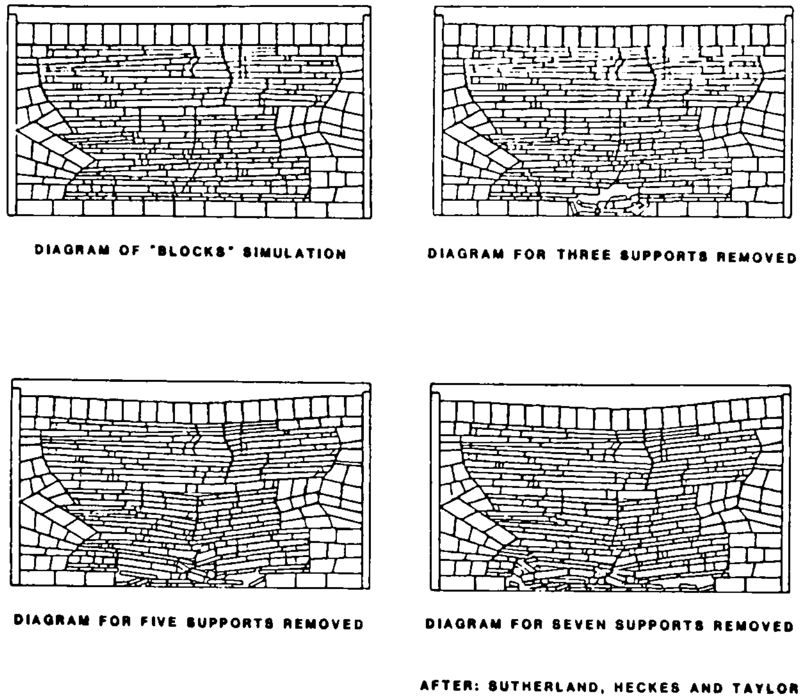

Figure 8. "Blocks" subsidence simulation.

Physical Simulations. For decades, scientists have proposed that movement sequences and stress fields related to underground mining can be duplicated in the laboratory if the body forces acting on a model are increased in the same proportion that the model scale is decreased. The materials used in the model must be the same as at the simulated mine. Therefore, using like materials and increased gravitational loads, the scale model should produce similar displacement and strain fields as would occur in the field.

A centrifuge can be used to physically simulate mine-related subsidence (Sutherland, et al, 1979). The centrifuge is used to increase the force of gravity on the scale model in the same proportion that the model is reduced in size. For example, a model of a coal mine constructed at a scale of 1:100 should experience forces 100 times the acceleration due to gravity (g forces) to correctly simulate displacement and strain fields. This method of modeling is believed more accurate than static model testing, where a uniform load is applied to a surface of the model. The centrifuge better simulates the stress state throughout the model. Fractures and bedding planes can be physically incorporated into the model.

The centrifuge is a very useful tool in research to develop and refine new predictive models. The technique is most useful when comparing solutions to computer models, empirical subsidence prediction techniques, and field measurements. However, the cost and availability of the centrifuge apparatus make use by the typical consultant impractical.

SUMMARY

Many advances have been made in the science of subsidence prediction. The National Coal Board and other mining-related European experiences have given investigators in the United States guidelines to develop predictive subsidence models. The experience gained in the United Kingdom is helpful in guiding research in the United States.

Major obstacles still to be overcome in the United States are: a lack of significant correlations between ground movements and mining activities, and few accurate models for room-and-pillar applications. We believe the rubble model and complementary influence functions will be useful techniques for everyday application by the subsidence engineer. However, these techniques should be refined to reflect local geologic and geometric anomalies. The ultimate goal of subsidence research should be to develop profile functions similar to those developed in the United Kingdom.

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ESTABLISHMENT AND USE OF MONITORING NETWORKS

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ABSTRACT

Modern Subsidence Monitoring should include the interdisciplinary tools from: Soils Engineering (Rock and Soil Mechanics Technology), Geophysical Engineering (Seismic and Earthquake Technology), Geological Engineering (Remote Sensing and Earth Structures), Geodetic Engineering (Positioning and Geodynamics), Mathematical and Electrical Engineering Data Processing Handling and Modeling Methods. The main emphasis of this discussion will focus on the current methodology in Geodesy and Geodynamics, where the interdisciplinary technology is in use to better determine absolute positions with Lasers and Microwave instruments, unconventional Photogrammetry and Global Positioning Systems.

I appreciate this opportunity to air my views concerning the current technical aspects of the planning for, establishment of, and utilization of monitoring networks for mine subsidence or any other earth oriented movements.

As you know, this is a multi-disciplinary opportunity requiring the scientific and engineering knowledge and experience from a vast array of traditional disciplines and subdisciplines. However, above and beyond the science, we need to step back from history and politics and use some common sense in the best interest for the health and welfare of our citizens.

After your field trip, I know that you have a better understanding of the subsidence problems. I recently came across a citation from a recent international symposium on mine surveying, "... in the area of the city of Denver alone, there are about 50 abandoned mines for which there is a lack of proper documentation on the location on underground excavation creating problems in issuing building permits. (Chrzanowski et. al., 1982). I do not know the current validity of that statement, however, I can understand the problems surrounding such determinations.

Once the planning and budgeting have been accomplished for a subsidence monitoring project I might suggest the following possible optimal scheme for the establishment of a monitoring network:

1. Obtain as much historical information as possible in order to determine the extent of the evacuated cavity. Several sources which come to mind are: well logs, soil samples, mine surveys, surface maps and construction site information.
2. From all of the gathered documentation, we need to estimate the extent of our subsidence area. The same methodology as for ore body or reservoir estimation can be valuable assets during the planning and estimation phase.
3. Additional information should be obtained from geophysical services with the drilling of boreholes on the subsidence area perimeter and then using borehole seismic and gravity technology to provide the 3-D map of the cavity. The geological engineer can also examine the core samples. The boreholes should be continued to bedrock or through the estimated depth of the cavity bottom, whichever comes last.
4. Survey monuments for control could then be placed in or adjacent to the boreholes. These monuments should be of the highest order and extended into the bedrock or until comparable resistance is encountered. The control network should be at least one order of magnitude of higher surveying accuracy than photogrammetry, if that method is under consideration.
5. Within the subsidence area itself the survey monuments should be connected to bedrock or until substantial resistance, but not through the cavity itself and:
    a. The pattern of the monuments should represent a strong geometric figure and/or one which is compatible with photogrammetry and/or development plans.
    b. All monuments should be intervisible from a minimum of two control points.
    c. Monumentation should be protected in a range box or at least as safe an environment.
6. Complete the initial survey and accomplish the adjustment to minimize the differences from the variety of different techniques, instruments, personnel, routes, and other conditions.

Now we are prepared to begin our monitoring efforts. Revisitation for ground surveys or rephotographing for photogrammetry can now be readied and/or rescheduled in accordance with the best knowledge of any expected movements or on a regular maintenance basis. Any evidence of slumping, movement of materials and/or any seismic or microseismic event in the area should also trigger a special set of remeasurements. Chrzanowski (Ibid.) mentions the following geophysical monitoring systems: "... tiltmeters, strainmeters, borehole inclinometers, rod and wire extensometers, in-situ stress measurements, use of microgravimetry and crosshole seismic monitoring, geophones, tomography and others." There is a new geophysical tool called a "superconducting gravity meter" which is becoming available and can achieve measurements of gravity in the 10^{-9} G range. The use of these types of instruments on or near site will provide real time alert to possible subsidence. A note of caution is that any geophysical observatory must be critically designed, emplaced and protected as well as monitored and maintained. CSM and CU Boulder have some capability and there is some talk of adding a facility at AFA and another in South Park on CSM's environmental research property. Comparisons can be made with the previous survey(s) and any earth movements can then be calculated as accurately as the system in use will permit.

Now for some information on the precision and accuracies of off-the-shelf technologies:

A. Electronic Distance Measurements (EDM):

There are several preferred types on the market which utilize two frequencies of light (laser instruments) or microwaves. These dual frequency instruments reduce several systematic error sources such as refraction and humidity to a minimum. With these EDM's: 5-6 mm results have been successfully achieved in mountainous terrain in Canada (Teskey and Gruending, 1985, p.157) and in Hawaii (Laurila, p.148).

B. Photogrammetry:

This technology requires the positive identification of the monuments on the photographic medium. The photography can either be flown or a terrestrial camera may be used. The Canadian study previously mentioned was flown in mountainous terrain and the results were in the 5-8 mm range (Ibid, p.155). One of the attendees, John Thorpe has an Analytical Photogrammetry business in Colorado Springs and has mentioned to me that he can rapidly fly and map any subsidence differences to the nearest 1/2 foot. This accuracy is dependent upon the flying height (the low flights may need too much control to be economical). The analysis of project cost takes these many variables into consideration. A footnote is that control may be densified using photogrammetry which could bring the cost down since the ground control is a considerable percentage of the project cost.

C. Global Positioning Systems (GPS):

It is now conceivable to locate "black boxes" and small antennae at the survey monuments and obtain relative positions in a half hour time period to centimeter accuracy. At the Bureau of Standards in Boulder using a Water Vapor Radiommeter (WVR) in addition to the black boxes, a base line was remeasured to millimeter accuracy. These equipment are now expensive, however, the cost should come down to around $50,000 for a two receiver system within a few years. The lowest price that I have seen is $57K per unit in October, 1985.

Thank you for your attention and I believe that you should seriously consider some of these technologies during your continuing deliberations.

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ARCHITECTURAL MITIGATING MEASURES TO CONTROL SUBSIDENCE DAMAGE

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ABSTRACT

With development of the Rocky Mountain region damage to buildings due to mine subsidence has increased dramatically. Much of the damage reported could be avoided by prudent planning and zoning practices. Where zoning doesn't keep buildings away from mine subsidence areas other measures have to be employed to avert or mitigate potential subsidence damage.

Paramount to deciding any mitigation measures a geotechnical site evaluation is to be obtained. This report aids in properly orienting buildings on the site and in determining which architectural and structural mitigating measures minimize subsidence damage.

Proper orientation in relationship to the subsidence profile, appropriate building shapes, care in placing building elements and carefully thought out relationships between buildings will help prevent subsidence damage. Appropriate structural framing methods, whether rigid or flexible, combined with foundation design suited to subsidence areas will further mitigate potential subsidence damage.

INTRODUCTION

With the rapid development of the Rocky Mountain region damage to buildings and homes due to mine subsidence has increased dramatically in the last 10 years. Much of the damage reported could be avoided by prudent planning and zoning practices. We are however faced with development pressures in many areas so that construction on land subject to potential mine subsidence is a common occurrence with resultant damage to property in many areas. Much of the damage to homes and commercial structures can be averted with simple damage mitigating measures.

The first step to avoid or minimize subsidence damage is to obtain a geotechnical site evaluation that assesses potential subsidence risk. This evaluation needs to evaluate records of mining activity in the area, information on mined seams and faults under and adjacent to the site based upon technical reports and mine maps. Based on the geotechnical report the proposed building or structure can be oriented or placed on the site to minimize the risk of subsidence damage. Beyond proper orientation or site planning there are a variety of architectural and structural design measures, some simple and some technically sophisticated, that will eliminate or minimize damage due to subsidence.

PLANNING AND ARCHITECTURAL MEASURES

1. Orientation. If lot size allows, buildings should not be located within 50 feet of any known geologic faults. Buildings or structures placed upon such faults are to be adequately designed to mitigate any potential damage due to subsidence. Buildings or structures are to be placed with their long sides parallel to predicted or existing subsidence contours to minimize strain upon the structure should subsidence occur.

2. Building Shape. Shapes of buildings should be simple and without projections. The number of corners or angles at ground level is to be kept to a minimum. Buildings or structures with stepped foundations are to be avoided unless precautions are taken to allow foundations at different levels to move independently of each other.

3. Relationships of structures. Buildings in subsidence areas are to be placed adequately apart to minimize negative visual impacts should differential settlement occur. Appurtenant structures, if required, are to have separate foundations and have adequate gaps or joints to allow them to move independently of the main structure.

4. Window and door openings. Windows and doors are to be placed as far from corners as practicable. Window openings are to be kept as small as possible with adequate wall areas in between. Door openings should be spaced so that they are not adjacent to each other. Window and door openings in masonry structures are to have lintels as head supports rather than arched openings.

5. Other considerations. Building elements exposed to view should have textured surfaces that minimize negative visual impacts associated with potential cracks.

STRUCTURAL METHODS

How a structure is designed depends on the specific site characteristics and building type. Either rigidly or flexibly designed structures may be used to mitigate damage due to subsidence. Generally, buildings of small plan area lend themselves to rigid design. Large structures are to be flexibly designed so that they may follow the subsidence contours or they may be divided into smaller segments which lend themselves to either rigid or flexible design.

1. Rigid Design. Buildings are to kept to independent units of small plan area. Foundations are to be isolated from the subsoil and are to be strongly reinforced concrete rafts or beams with sufficient rigidity to support the superstructure over a subsidence wave. The superstructure is to be as rigid as possible. It is recommended that provisions be made for jacking to relevel the building should subsidence cause tilting beyond tolerable limits.

2. Flexible Design. Structures are to be designed so that they can deflect sufficiently to follow the subsidence profile. Foundations are to allow the ground to slide horizontally beneath them. The superstructure of walls, floors and roofs should give support to the frame while allowing it to follow the subsidence profile.

   The weight of the superstructure should be kept to a minimum to reduce horizontal and vertical strains upon the structure. The structure should be pin-jointed to allow it to lozenge out of square to calculated distortion levels yet with adequate diagonal bracing to resist wind loading. Floors and roofs should be designed as diaphragms to keep the building plan form while being flexible enough to bend with the curvature of the ground.

   Door and window openings in flexibly designed structures are to have adequate tolerances to prevent jamming due to differential settlement. Glazing tolerances are to be increased over normal requirements.

SPECIFIC RECOMMENDATIONS TO MINIMIZE SUBSIDENCE DAMAGE

The following recommendations as applicable are to be incorporated as a minimum into the design and construction of any building or structure:

1. Foundation Design. All foundation types, except deep foundations bearing on stable material such as drilled piers, are to be placed on a layer of compacted sand or granular soil with a layer of polyethylene between the foundation and the granular soil to allow the ground to slide freely beneath the foundation. Projections below the bottom of the foundation are to be avoided. Side thrusts or horizontal strains upon foundations are to be minimized by placing a vertical layer of relatively compressible soils or other compressible materials at the perimeter of foundations for the full depth of the foundation or footing. Where deep foundations are to be used, the design should consider appropriate unsupported lengths in the event of subsidence around the foundation.

2. Foundation Walls. Foundation walls are to be protected from horizontal ground strain by backfilling with relatively compressible soils. Alternately walls may be designed to resist soil pressures of not less than 100 p.s.f. per foot of depth, and not less than 120 p.s.f. per foot of depth where subsidence risk is considered severe.

3. Slabs on Grade. All slabs on grade are to be placed on a layer of compacted sand or granular soil a minimum of 6 in. thick. A sheet of polyethylene is to be placed between the soil and the concrete slab to allow relative horizontal movement.

   Slabs are to be reinforced in both directions to accomodate compressive and tensile strains. Slabs 5 inches thick or less may be reinforced with a single layer of welded wire fabric placed mid-point between the top and bottom of the slab. Welded wire fabric is to be a minimum of 6 X 6 - 8/8. Slabs thicker than 5 inches are to be reinforced both near the top and bottom with welded wire fabric or steel reinforcing rods adequate for the stresses placed upon the slabs.

4. Length of Buildings. All buildings whether short or long shall be designed to resist or accomodate anticipated subsidence effects. Long buildings may be divided into several small units to minimize strain in each unit. Gaps of at least 2 inches or more are to be provided between units and should extend through foundations and roof structures. Such gaps should be wide enough so that the tops of walls will not touch when building segments tilt together. Gaps may be filled with flexible and compressible materials and closed in such a way that stresses from one segment of the building are not transmitted to other segments of the building.

5. Height of Buildings. All buildings regardless of height shall be designed to resist or accomodate anticipated subsidence effects.

6. Tolerances for Tilt and Distortion.
   a. Tilt. Maximum allowable tilt for buildings less than 3 stories or less than 36 feet in height shall be 1 horizontal in 200 vertical. For buildings taller than 3 stories or 36 feet maximum allowable tilt shall be 1 horizontal in 500 vertical.
   b. Distortion. Distortions or deflections shall not exceed 1/240 times the height unless special provisions are made to relieve the strains such as sliding joint and extra clearances in door or window jambs.

7. Joints. All joints are to be designed to accomodate at least two times the anticipated translations, rotations, and distortions. Joints shall also resist vertical displacement between adjacent structural elements. Joints are to be appropriately detailed to avoid negative visual impacts when subsidence occurs.

8. Masonry Construction. All masonry construction should be designed to conform to good design practices as used in earthquake prone areas.

9. Interaction between Foundation and Superstructure. The superstructure of any building may be designed to give rigidity to the foundation provided that connections between foundation and superstructure are designed for composite action. Alternately, the foundation and superstructure may be designed as separate elements so that they may move independent of each other. Roller bearings or similar devices applicable to seismic design may be used.

10. Stairways. Stairs shall be designed so that one end of the stairway is attached to the structure using a rigid or hinged connection and that the other end has a flexible or moveable connection that moves freely.

11. Utility Connections. All utility connections entering a building or structure from underground are to have adequate free space around them to allow differential movement between the ground and structure. Flexible connections, if allowed by specific codes are recommended. All pressure lines are to have shut-off valves at the exterior of buildings or structures.

12. Periodic inspection. Building officials should require that periodic inspections be performed on all buildings and structures subject to potential mine subsidence effects. The severity of specific local subsidence problems as determined by the building official is to be a guide for determining the inspection period.

These are some of the architectural and structural mitigating measures that may be employed to minimize potential damage to buildings. There also are site planning and civil engineering methods that may be used to prevent damage to buildings. Specifically, it is good practice to keep water from seeping into seams and mine openings under and near buildings. Roof drains and sumps should be discharged into storm sewers if possible or else water is to be led away from undermined sites in paved drainage swales. Utility lines coming into buildings should not be restrained by the building structure.

CONCLUSIONS

The question that remains is "what does this all mean?". For the designer of large building the answers cannot be simplified. Designers and builders of small buildings or single family residences can generally conclude that simple building shapes and adequate reinforcement in the foundations along with measures to minimize soil strains and stresses on foundations will go a long way to minimize or eliminate damage due to subsidence. Studies in Illinois have shown that damage to homes with heavily reinforced foundations was usually superfluous. Homes with poor foundations suffered heavy damage.

There is no one best way to avoid subsidence damage. The easiest method would be not to build on subsidence prone areas of course. That isn't a realistic option in many areas so a combination of the above methods is to be used to mitigate subsidence damage to buildings or structures.

HAZARD REDUCTION TECHNIQUES USED FOR PIT SUBSIDENCE NEAR HANNA, WYOMING

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ABSTRACT

Three different backfill techniques were used to reduce immediate hazards associated with pit subsidence over shallow coal mines near Hanna, Wyoming. The subsidence pits developed above abandoned mine workings in coal seams which dip between 15 and 25 degrees and have less than 160 feet of cover. The hazardous subsidence pits were from 20 to 50 feet in diameter and from 20 to 30 feet deep. All of the hazardous pits had very steep sides, indicating either recent caving at the ground surface or reactivation of older pits. Mining took place in the area of the subsidence pits about 75 years ago. At Site No. 1, backfilling with granular soils was used to eliminate the hazard at pits where backfill running was considered to be low. A grouted boulder wedge was used at the subsidence pit where backfill running was considered to be high. At Site No. 2, one of the subsidence pits broke to the ground surface along Standpipe Draw, causing runoff from this ephemeral stream to be diverted into the mine workings. Open boulder backfill was used in the area of Standpipe Draw to eliminate the hazard, but still allow runoff waters to enter the mine workings.

INTRODUCTION

Three different backfill techniques were used to reduce immediate hazards associated with pit subsidence over shallow, abandoned mine workings near Hanna, Wyoming. The backfilling was done as part of Wyoming Land Quality Division's Abandoned Mine Land Reclamation program in the Hanna area. The subsidence pits are located on open range land and, because of their depth and steep sides, the pits were considered to present an immediate hazard to humans and livestock. The subsidence pits were not in an urban area or where future land developments were anticipated; therefore, the goal of the backfill program was to eliminate the immediate hazard only. It was recognized that after backfilling, there would still remain a potential for the development of new subsidence pits within the project area.

The backfill operations discussed in this paper are part of the larger Project 7 reclamation efforts in the Hanna area being administered by the Wyoming Department of Environmental Quality, Land Quality Division, under their Abandoned Mine Land Reclamation Program. It is hoped that the experience gained during this backfilling project will be of use to others working in abandoned mine land reclamation and immediate hazard reduction.

PROJECT LOCATION AND GEOLOGIC SETTING

The hazardous subsidence pits were located about two miles east of the town of Hanna, Wyoming. The hazard reduction project involved two sites along the eastern limb of the Hanna syncline as shown on Fig. 1. The coal mines in this area were in the No. 1 seam of the Paleocene-age Hanna Formation. The Hanna Formation is made up of interstratified brown to gray sandstone, shale, conglomerate and coal which were deposited in a fluvial environment. The formation is usually weakly cemented, and friable sandstones are common in the vicinity of the subsidence pits. The Hanna No. 1 coal seam varies from 4 to 27 feet thick. The subsidence pits occur near the outcrop of the No. 1 seam in areas where the cover is less than 160 feet thick. The No. 1 coal seam along the east limb of the Hanna Syncline dips between 15 and 25 degrees toward the northwest. Several northwest trending small displacement faults offset the coal seams along the eastern and western limb of the syncline.

MINING METHODS

In 1889, the Union Pacific Coal Company began underground mining of coal near Hanna. These underground mines were operated until 1954. The drift method of mine layout was commonly used. The main haulage ways were driven along the dip of the coal seam, and secondary haulage entries were extended off the main haulage ways along the strike. Fifteen-foot wide double and triple drift entries were used, and cross cuts connected the haulage drifts on 50 to 200-foot centers. The

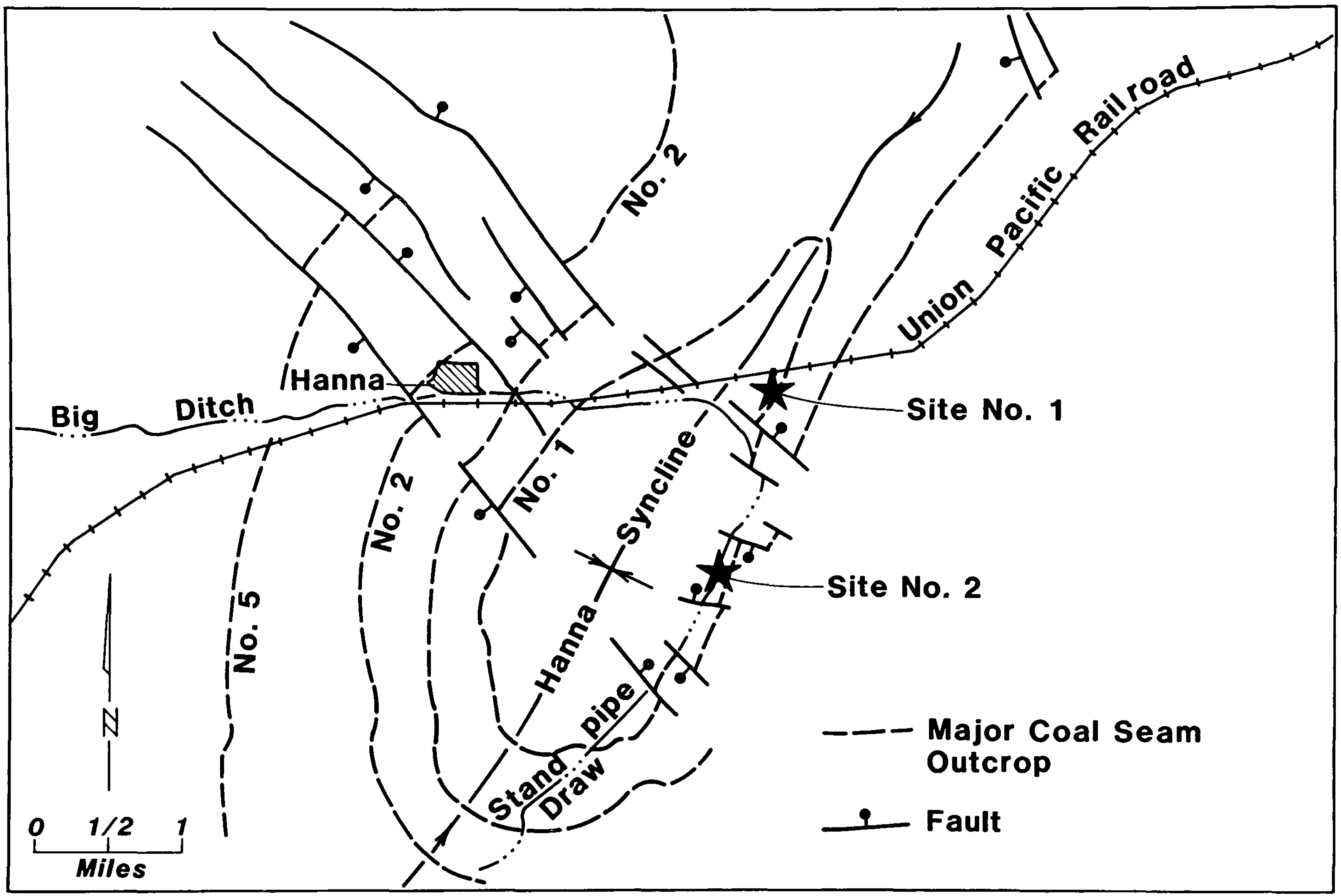

Union Pacific Railroad
Site No. 1
Site No. 2
No. 2
No. 1
No. 2
No. 5
Hanna
Big Ditch
Hanna Syncline
Stand pipe Draw
Major Coal Seam Outcrop
Fault
N
0 1/2 1
Miles

Figure 1.

height of the mine workings commonly ranged from 10 to 14 feet. Panel and pillar production areas were developed updip of the haulage drifts. The production panels typically were about 30 feet wide and from 100 to 200 feet long. At completion of first stage mining, 30-foot wide pillars separated the worked-out production panels. It was common practice during second stage mining to remove as much of the first stage pillars as practical. Mining took place in the area of the subsidence pits about 75 years ago.

SUBSIDENCE PIT SITE NO. 1

Subsidence Pit Site No. 1 is located just to the south of the main line of the Union Pacific Railroad as shown on Figure 1. Four subsidence pits were present on Site No. 1 at the beginning of our field investigation in the spring of 1984. The general relationship of the pits to the mapped mine workings is shown on Figure 2.

Description of the Hazard: When Site No. 1 was first visited in the early spring of 1984, all four subsidence pits were filled with snow and an assessment of the immediate hazards posed by the pits was difficult to make from the surface observations. After the snow melted, only Pits A and B were considered to present an immediate hazard. Pit A was about 20 feet in diameter, and Pit B was about 50 feet in diameter. The top of the caved material in the bottom of the pits ranged from 10 to 20 feet below the ground surface. The pit walls were nearly vertical to overhanging, indicating that caving to the ground surface had occurred relatively recently. During the field investigations, the floor of Pit B abruptly dropped an additional 10 feet. The other two pits at Site No. 1 appeared older than Pits A and B. These pits were from 4 to 10 feet deep and had relatively gentle sidewalls, indicating wall erosion subsequent to the initial breakthrough at the ground surface.

Site Investigations: The subsidence conditions at Site No. 1 were investigated by reviewing the available mine maps, observing surface conditions and drilling several exploratory holes. The general subsurface conditions at Site No. 1 are shown on Figure 3, which is a cross-section through Pit B. The section parallels the main haulage way shown on Figure 2. The mine workings and coal seam dip from 15 to 25 degrees toward the northwest. The cover between the mine workings and the ground surface is about 60 feet at Subsidence Pit A, 40 feet at Subsidence Pit

SITE NO. 1

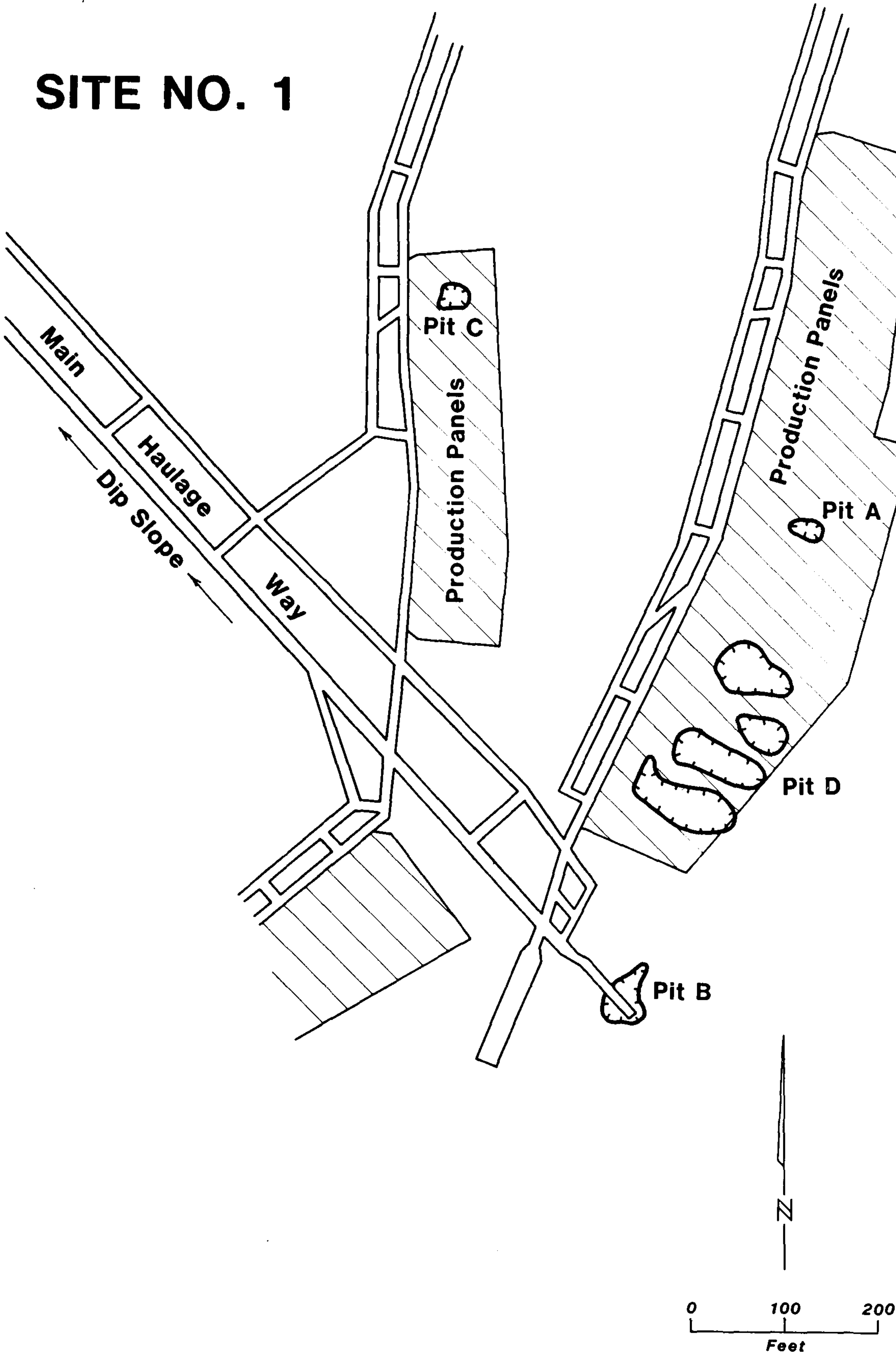


Figure 2.

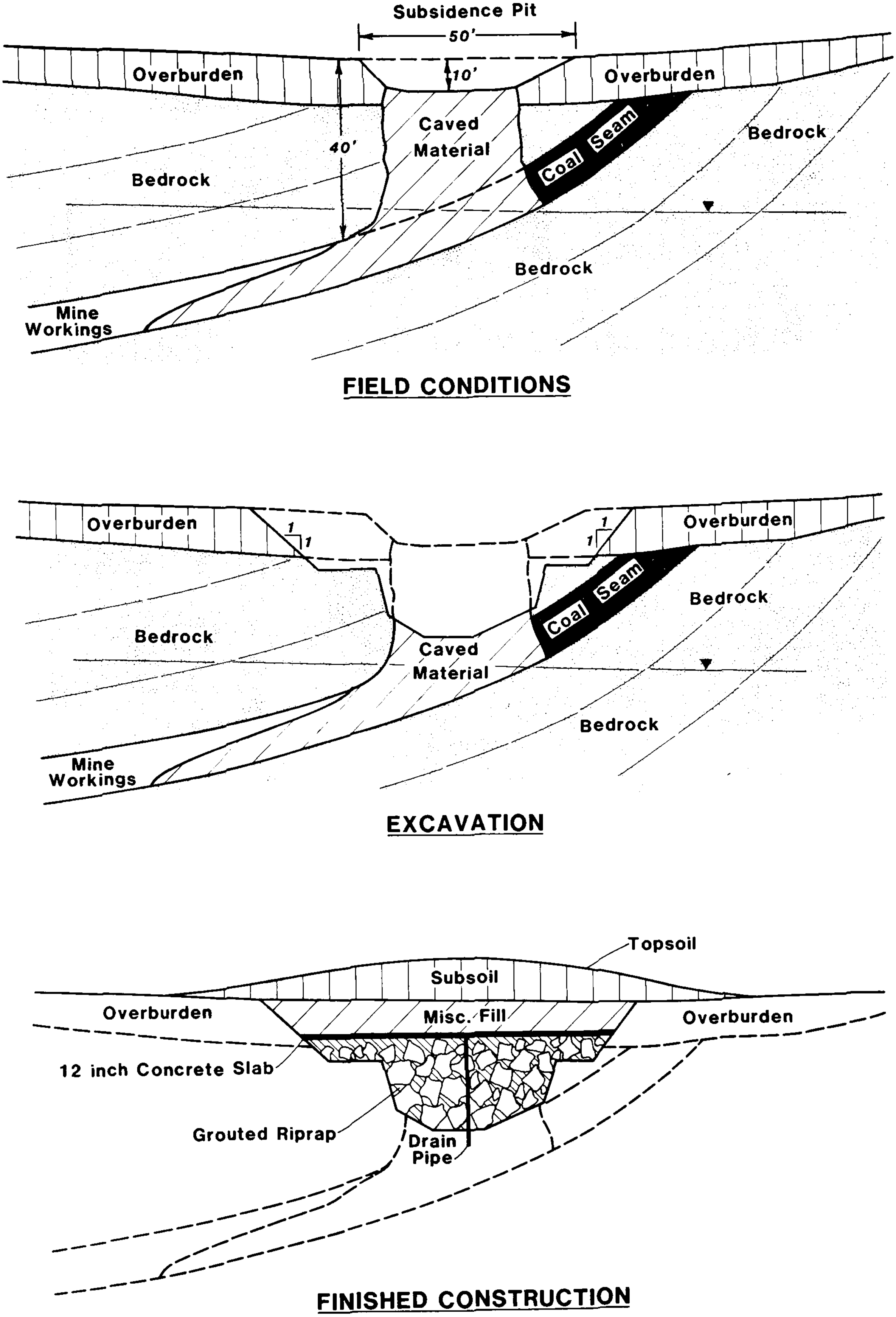

Subsidence Pit
50'
10'
40'
Overburden
Overburden
Caved
Material
Coal Seam
Bedrock
Bedrock
Bedrock
Mine
Workings
FIELD CONDITIONS
Overburden
Overburden
1
1
1
1
Coal Seam
Bedrock
Bedrock
Caved
Material
Bedrock
Mine
Workings
EXCAVATION
Topsoil
Subsoil
Overburden
Misc. Fill
Overburden
12 inch Concrete Slab
Grouted Riprap
Drain
Pipe
FINISHED CONSTRUCTION

Figure 3.

B, 160 feet at Subsidence Pit C and 50 feet at Subsidence Pit D. The mine workings at Site 1 are below the water table. Subsidence Pit B is located near the southeast end of the main haulage way, whereas the other three pits are located in production panels.

Based on the mine geometry, it was inferred that there was a limited potential for large-scale running of the cave material and this material was considered relatively stable for the pits located in the production panels. This is not the case for Pit B, which is located on the main haulage way. Pit B presented a condition where periodic running of the caved material was likely. This inference was supported by the renewed subsidence in Pit B during the spring of 1984. In addition to the existing subsidence pit, field investigations also indicated that there is a potential for additional pit subsidence associated with other shallow undermined areas at Site 1.

Method of Hazard Reduction: After presenting the findings of the field investigation and reviewing several hazard reduction methods with the Wyoming Abandoned Mine Land Reclamation staff, it was decided that the most appropriate method of hazard reduction for the immediate hazards at Pits A and B was to backfill these two pits. It was not considered cost effective to stabilize the entire site or to do work at Pits C and D which were not considered to present an immediate hazard.

Since it was inferred that there was a relatively low potential for large-scale running of the caved material in Subsidence Pit A, it was decided to fill the pit with a granular backfill. The backfill used was scoria (baked shale) from a nearby source. The pit was filled by dumping from the ground surface, and the backfill was mounded to provide for settlement. The construction area was topsoiled and seeded after backfilling. Some settlement of the mounded backfill occurred in the fall of 1984, and additional backfill was placed in Pit A at that time.

Because of the potential for large-scale running of the caved material in Pit B, it was decided that a grouted boulder wedge would be used. The required excavation and finished construction of the wedge is shown on Fig. 3. The caved material was excavated above the water table and the key for the wedge excavated into undisturbed bedrock. Three to 8-foot diameter sandstone boulders were placed in the excavation and the voids between the boulders grouted. Grouting was done by placing a quick setting portland cement grout through pipes installed prior to backfilling. A drain through the wedge was provided to prevent the development of perched groundwater. The drain consisted of a 12-inch concrete cap sloping to a drain pipe which was installed as the boulders were placed prior to grouting. A filter was placed over the pipe to prevent piping of the overlying soil backfill. After construction of the drain, the remainder of the excavation was backfilled with miscellaneous on-site soil, and subsoil and topsoil were mounded over the wedge. The construction area was then seeded.

SUBSIDENCE PIT SITE NO. 2

Subsidence Pit Site No. 2 is located adjacent to Standpipe Draw about two miles south of Site No. 1, as shown on Figure 1. Standpipe Draw is a major ephemeral stream with a large drainage basin. Relatively high discharges on the order of 300 cfs occur during the spring snowmelt period; however, the stream channel is usually dry during other times of the year. Three subsidence pits were present at Site No. 2 at the beginning of the field investigation in the spring of 1984. The general relationships of the subsidence pits to Standpipe Draw and the mapped mine workings are shown on Figure 4.

Description of the Hazard: Both Subsidence Pits A and B were designated as immediate hazards. These pits were about 20 to 30 feet deep and had very steep side slopes. Pit C was not considered an immediate hazard. This pit was about 3 feet deep and had relatively gentle side slopes. Caving in Pit A intersected the channel of Standpipe Draw and diverted the water flow into the mine workings. During the initial field investigations in the spring of 1984, the entire flow of Standpipe Draw was cascading into Pit A.

Site Investigations: The subsidence conditions at Site No. 2 were investigated by reviewing the available mine maps, observing surface conditions and drilling several exploratory holes. The general subsurface conditions at Site No. 2 are shown on Figure 5, which is a cross-section through Pit A. The section parallels the main haulage way shown on Figure 4. Subsidence Pit A developed over the slope entry to the mine near the bedrock-overburden contact. Pits B and C were located

SITE NO. 2

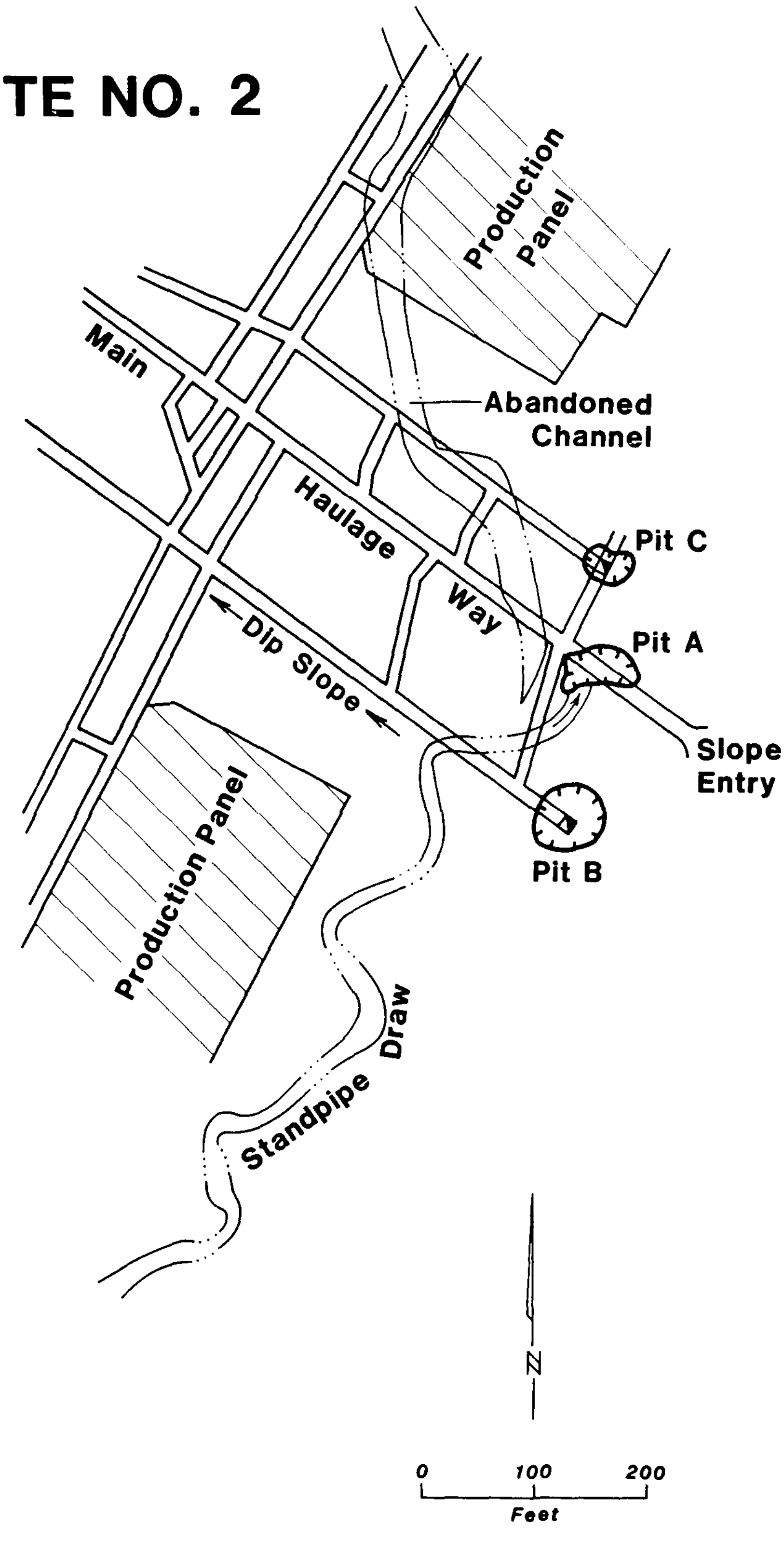
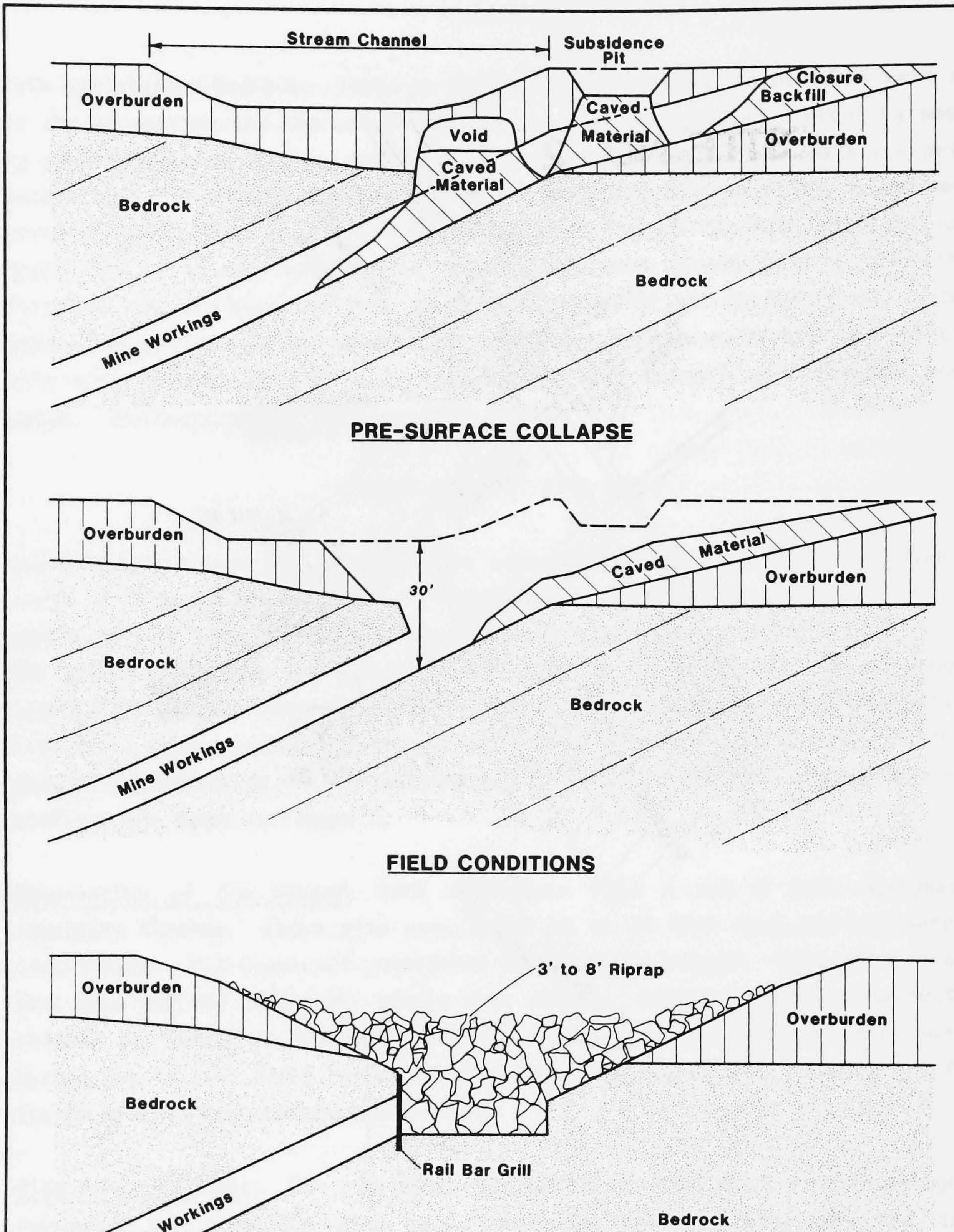


Figure 4.



Stream Channel
Subsidence Pit
Closure
Backfill
Overburden
Caved Material
Void
Caved Material
Overburden
Bedrock
Bedrock
Mine Workings
PRE-SURFACE COLLAPSE
Overburden
30'
Caved Material
Overburden
Bedrock
Bedrock
Mine Workings
FIELD CONDITIONS
3' to 8' Riprap
Overburden
Overburden
Bedrock
Rail Bar Grill
Mine Workings
Bedrock
FINISHED CONSTRUCTION

Figure 5.

at shallow vertical shafts which connected to the main haulage ways. The mine workings and the coal seam dip about 25 degrees toward the northwest. The open haulage drifts downdip of the subsidence pits appeared to be in good condition and evidence of roof collapse was not observed. However, the potential for additional pit subsidence is recognized at Site No. 2.

Methods of Hazard Reduction: After presenting the findings of the field investigation to the Wyoming Abandoned Mine Land Reclamation staff, it was decided to evaluate two general hazard abatement concepts. The first concept was to divert Standpipe Draw to the southeast around the shallow mine working and to provide stable seals and backfill the hazardous subsidence pits. The second general abatement concept was to reduce the immediate hazard by a design which would allow the water to continue to enter the mine workings. The second concept was adopted in the final design by construction of an infiltration gallery. The construction consisted of excavating the three subsidence pits down to the level of the first cross-cut drift as shown on Figures 4 and 5. Rail bar grills were constructed where the excavation intersected the three main haulage drifts, and the excavation was backfilled with 3 to 8-foot diameter sandstone boulders.

ACKNOWLEDGMENTS

The backfill operations were part of Project 7 reclamation efforts under the administration of the Wyoming Abandoned Mine Land Reclamation program. We wish to acknowledge the cooperation and assistance of the Wyoming Abandoned Mine Land Reclamation staff, particularly Mr. Gary Beach, Manager, Mine Land Reclamation Program; and Mr. Kurt Anselmi, Project Officer. The project consultant's team consisted of Chen & Associates, Inc.; Worthington, Lenhart, Carpenter and Johnson, Inc.; Range Inventory and Analysis; and Skelly & Loy, Inc.

COAL MINE SUBSIDENCE CONTROL CASE STUDIES
COLORADO SPRINGS, COLORADO

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ABSTRACT

Subsidence of the land surface over abandoned underground coal mines is a continuing problem in Colorado Springs, Colorado. Subsidence events pose varying problems depending on subsidence type, local geology, and proximity to buildings and other improvements. Each subsidence event may be classified as a sinkhole, trough, or shaft collapse. Examples of these subsidence types and control methods are presented in the form of case studies. The Corley Shaft case is of the collapsing shaft type. An air shaft located beneath the house foundation had apparently been backfilled with random debris which settled about eight years after the house was built. Remedial action included the injection of concrete and grout through angled and vertical drill holes. The Country Club Drive case is an example of a sinkhole collapse beneath a house foundation. Exceptionally bad ground conditions made it necessary to construct drilled piers with an I-beam cross member to support the foundation corner. The surrounding area was supported with pumped slurry confined by gravel barriers. At Portal Park, an areal depression (trough) was forming at a municipal swimming pool, and pumped slurry backfilling was performed to support the area. Gravel barriers were used to contain the fill to the problem area. Sinkhole type events occurred at Locust Street, and the Ascension Church. These problems were controlled by constructing reinforced concrete plugs and/or grouting through vertical or angled drill holes. The North Point Centre project is an example of pumped slurry backfilling for preventive subsidence control. Backfill areas were chosen on the basis of high extraction ratios shown on the mine map, and planned building sites. These cases are presented as

examples of practical, effective methods of underground coal mine subsidence control for remedial and preventive purposes.

INTRODUCTION

In the past several years, mine related subsidence has become an increasing concern to homeowners, developers, and city officials in Colorado Springs, Colorado. This paper addresses six subsidence occurrences in Colorado Springs and the remedial actions taken to solve the problems. Subsidence events pose various problem situations depending on subsidence type, local geology, and relationship to buildings and other improvements. Control methods are directly related to the local geology. The overburden strata in Colorado Springs consists of generally incompetent sandstones and claystones with alluvial and aeolian surficial deposits of varying thickness and extent. Subsidence features may be classified as a sinkhole, trough, or shaft collapse. Each feature requires a site specific subsidence control method. Subsidence control methods cited in this paper include: 1) pumped slurry backfilling, 2) reinforced concrete plug, 3) direct structural support, and 4) grout injection.

Portal Park

Portal Park was a project designed to prevent further subsidence occurrence under a municipal swimming pool. The project used a pumped slurry system to backfill inaccessible mine workings. The pumped slurry backfilling method was first developed and tested in 1970, by the Bureau of Mines (1).

Portal Park is located east of Interstate 25 between Austin Bluffs Parkway and Fillmore Street (see Figure 1) and is positioned above the Curtis Mine. The mine, abandoned in 1913, is approximately 30 feet below the surface at the park. Several subsidence incidents in the park and near the pool had been noted prior to this project. Eventually, an areal depression formed under a corner of the swimming pool, prompting the Office of Surface Mining (OSM) to take action. Under the OSM emergency program, Goodson and Associates, Inc., (G&AI) used a pumped slurry system to stabilize the swimming pool.

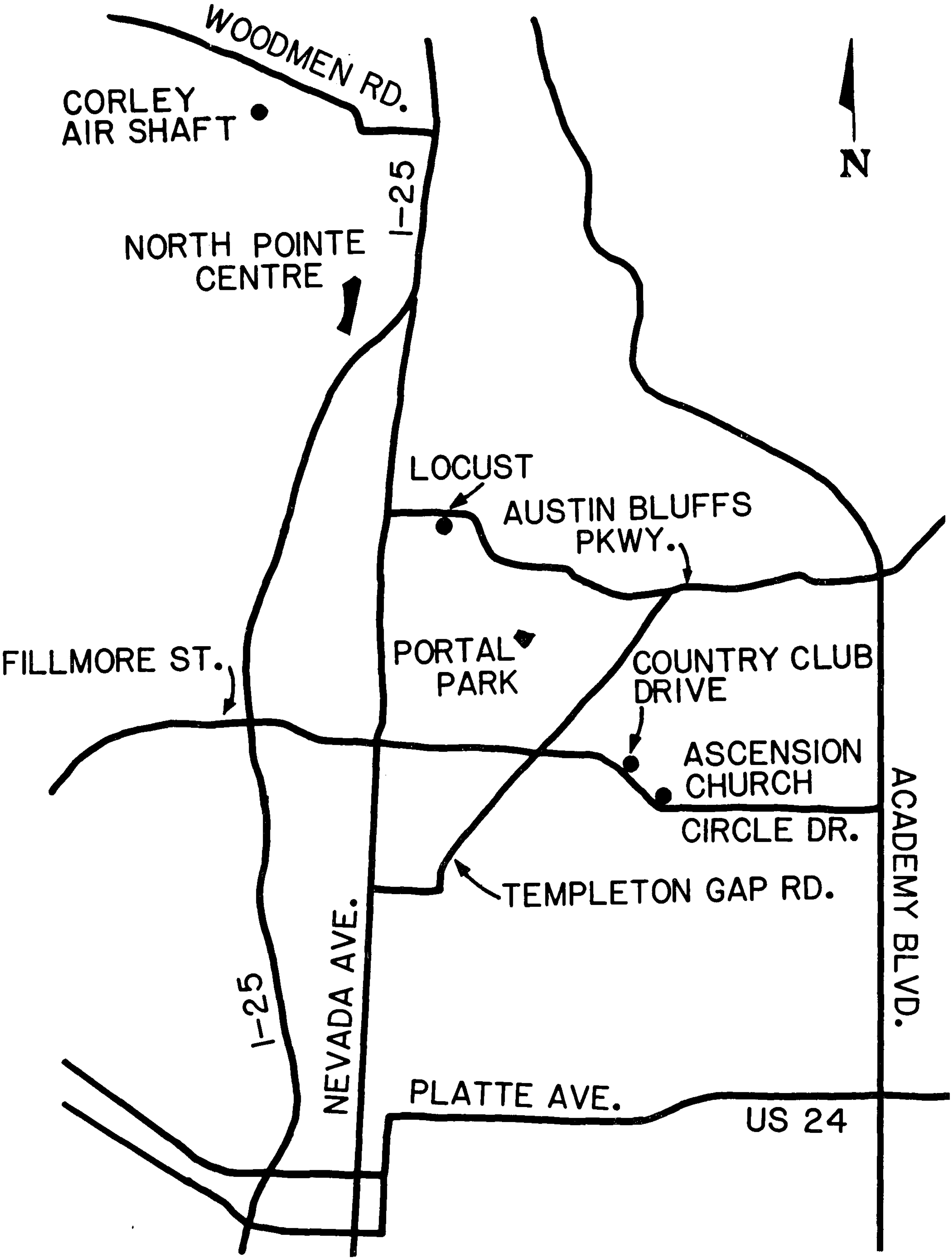


Figure 1. Site location.

The mine is in the "A" seam of the Cretaceous Laramie Formation. Overlying strata is composed of weak sandy shale. The "A" seam ranges from 9.5 to 11 feet thick; however, from drilling data, the actual mining height was found to range from 6 to 8 feet. In preparation for backfilling, one injection hole and seven gravel barrier holes were drilled. Gravel barriers were used to restrict the slurry flow and to concentrate backfill material under the pool. The holes were drilled into voids at the mine level. The injection hole was 6 inches in diameter. Barrier holes were 12 inches in diameter and drilled on 5 foot centers. All holes were cased to the top of the voids. Barriers consisted of conical piles of 3/4 inch washed river gravel. Approximately 220 tons of gravel was used to create the barriers. Water from the mine was used to supply the slurry pumping system. The water well was drilled into the mine at a great enough distance from the injection hole to ensure that fill material would not migrate back toward the water well pump.

The slurry pumping system was assembled several hundred feet from the injection hole. Figure 2 illustrates a plan view of the slurry pumping system. The main components of this system consist of a receiving hopper, conveyor, slurry mixing tank, slurry pump, and slurry distribution lines. Water is pumped from the mine to the mixing tank, and at the same time, sand or other suitable material is conveyed from the receiving hopper to the mixing tank. In the mixing tank, high pressure water nozzles mix, agitate, and suspend the sand creating a slurry. The slurry is then drawn from the tank by the slurry pump, and discharged into the slurry lines. The sand is then deposited in the open voids of the mine through injection holes (see Figure 3). The capacity of the slurry system used at Portal Park is approximately 50-75 tons of solids per hour. A system of this size requires approximately 400-600 gallons per minute of water to provide an acceptable slurry mix. The mix is composed of approximately 12% solids by volume or 30% solids by weight at 600 gallons of water per minute.

Almost 1000 tons of sandfill were injected into the single injection hole. The mine in the immediate vicinity of the pool was filled to refusal. Video monitoring with a downhole camera confirmed that the mine in this vicinity was indeed backfilled. The camera revealed that sandfill was deposited to within one inch of the mine roof.

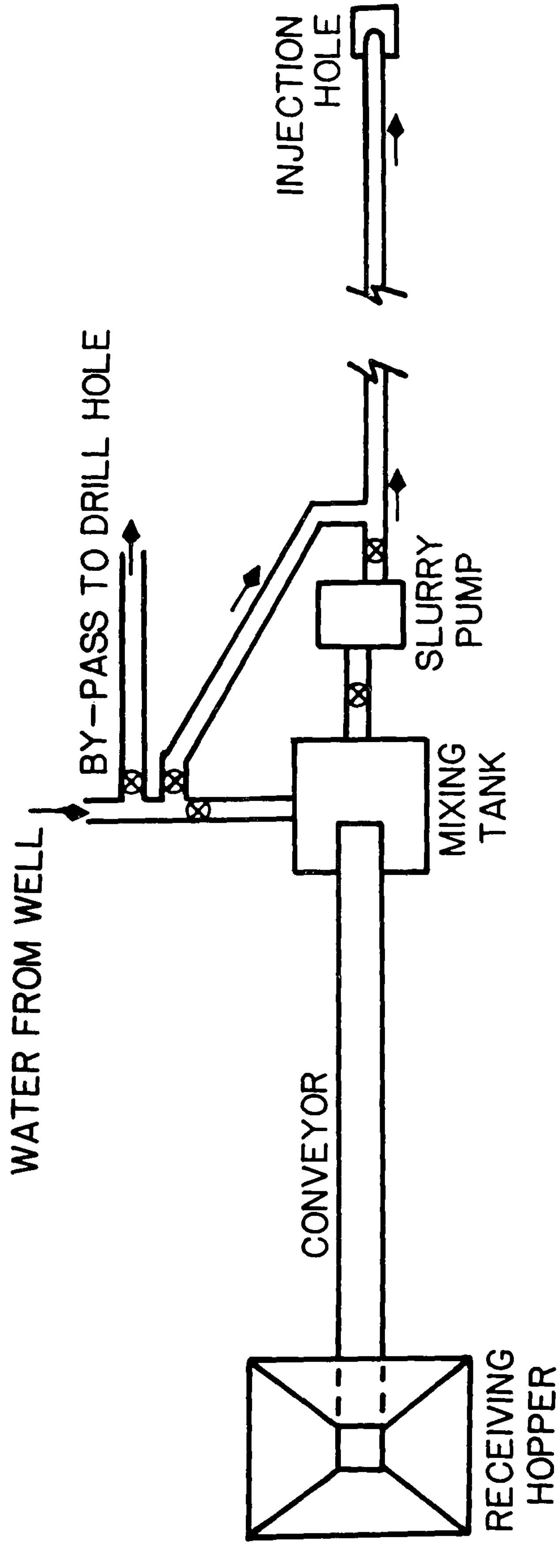


Figure 2. Plan view slurry pumping system.

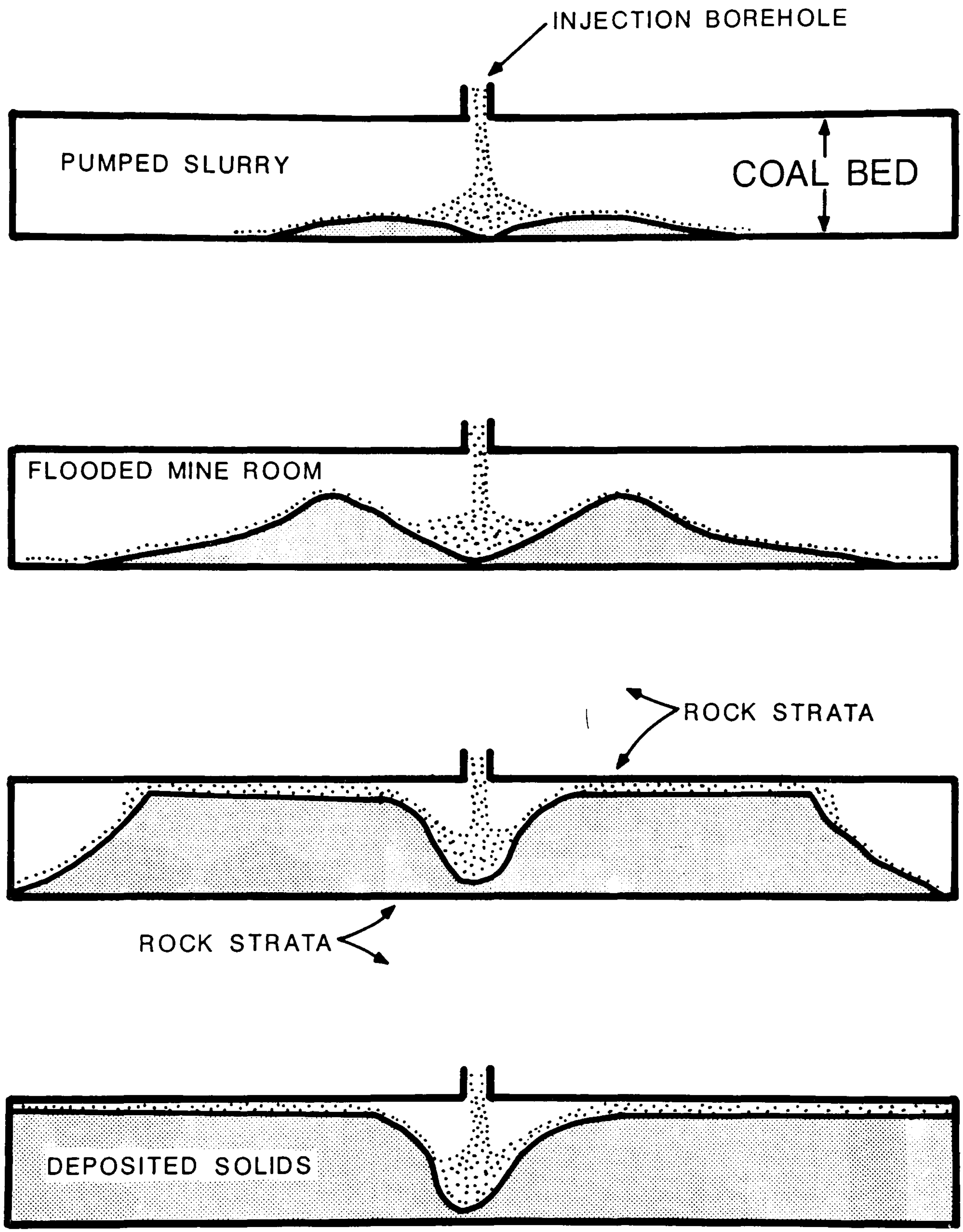


Figure 3. Section view of slurry deposition.

North Pointe Centre

The North Pointe Centre project is an example of pumped slurry backfilling for preventive subsidence control. The objective of the project was to limit or prevent future subsidence by pumping slurry backfill into the mine voids to reduce the potential downward movement of a mine roof failure.

The North Pointe Centre is located on the northern end of Colorado Springs, Colorado, near Interstate 25 and Rockrimmon Boulevard (see Figure 1). The Centre overlies a portion of the abandoned Pike View Coal Mine. The mine was last active in 1957 and was one of the largest in the area.

A drilling investigation conducted in 1984 revealed a potential subsidence hazard at the Centre site. Owing to previous subsidence occurrences, city and state agencies have adopted ordinances that restrict development over subsidence prone areas. The ordinances require site investigations and possible subsidence mitigation prior to construction. Since the site investigation revealed potential danger of subsidence, a hydraulic backfilling process was chosen to alleviate the problem.

In conjunction with the Colorado Geological Survey, mine maps of the Pikeview Mine and building plans of North Pointe Centre were reviewed. After the review, five locations within the property were designated as backfill sites. Criteria used in choosing the sites were high extraction areas of the mine and proposed building locations. Prior to backfilling, a total of twenty-nine 8-inch boreholes were drilled into mine voids. Average depth to the mine was 180 feet. Voids at the mine level ranged in height from 1 to 11 feet. Figure 4 shows a typical site within North Pointe Centre. Boreholes 2, 4, and 5 are not shown because they did not intersect voids and were not used as injection holes.

Backfilling was accomplished in the same manner as the Portal Park Project (see Figures 2 and 3), with minor adaptations made to the water supply system. Water for the slurry was obtained from the City of Colorado Springs via a fire hydrant. Sand slurry was injected into mine voids at approximately 50-75 tons per hour, utilizing 400-600 gallons of water per minute. Area B (Figure 4) required approximately 5400 tons of sandfill. It was estimated that 17,775 tons of sand

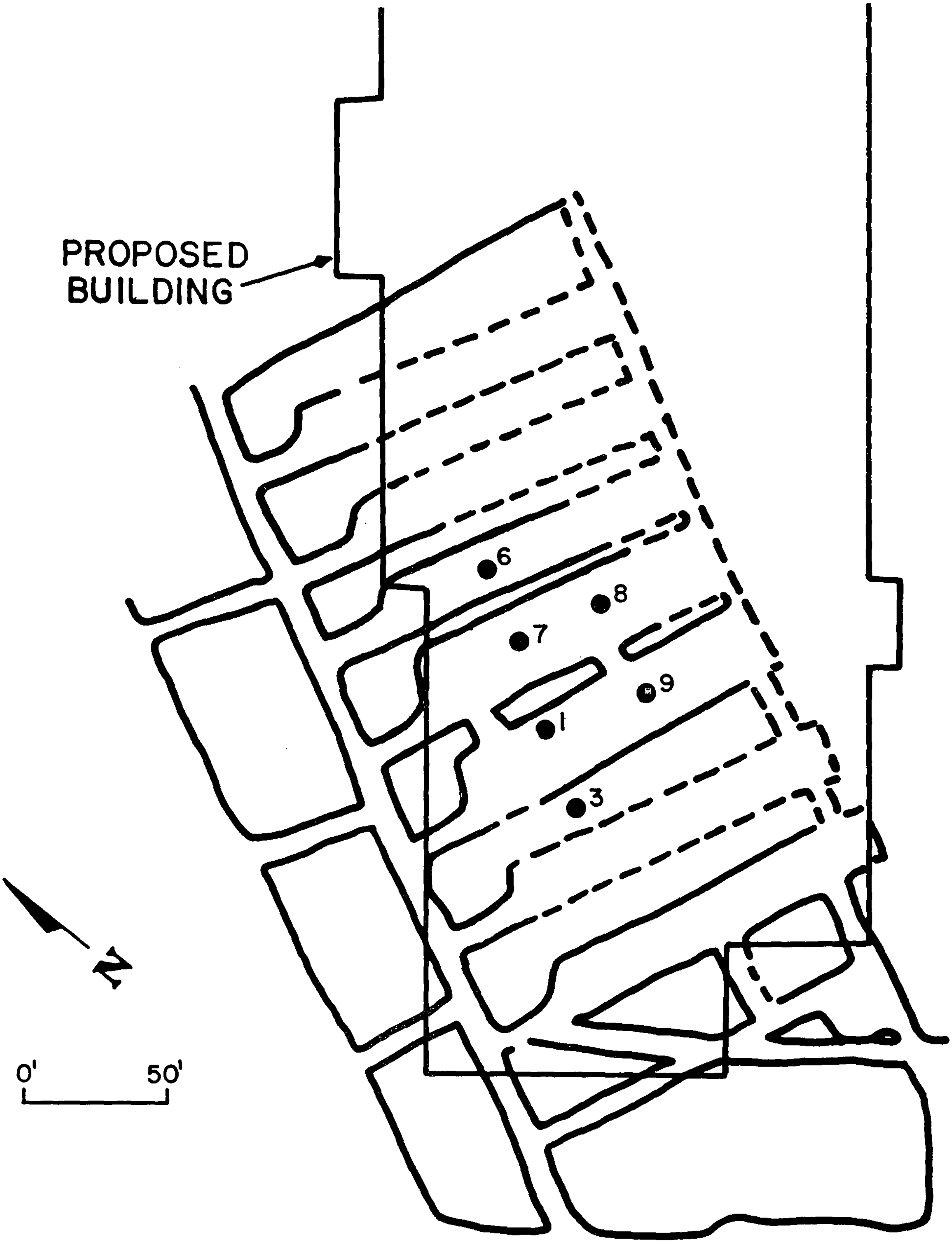


Figure 4. North Pointe Centre backfill area "B".

would be required to stabilize the five sites. Upon completion of the project, and injecting all holes to refusal, 99% of the estimated tonnage had been successfully placed into mine voids beneath the building sites. Individual boreholes throughout the project site took from 0 to 2153 tons. Many of the boreholes that did not take significant amounts of material were confirmed to be backfilled from adjacent holes by the video camera.

Backfilling in advance of subsidence is considered to be more cost effective than treating damaged structures after subsidence occurs. It was estimated that backfilling to alleviate future subsidence cost less than 1% of the total development cost.

Locust Street

The Locust Street project is one that exemplifies one of the most common types of subsidence (sinkholes) throughout the undermined areas of Colorado Springs. This particular hole surfaced on Locust Street, a residential area of Colorado Springs (see Figure 1). The hazards of such holes are apparent; therefore, this project was funded by OSM's emergency program.

Figure 5 shows the likely subsurface configuration of the sinkhole at Locust Street. The mine in the area is approximately 70 feet below the surface. The initial hole measured 8 feet long, 6 feet wide, and 4 feet deep. The objective of the project was to seal the hole by placing a reinforced concrete plug in it.

In preparation for the plug, the hole was excavated in the shape of an inverted cone or pyramid. By excavating the hole in this fashion, any downward movement of the plug would cause it to be wedged against the competent strata surrounding the hole. Excavation of the hole exposed competent strata several feet below the surface. A utility line was also exposed in the sinkhole, further emphasizing the possible hazards. Forms were built to isolate the utility line from the plug. After excavating 12 cubic yards of material, #5 rebar was placed in the hole to reinforce the plug. Concrete was then poured, filling the sinkhole. In addition to the 20 cubic yards of concrete used to fill the hole, road base and asphalt were used to top off the hole and reconstruct the road.

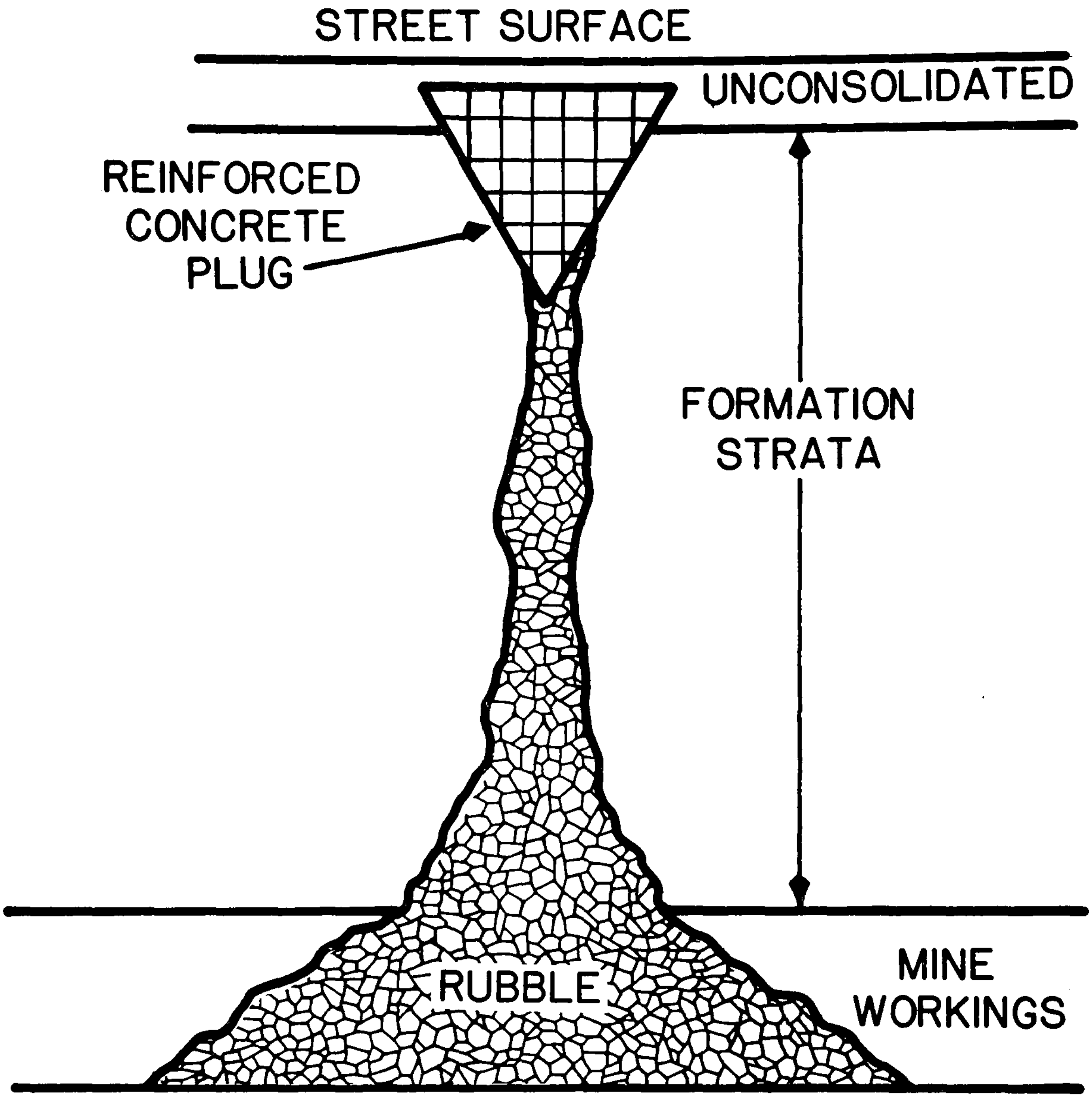


Figure 5. Cross section reinforced concrete sinkhole plug.

Ascension Church

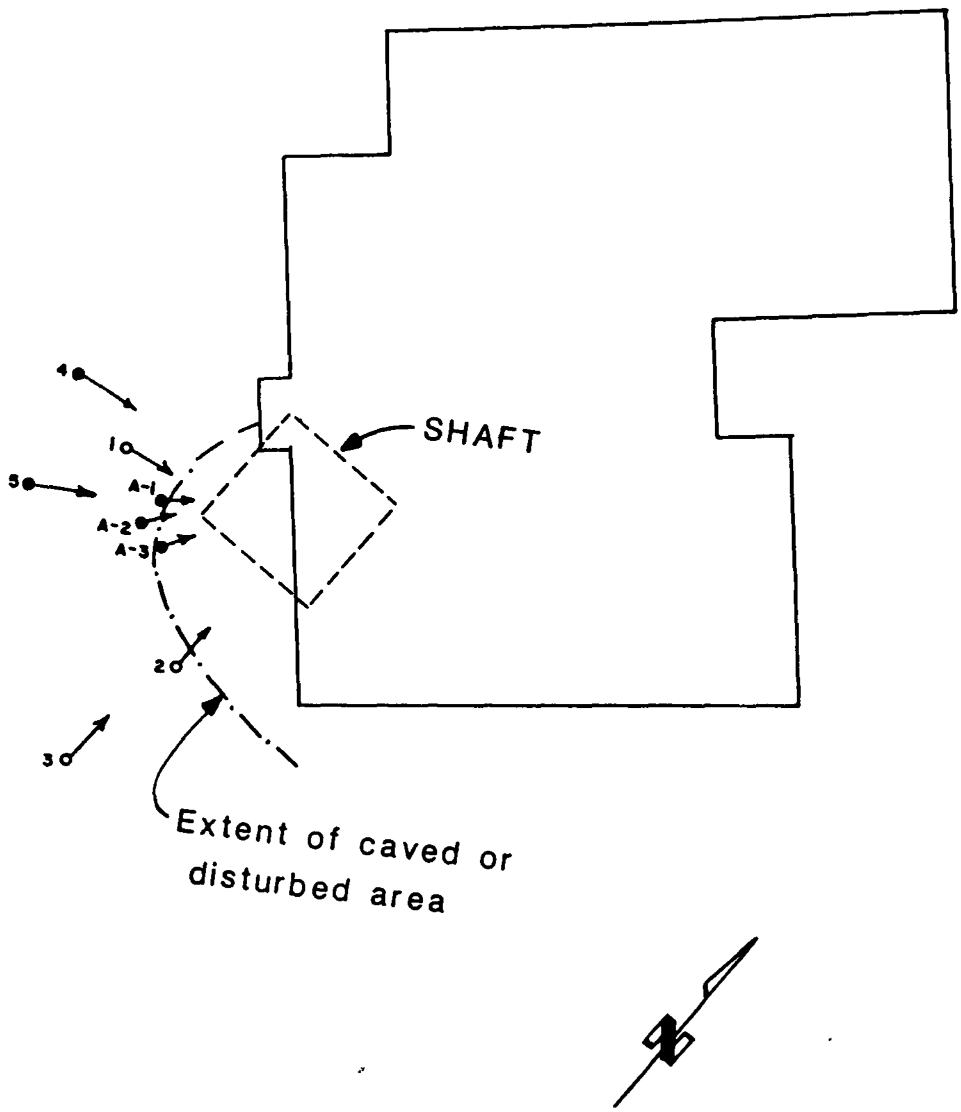
Like the Locust Street Project, the Ascension Church was also an Office of Surface Mining emergency project. A sinkhole developed on the shoulder of Circle Drive near the Church (see Figure 1 for location). Like Locust Street, the objective of this project was to seal off the sinkhole by installing a reinforced concrete plug.

The sinkhole, created by the collapse of a portion of the Rapson Mine, was approximately 15 feet long, 12 feet wide, and 4 feet deep. The Rapson Mine in this vicinity is nearly 70 feet deep.

Work began by excavating the sinkhole in preparation for the plug. After excavating the hole to 12 feet, no competent strata was found. A decision was made to place the plug in the same manner as the Locust Street project; however, the plug would be supported by grouting the mine voids and the unconsolidated overburden around the sinkhole. The plug was constructed by placing #5 rebar on 12 inch centers and pouring 16 cubic yards of concrete into the hole. Upon completion of the plug, 6 holes were drilled around the circumference of the sinkhole. Of the six holes drilled, 4 were vertical and 2 were angle holes. The 4 vertical holes were drilled to the mine level. The angle holes were located on opposite sides of the sinkhole and were drilled toward the center of the sinkhole at depth. Of the 4 vertical holes drilled, 2 intersected coal and 2 intersected voids. Both angle holes and the 2 vertical holes intersecting voids were cased and used for injecting grout. A total of 27 cubic yards of grout was pumped into the 4 holes, filling mine voids and rubble zones, and stabilizing the concrete plug.

Corley Air Shaft

In July of 1984, the Office of Surface Mining (OSM) contracted the work for the Corley Air Shaft emergency project. The Corley Air Shaft project is located west of Interstate 25 near Woodmen Road (see Figure 1). The project involved stabilizing a debris-filled mine shaft which had opened up in a residential area under a house foundation. The shaft underlies the rear foundation wall and is centered about 16 feet from the southeast corner of the house. After reviewing mine maps, it was determined that the shaft, 12 feet square, served as the



→ Angle Boreholes
o Exploratory Boreholes
● Exploratory/Grout Injection Boreholes

Figure 6. Corley air shaft.

ventilation shaft for the Corley Mine. The Corley Mine lies some 400 feet below the surface.

Previous to Goodson & Associates' participation, OSM hired a contractor to support the foundation and stabilize the shaft. A steel I-beam was attached to the foundation and footer to provide structural strength; however, the foundation wall still lacked adequate bearing support and the shaft remained unstable. Goodson & Associates, Inc. proposed a drilling/grouting plan to alleviate the problem. Eight angle holes were drilled from varying surface locations. The holes were drilled into the shaft at varying depths (see Figure 6). Intersecting the shaft at different elevations revealed the nature of the material in the shaft and confirmed the shaft's location. The 8 holes intersected the shaft at depths from 30 to 210 feet. Figure 7 shows the approximate shaft intersection locations of 4 of the 8 angle holes and interpretation of shaft conditions from available data. While drilling, material in the shaft intermittently subsided. Approximately 85 tons of pea gravel were placed in the shaft at the surface during drilling operations. Hole 5 was drilled to the mine level, 403 feet below the surface; however, casing of hole 5 could only be accomplished to 235 feet.

Upon completion of the drilling and casing operation, concrete was pumped into voided areas in the shaft. Concrete (3/8" aggregate) was pumped to the lowest possible depths. A total of 18 cubic yards of concrete was pumped into the shaft from 235 feet up to 15 feet below the surface. During pumping operations, previously placed pea gravel settled nearly 3 feet.

Unconsolidated material at the surface required grout to be used to stabilize the upper 15 feet of the shaft and surrounding overburden. A total of 12 holes were drilled for this purpose. The holes were drilled on 4 foot centers, averaging 12 feet in depth. An average of .85 cubic yards of grout were placed in each hole, totaling 10.25 cubic yards. Grout was composed of sand, cement, and fly ash. The mix was pumped at a 1 inch slump to insure excellent compaction of overburden and placement of grout.

Country Club Drive

Sinkhole subsidence due to the roof collapse of the abandoned Rapson Mine underlying Country Club Drive, (Figure 1), required the use of several control

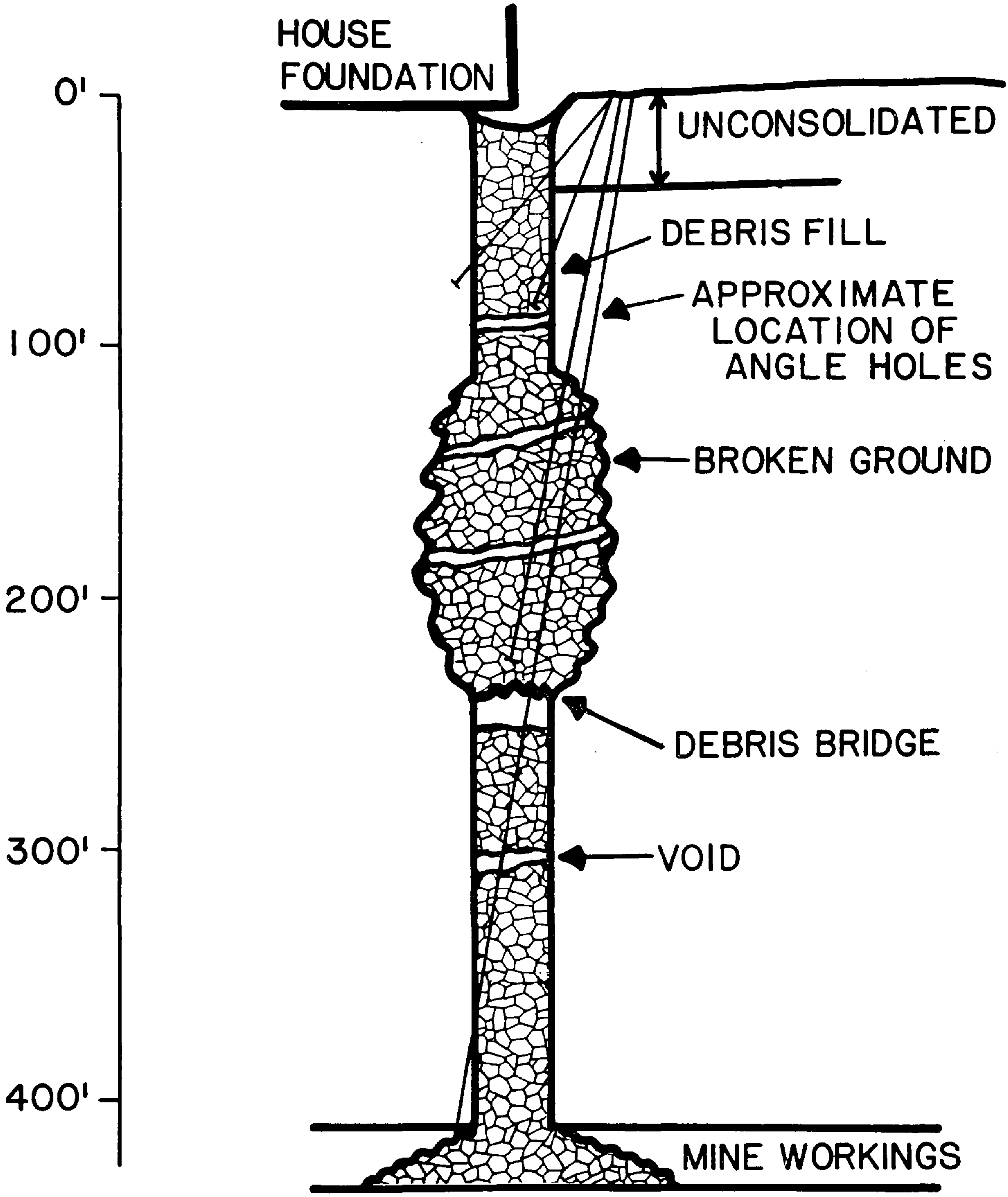


Figure 7. Interpretation of drilling results.

methods for this project. Designated an OSM emergency, the subsidence directly affected one private residence and was endangering a second, thus necessitating expedient design and construction to abate the hazard. The control methods utilized were a reinforced concrete plug, direct structural support, and pumped slurry backfill.

The Rapson Mine operated from 1901-1916 and had a mineable coal seam thickness of 5 to 8 feet. At depths of 72 to 74 feet, the mine overburden consists of 32 to 37 feet of aeolian sand overlying Laramie Formation bedrock, comprised of shales, carbonaceous shales, and thin sandstone and siltstone layers.

The site at Country Club Drive had experienced the initial sinkhole subsidence several months before. Under a previous OSM task order with another contractor, a reinforced concrete plug was placed to alleviate the hazard. With insufficient bearing material to support the concrete plug (Figure 8), further settlement occurred.

Goodson & Associates, Inc., under contract to OSM, implemented a design scheme that provided immediate direct structural support to a private residence in advance of a pumped slurry backfilling program. The backfilling program was designed to fill the mine voids directly under the endangered structures. The first step in the construction sequence was to excavate around the sinkhole. This provided access for placement of backfill material which was placed and compacted to below footing level in the sinkhole, while at the same time providing a working platform for a drill rig. The excavation also exposed electrical and sprinkler lines which were damaged during the cave-in. Next, 12 inch nominal, pipe piles were placed on both sides of the southeast corner of the structure (Figure 9). The pipe piles were placed in predrilled holes to a depth of 70 feet (2 feet into the mine floor) to obtain sufficient bearing capacity. The pipe piles were then filled with reinforced concrete. A W14x82 steel beam was placed under the foundation wall of the structure and on top of the pipe piles. Hydraulic jacks, placed on reaction plates welded to the pipe piles, were used to lift the beam (and the structure) back to a level configuration.

Once the endangered structure was supported and protected from further subsidence, the next step in the construction sequence was to backfill the mine voids below

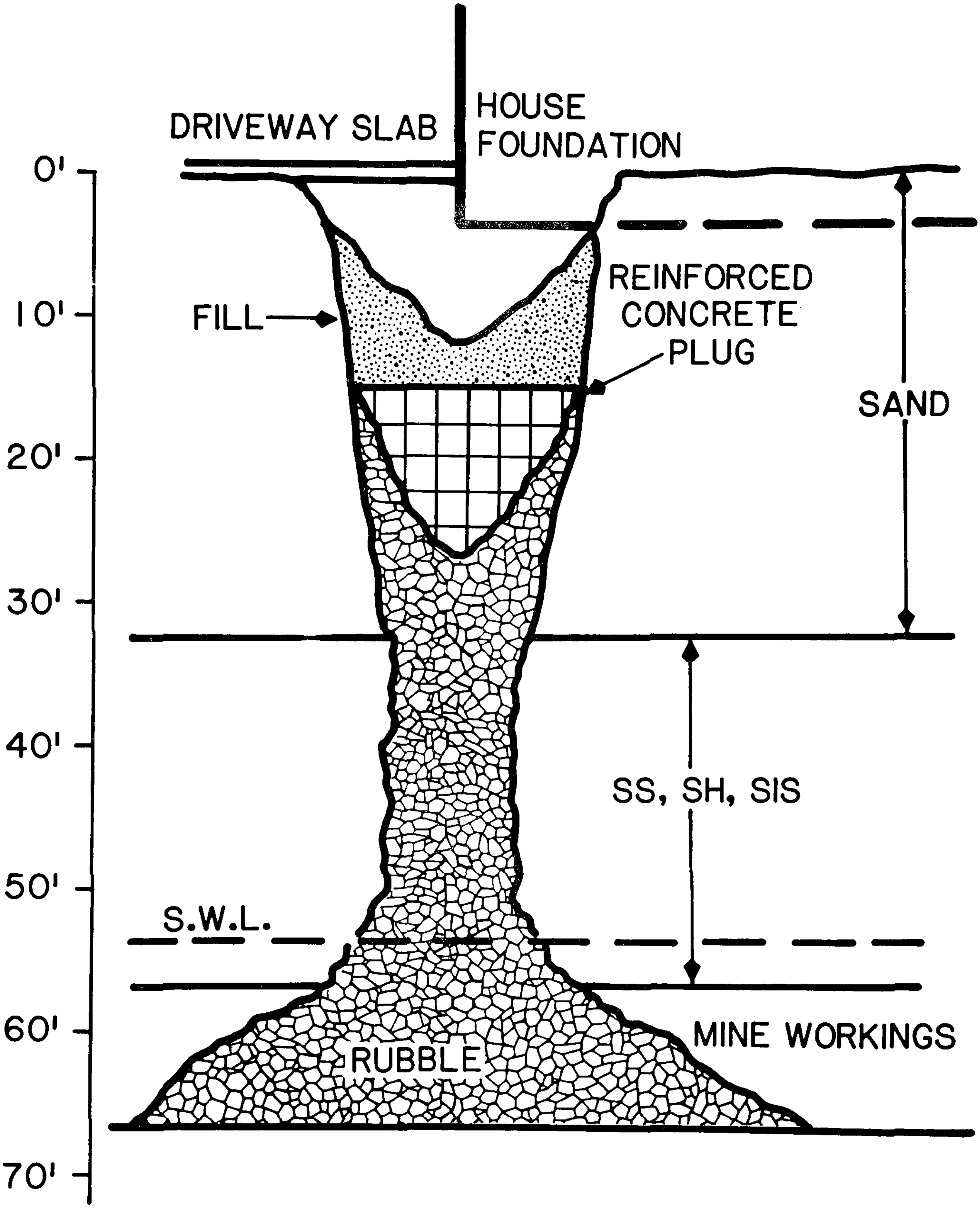


Figure 8. Cross section through sinkhole.

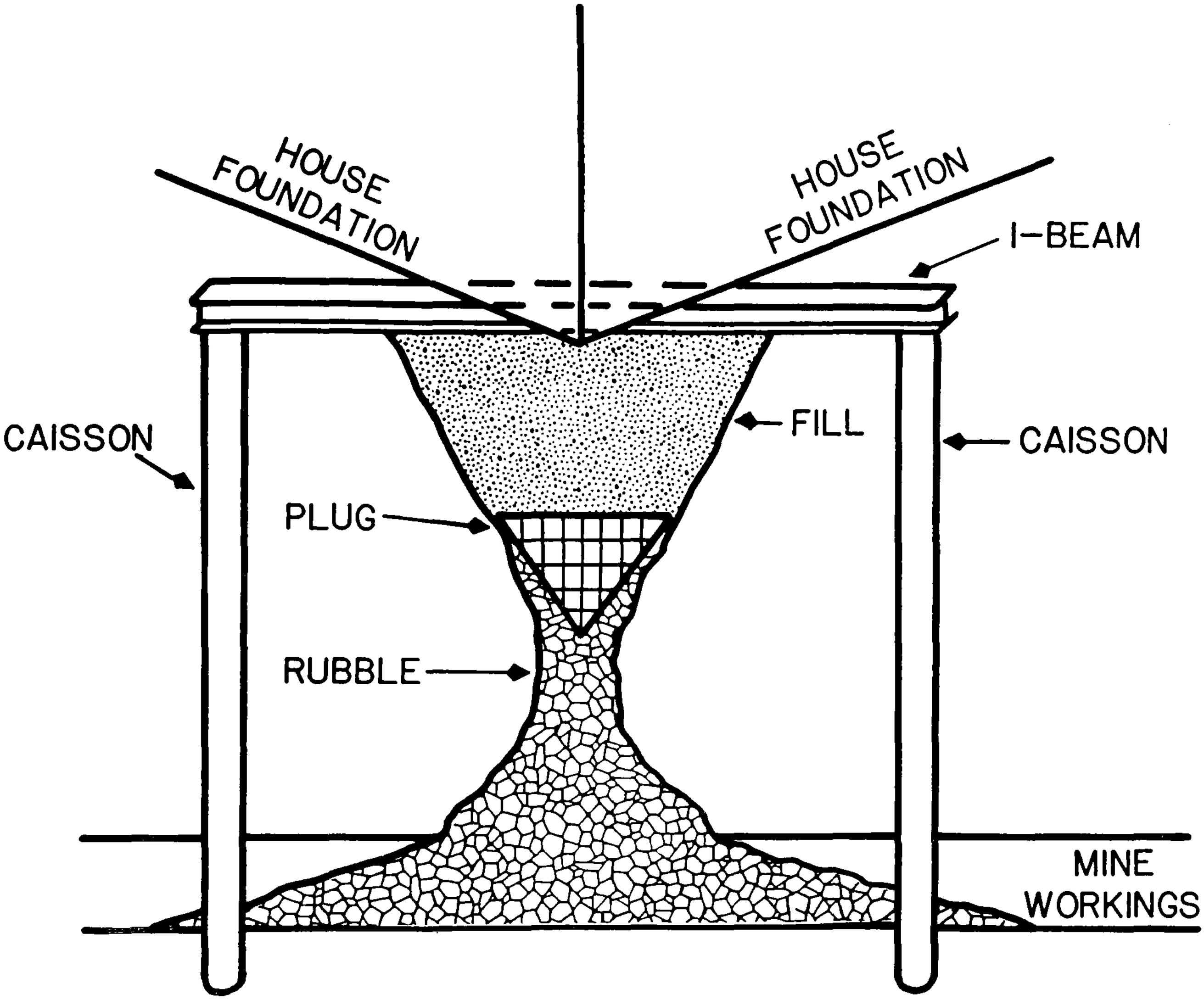


Figure 9. Structural support.

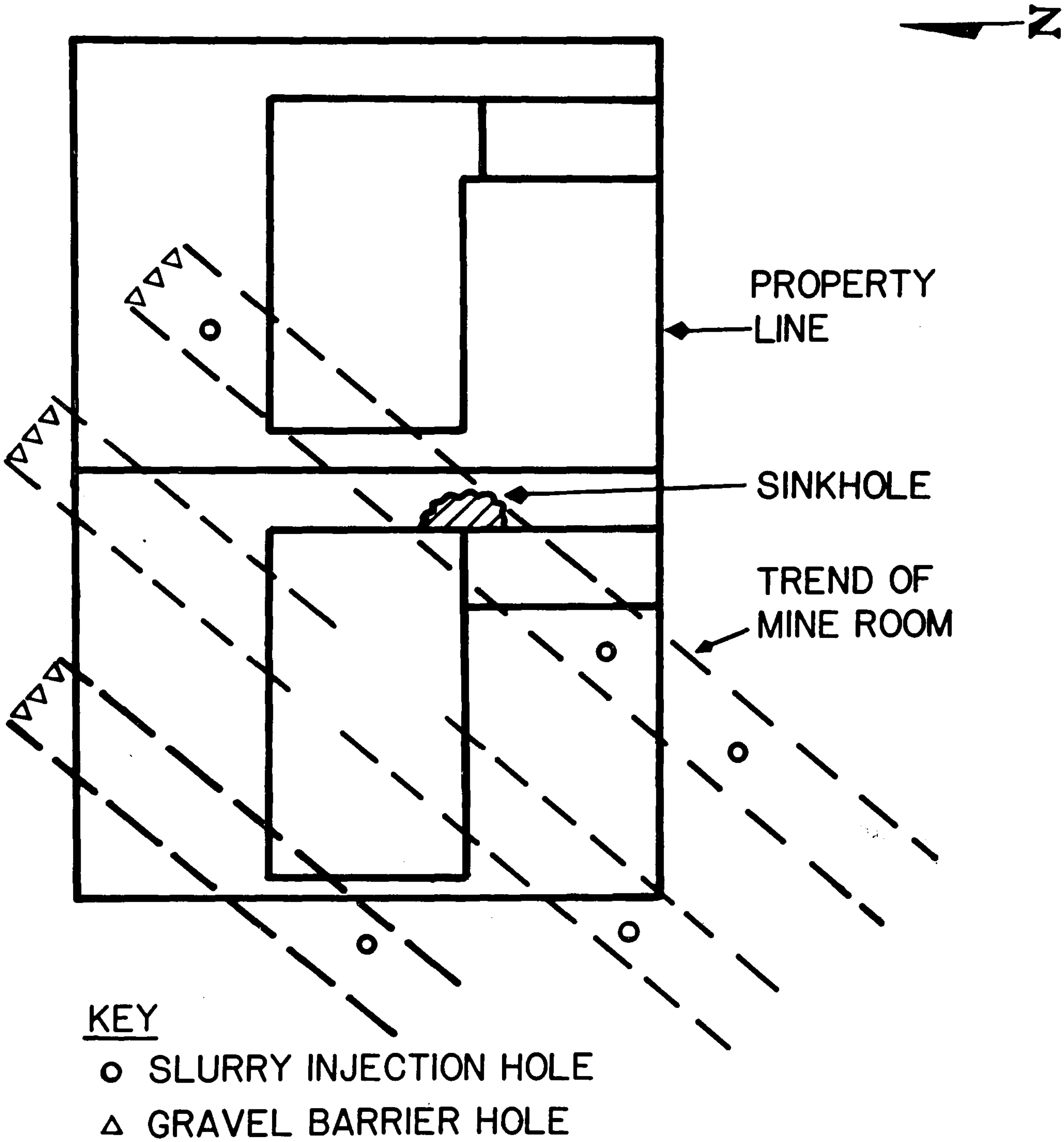


Figure 10. Map view of backfilling.

both affected houses. This was accomplished using pumped slurry backfilling. In order to contain the backfill material directly under the structures, gravel bulkheads were installed by drilling and casing 12-inch diameter holes and placing 3/4-inch gravel to the roof of the mine (Figure 10). Injection holes (6-inch diameter) were then drilled and cased to mine level. Utilizing the pumped slurry injection system previously described, 1050 tons of backfill were placed in the mine voids beneath the structures. Placement of both the gravel barriers and the pumped slurry were monitored by a remote video camera.

The project was completed by placing compacted backfill in the remaining portion of the excavation and by pumping concrete under the garage floor slab of the directly affected structure. Finally, the landscape was restored to pre-subsidence conditions.

SUMMARY

Mine related subsidence will undoubtedly continue to create problems in the Colorado Springs area. Subsidence troughs, sinkholes, and shaft collapses will occur that will require emergency action. The case studies described are a good representative cross-section of the subsidence events that have occurred or may occur in the future. Pumped slurry backfilling, concrete plugs, direct structural support, and grout injection are practical and effective methods to alleviate these hazards.

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BACKFILLING OF THE PIKEVIEW MINE MANWAY

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ABSTRACT

The Pikeview Mine in northwestern Colorado Springs, Colorado produced about nine million tons of coal. From 1897 to 1940, the main entry to the mine was a 173 foot vertical shaft. After 1940, access to the Pikeview was gained via a sloping manway descending at a grade of 33 percent to a depth of about 150 feet.

Evaluation of the condition of the manway in the Fall of 1983 indicated a significant risk of damage to proposed surface construction above the entryway. Backfilling was chosen from various alternatives to reduce the subsidence hazards. Backfilling of the manway to a depth of 120 feet was accomplished in 1984. The backfilling procedure consisted of four stages including the construction of a grouted gravel blockage in the manway and the placement of three progressively larger lifts of sand-cement slurry. A total of 900 cubic yards of slurry, 33 cubic yards of gravel and 19 cubic yards of grout were used to backfill the entryway. Field observations and laboratory test results suggest the risk of future subsidence over the backfilled portion of the manway is very low.

INTRODUCTION

Evaluation of subsidence potential over the Pikeview Coal Mine sloping entryway in Colorado Springs, Colorado indicated a substantial risk of future ground movements. A procedure was formulated to block the lower end of the entryway and backfill the upslope portion of the opening with cement slurry. Based upon video and personal inspection of the entryway, quantity estimates versus actual materials required to fill the manway, and field observations during backfilling operations, it was concluded the Pikeview manway was completely backfilled to a depth of 120 feet. This paper details some of the findings of the subsidence evaluation and describes the methods used to backfill the entryway.

MINING HISTORY

Abandoned workings of the Pikeview Coal Mine are located in the northwest portion of Colorado Springs, Colorado. The mine was originally opened in 1897 as the Carlton Mine and closed in 1957 operating under the name of the Pikeview. The Pikeview is thought to be one of the largest underground mining operations in the State of Colorado, covering approximately four square miles and having produced nearly nine million tons of coal during its 60 years of operation. More than half of the coal mined in the Colorado Springs coal field was produced by the Pikeview Mine.

Existing records and conversations with former mine workers indicate the Pikeview was developed by driving a series of haulways through the coal seam and extracting the coal in a room-and-pillar fashion. A more complete exploitation of the reserve included the sequential removal of support pillars in many parts of the mine.

The main entry to the Pikeview Mine was a 173 foot vertical shaft completed in January of 1897. The shaft was located in the S.W. 1/4 of Section 18, T13S, R66W, near what is now the intersection of Rockrimmon Boulevard South and Delmonico Drive. The vertical shaft was used for miner access and to hoist loaded coal cars from the mined level. In 1940, a sloping manway was constructed several hundred feet to the east of the hoist shaft. The manway was used to transport personnel from the ground surface to the mine level using an electric tramway system. According to available information, the manway was a timber supported, square tunnel having dimensions of 8 feet by 8 feet. The manway reportedly sloped downward from the ground surface to a depth of 150 feet at a grade of about 33 percent. The upper end of the entryway was sealed in 1957 when the Pikeview Mine closed.

PROPOSED DEVELOPMENT

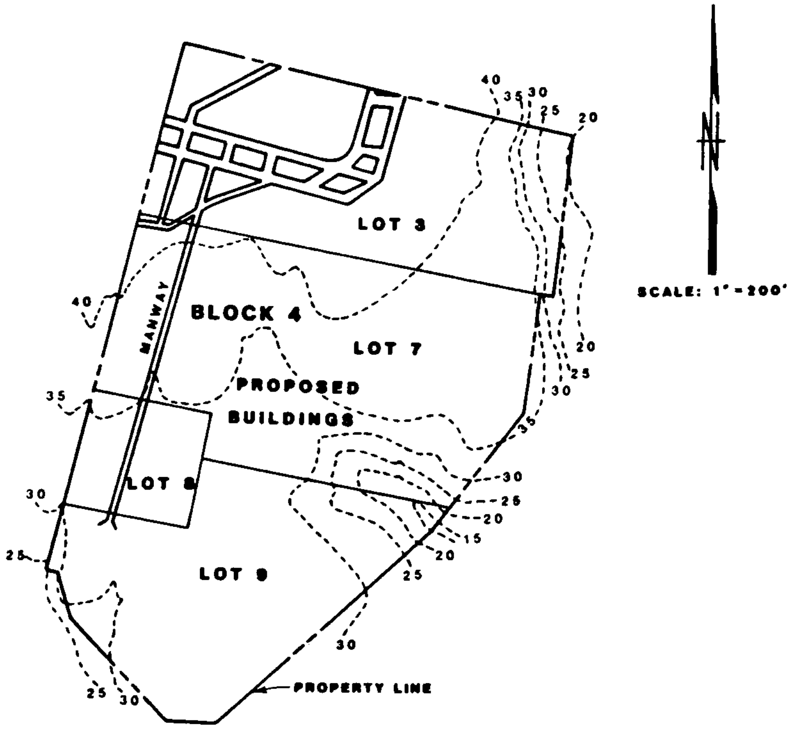
During the fall of 1983, a plan was submitted to CTL/Thompson, Inc. for development of land suspected to be above the abandoned manway and several adjacent haulways of the Pikeview Mine. A commercial office park was proposed for the site. The development was to consist of three office buildings, each three stories in height. No below-grade construction was planned. A considerable amount of overlot grading would be necessary along the eastern edge of the site to make this portion of the property suitable for construction.

SUBSIDENCE INVESTIGATION

A preliminary investigation of the site using existing mine maps indicated the property was indeed underlain by the abandoned sloping entryway and several adjacent haulways, as shown on Fig. 1. Based on the available information and mine maps, a plan for evaluation of the potential for ground subsidence due to the mining activity was formulated. The purpose of the subsidence study was to determine stratigraphic and lithologic sections of the site geology, verify the locations of the entryway and haulways, determine the depth to mining, provide data and samples for analysis of the mine conditions, and evaluate possible subsidence hazards.

A total of eight exploratory borings were drilled at the site during the 1983 subsidence evaluation using a Portadrill Prospector drill rig. The rig utilized air rotary, water rotary, and core drilling techniques to advance the borings. The drilling program involved plug drilling with a 5-5/8 inch diameter bit and some continuous coring using a 4-7/8 inch diameter core barrel. After drilling, the majority of the borings were electrically logged with a gamma detector, high resolution density tool, caliper, and downhole video camera to provide additional detail on the site stratigraphy and lithology.

Two borings drilled along the estimated entryway alignment penetrated 7.5 to 8.0 foot voids at depths of 37 and 82 feet. Borings drilled in the northwest corner of the site indicated the haulways were at a depth of 150 feet or more. Both the entryway and haulways appeared to be substantially open. No indication of any surface subsidence was evident above the entryway or adjacent haulways.



NOTE:
MINE PLAN FROM RECORDED MINE MAP
DATED JULY 1957 AS FILED WITH
COLORADO DIVISION OF MINES.

Figure 1. Location of manway and haulways.

Field observations at the property revealed numerous relic foundations and structures presumably related to the town of Pikeview (which provided housing and support functions for the mine) or the mobile home trailer park constructed at the site following the closure of the mine. Among the structures identified were remnants of a bath house, trackage leading to the manway tunnel, and the tramway powerhouse.

Two cast-iron manholes were observed on either side of the estimated entryway alignment. These manholes were reported to be emergency escape tunnels leading to the entryway. Based on this assumption, a boring was drilled inside each of the manholes. The borings encountered 2 to 10 feet of very foul smelling organic soil and debris overlying hard to very hard sandstone bedrock to the maximum depth of 60 feet. A boring directly south of the manholes, on the centerline of the entryway, encountered the manway at a depth of 37 feet. It appeared the manholes were not connected to the entryway in any fashion and were actually part of a sewage disposal system. This assumption was later confirmed in an interview with the former mine superintendent.

Several conclusions were drawn from the 1983 subsidence evaluation. The possibility of damage to the proposed office buildings was considered negligible because of the structures' positions to the east and south of the mine (Fig. 1). Furthermore, the study indicated the risk of subsidence features reaching the surface would be low for portions of the mine at least 120 feet below the ground surface. This value was based upon experience with bulking factors from other portions of the Pikeview Mine having similar lithology and the results of laboratory data obtained during the 1983 study. Calculations indicated for an 8 foot opening at a depth of 120 feet, the factor of safety against subsidence features reaching the surface was 1.5, even using the worst-case analysis procedure.

However, it was concluded the level of subsidence risk was substantial over the portion of the mine less than 120 feet below the ground surface, or the majority of the sloping entryway. Historically, subsidence problems in the Colorado Springs coal field have been associated with shallow workings (less than 100 feet) or mine features such as air shafts and access tunnels. For these reasons, it was recommended some mitigation measure or precaution be taken to reduce the risk of subsidence over the entryway to an acceptable level.

Several alternatives for dealing with the potential for subsidence over the manway were discussed as a part of the 1983 study. The simplest method was to avoid construction over the entryway. since virtually all traffic entering and leaving the development would cross the entryway, this alternative was not a suitable solution. The second method was to structurally bridge the area above the manway with a heavily reinforced mat. This procedure was judged to be expensive and time-consuming to construct. A third alternative was to bring down the roof of the entryway using explosives. This method was considered inappropriate as damage to existing structures to the north might result and a substantial layer of unconsolidated material would be created. The fourth and final alternative was to backfill the portion of the manway thought to be particularly hazardous to surface construction. Based on practicality, reliability, cost, and the amount of time needed to complete the reclamation procedure, the backfilling option was chosen.

PROPOSED BACKFILLING PROCEDURE

Preliminary calculations indicated about 950 to 1,000 cubic yards of material would be needed to backfill the entryway to a depth of 120 feet. A backfill procedure was formulated consisting of four distinct steps. The initial step was to provide a blockage in the entryway to prevent backfill slurry from flowing downward into the mine workings. The blockage was envisioned to consist of crushed gravel to be cemented in-place with cement and fly ash grout. The final three steps were to be the placement of progressively larger lifts of about 100, 200, and 700 cubic yards of cement slurry. Approximately a one week curing period would be allowed between construction of the gravel plug and placement of the first slurry lift and between each successive slurry lift. The purpose of the staged construction procedure was to allow the grouted plug and first and second lifts of slurry to gain strength, thereby reducing the risk of pushing out the plug and loosing all or a portion of the slurry backfill. Progress of the slurry backfilling was to be observed using a downhole camera in monitoring borings drilled at 50 to 100 foot spacings along the manway alignment. Slurry was to be injected into the upper end of the entryway through a large diameter, cased boring. Diagrams for construction of the gravel plug and slurry placement are shown on Fig. 2.

FIELD DRILLING PROGRAM

The initial step in the drilling program was to locate the entryway alignment using available mine maps showing the manway and existing Denver and Rio Grande Western Railroad. Borings drilled previously at the site that were known to penetrate the entry way were also helpful in locating the manway alignment. The positions of borings for construction of the gravel plug were field staked near the lower end of the entryway, adjacent to the haulways. The location of the Slurry Injection Point was initially planned about 450 feet to the south. Six monitoring bore holes were staked along the entryway alignment.

Drilling of the monitoring borings was begun in February of 1984 using a Portadrill Prospector drill rig. The monitoring borings were 5-5/8 inch diameter, rotary drilled holes cased with 4 inch diameter PVC pipe. The positions of the monitoring borings are shown on Fig. 3. As expected, voids of 5 to 9 feet were encountered at progressively shallower depths southward along the entryway.

The first exploratory boring drilled for the Slurry Injection Point at the upper end of the entryway (Boring SP-1) did not encounter any void. However, a large piece of wood was penetrated at a depth of 26 feet. Boring SP-1 appeared to be situated in the fill that was pushed into the upper end of the entryway when the mine was sealed in 1957. The Slurry Injection Point was moved about 20 feet to the north where an 8 foot void was encountered at a depth of 22 feet (Boring SP-2, Fig. 3).

Some difficulty was encountered in locating the borings for placement of the gravel and grout comprising the gravel plug. Borings were drilled at the positions designated as GH-1, GR-1, and GH-2 on Fig. 3. Video inspection of these borings in the lower end of the manway, the height and elevation of the voids, and the amount of water found in Boring MP-2 suggested a portion of the roof in the entryway had collapsed, creating a flat, pond-like zone and a partial blockage. For this reason, the gravel plug position was moved upslope to the location of Borings GH-3 and GR-2.

A 36 inch diameter bore hole was drilled at the same location as Boring SP-2 (Fig. 3) using a caisson rig. The entryway was penetrated at a depth of 22 feet. This

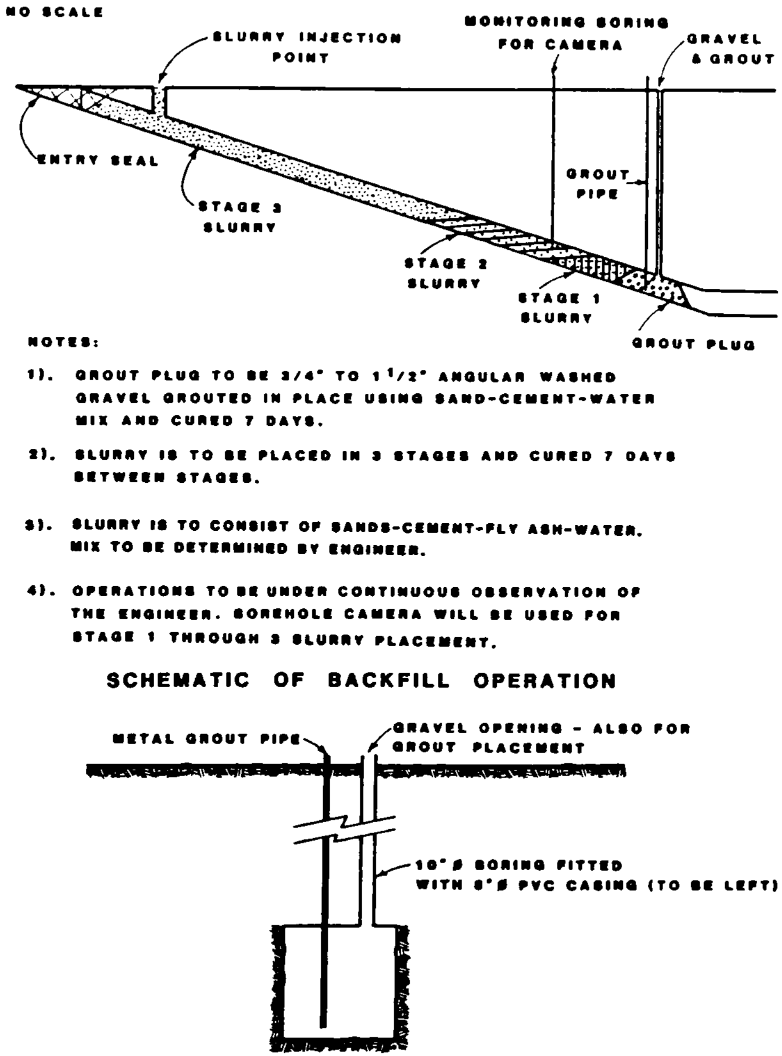


Figure 2. Cross section of grout plug installation and schematic of backfill operation.

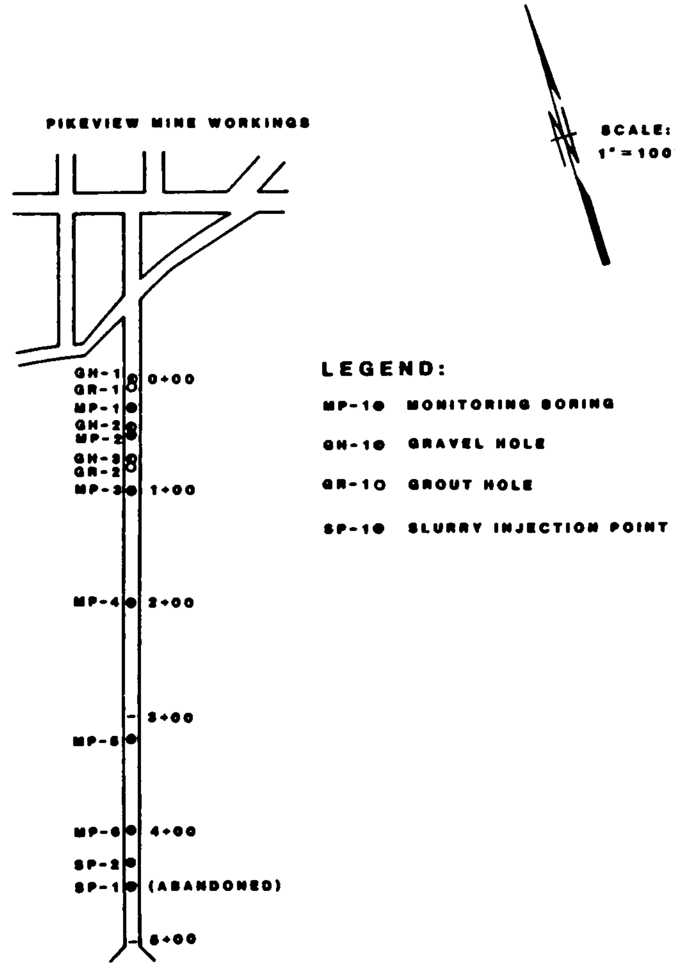


Figure 3. Location of borings and manway plan.

boring was cased with corrugated metal pipe (CMP) and would serve as the Slurry Injection Point. The portion of the manway visible from the bottom of the CMP casing was visually inspected. Some large timbers, loose backfill, and auger cuttings were present directly below the CMP casing. The manway appeared to be substantially unobstructed about 30 feet downslope from the Slurry Injection Point. The entryway was sealed with sandy fill and timbers about 20 feet upslope. The loose fill and auger cuttings were moved out from beneath the CMP casing by hand as much as possible to create sufficient clearance and slope to allow the slurry backfill to flow downward into the open portion of the manway.

GRAVEL PLUG CONSTRUCTION

The grouted gravel plug was constructed at the location of Borings GH-3 and GR-2 (Fig. 3). About 27 cubic yards of 3/4 to 1-1/2 inch crushed rock were placed in the entryway. About 19 cubic yards of cement and fly ash grout were then pumped into the gravel mass. After grouting, an additional 5.5 cubic yards of gravel were placed in the manway through Boring GH-3. This amount of material filled a small void created in the gravel plug by the grouting pressure and also filled the 8 inch casing to the ground surface.

A total of about 50 cubic yards of gravel and grout were placed in the lower end of the manway. Based on the estimated dimensions of the entryway, the amount of material introduced, video camera observations, and the changes observed in the water level in several of the bore holes, it was concluded the manway had been blocked at a depth of about 120 feet below the ground surface. Following a ten day curing period, the entryway was ready for placement of the first lift of cement slurry backfill.

SLURRY BACKFILL PLACEMENT

A slurry mix design was performed using the on-site sands and variable quantities of water, cement, and fly ash. The mix design indicated slurry containing about 4 percent cement (14 percent total cementitious material, including fly ash) and exhibiting a slump of 10 to 12 inches would achieve a 28 day compressive strength of 50 psi or more. The feasibility of using the on-site sands to manufacture the backfill slurry was discussed with the supplier. Taking into account the costs of excavating, transporting, and processing these sands, it was concluded the savings per yard would be minimal as compared to simply batching the slurry at the nearby plant using commercial sands.

The consistency of the slurry was visually checked upon its arrival at the site in conventional concrete trucks and water was added as needed. The downhole video camera was used to observe the movement of the slurry down the entryway to the gravel plug. The speed of travel of the slurry was generally between 10 and 20 feet per second. During the three slurry backfilling stages, 134, 203, and 564 cubic yards of slurry were placed in the manway through the Slurry Injection Point. As planned, a seven day curing period was allowed between each slurry lift. All samples of the slurry taken at random points during the three pours exhibited compressive strengths in excess of 85 psi.

The most significant problem encountered during the backfilling procedure involved the build up of slurry beneath the CMP casing of the Slurry Injection Point. The slurry appeared to accumulate due to the presence of the timbers and loose fill in this portion of the entryway and created a steep mound from near the entryway roof down to the comparatively open part of the manway, about 30 feet to the north. To maintain an open flow path for the backfill material, a small spillway was dug by hand from the bottom of the CMP casing, down the face of the mound, after placement of the first and second lifts of slurry. Although time consuming and requiring difficult hand labor, the spillway procedure worked well and allowed the slurry to move rapidly into the open part of the entryway with no build up in the CMP casing.

Using the downhole camera in the monitoring borings spaced at 50 to 100 foot intervals along the alignment, the slurry level was observed moving progressively upward in the manway to the Slurry Injection Point and ultimately to the ground surface. A total of 950 cubic yards of gravel, grout, and slurry were placed in the entryway. This result correlated well with the original estimate of the amount of material needed to backfill the entryway to a depth of 120 feet.

The total cost of the reclamation procedure was about $90,000 and was completed in a period of just over four weeks. Furthermore, it is believed the risk of future subsidence movement over the backfilled portion of the entryway can be considered very low.

ACKNOWLEDGEMENTS

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SUBSIDENCE AWARENESS AND PLANNING IN THE CITY OF COLORADO SPRINGS

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The City of Colorado Springs' heavy involvement in the mined land fields dates back to 1963 when the Colorado Springs Planning Department Geology Section prepared a mining report of the Colorado Springs coal field entitled "Guide for Future Land Use". The report presents results obtained in a study of hazards to man-made structures due to the presence of coal mines in the metropolitan areas of Colorado Springs. The intent was not to devaluate land values nor to discourage development of undermined areas but rather to present the problem and to offer possible alternate land use suggestions over areas deemed hazardous due to unstable soil conditions created by underground mining operations. It was also the intent of the Planning Department to acquaint land developers with the need to design buildings in accordance with the hazards present in undermined areas.

During the spring and summer of 1963 several instances of subsidence were noted. It was felt that these cave-ins or subsidences were primarily due to a 22 month drought which was broken in late August, 1963. It is an established fact that moist soil has a greater plastic strength than dry soil. The report goes on to provide builders or developers ideas as to how to build over the mined areas.

The City's Comprehensive Plan encourages, based on sound planning and engineering principles, high density, multi-family residential, commercial, industrial, public and quasi-public uses as well as parks, golf courses and other open space uses on property that has been undermined, to amortize the cost of, or eliminate the need for special construction techniques. As a result of this study the City Planning Commission issued the following resolution:

"A resolution relating to the subdivision of land areas known or suspected to be overlying underground coal mine workings whereas, by reason of the rapid and extensive development of land within the area of the Colorado Springs coal field, it has become increasingly important to adopt a general policy and method of procedure respecting the subdivision and development of said lands and whereas, coal mining has been in progress continuously since 1883 with extensive mining during the years 1900 to 1950 when annual production exceeded 100,000 tons and whereas, during the years since it has been noticed that considerable subsidence has occurred in said land, and whereas, said subsidence is most adverse to the development of the overlying land area, and whereas, extensive study has been devoted to this problem by the City Planning Commission and other officials of the City, the City Planning Commission has resolved the following policy to guide developers in the preparation of their subdivision; now therefore be it resolved by the City Planning Commission: If any area known to be or suspected to be undermined is to be subdivided then the developer, at his expense, furnish a satisfactory engineering report to the Department of Public Works at the time the preliminary plat of subdivision is submitted for the Planning Commission approval". Signed the 27th day of July, 1964 for the Planning Commission by Chairman Andrew Marshall, Jr.

Since 1963, the City has provided the guide to the developers in these areas. Most recently the City's involvement with my office has been as to act as a local office to notify in the event subsidence occurs. Our office will contact OSM and the Mined Land Reclamation Office immediately of the subsidence and take necessary steps to safeguard the area and our underground utilities. It is not necessary for you to try and remember all of the offices of either the State or Federal Government to notify in the event of a problem. Simply call the City Safety Office and proper notification will be made.

On October 3, 1983 this office advised the U.S. Department of Interior, Office of Surface Mining that they would enter into a cooperative agreement to assess current land uses within the City in those areas which have been undermined during past coal extraction operations. The results of this study would be the preparation of reproducible land use maps which could be overlayed upon the original mine maps. A second portion of the study would assess existing City and County regulations, or the need therefore, with regard to surface development in the areas overlying abandoned coal mines. From this study would come recommendations for any desirable changes, updates or modifications to existing City and County regulations regarding control of development in such areas. These maps have been prepared and are available at the City Safety Office for review. Concurrent with this mapping program was a study funded by the State of Colorado Division of Mined Land Reclamation to evaluate the potential for future subsidence associated with abandoned coal mines in our City. The interest of this investigation was to delineate the type and probability of future subsidence events in order to anticipate the costs of future subsidence events, and serve as a basis for the development of a subsidence insurance program. This study consisted of 4 general phases.

1. Review and integration of existing data.
2. Field exploration and laboratory testing.
3. Engineering analysis of subsidence potential and
4. Evaluation of subsidence abatement and remedial actions alternatives and costs.

The field program consisted of drilling about 120 rotary boreholes in 8 prioritized zones to evaluate conditions within the abandoned mines. Based upon this study, the following conclusion and recommendations were reached.

1. Although abatement of shafts and slopes may not prove to be cost effective, the hazard to public safety from these structures warrants special consideration for abatement prior to an actual subsidence event.

2. Since the exact location and magnitude of subsidence cannot be predicted, a wide-spread program of subsidence abatement (i.e., mine backfilling, etc.) under existing residences is not recommended. Instead a subsidence insurance program, which would insure homeowners up to the market value of their property and provide for remedial action or repairs, should damaging subsidence occur, is highly recommended.

3. Removal or replacement of utility lines in the high hazard zones is not recommended. Although there is a high probability of future subsidence, the history of the study area indicates that damage to utilities has not been sufficient to cause a public safety hazard. However, the types of measures outlined in the report to protect utilities are recommended for all utility lines installed in the future. These types of measures should also be incorporated into building codes. Regardless of the measures taken or not taken, a potential for utility damage which could cause a public safety hazard does exist in the study area.

Unfortunately from any study of this nature the thoughts of the homeowners are varied. They consist of feeling their property has been devalued by the location of a mine under their house or adjacent to it, resale would be jeopardized, and that there home or themselves could sink into an abandoned shaft or room. The public perception in many of the cases feels the government has done it to them again. The only thing we have done is explore just a little more the conditions that exist and did exist under their homes prior to the study.

Perhaps the best explanation of their fears is the "fear of the unknown" or "what I don't know won't hurt me". The City feels based on all of the existing studies that we may be better equipped to sensibly predict the outcome of our subsidence zones and to build over or around any potential problem area. If this is accomplished we would then feel our efforts were not in vain regardless of any adverse public perception.

KEY ADMINISTRATIVE ASPECTS OF SUBSIDENCE ABATEMENT PROJECTS

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ABSTRACT

Currently the State of Wyoming's AML Program is administering nine subsidence abatement projects. The projects include four hydraulic backfill contracts and five drill and grout contracts. Three of the contracts have been completed and the other six are in various stages of completion.

The Wyoming AML Program is structured such that the investigation, design, and construction management is done by consulting engineers. The investigative work and the design have been completed or are in the process on the above mentioned projects. Construction management is ongoing. During the administration of these projects, it became apparent that not only is the design of vital importance, but also many "non-engineering" items play a key role in the projects overall well-being.

Issues such as public inconvenience, public conception, landowner agreements, design quantities, and construction management must be given equal importance and dealt with in a timely manner, along with the design. All to often all energy is directed towards the design and ultimately the bid document. The engineer and administrative personnel must also concentrate on external aspects. The "non-engineering" aspects have the ability to alter or even change the design and must be addressed prior to, during, and after the design phase.

INTRODUCTION

As the railroads headed west across Wyoming, coal was needed to supply power to the locomotives. The supplying of coal left vast areas of underground coal mines. With the disappearance of the steam locomotives another sight, mine subsidence, is becoming familiar to those people living in towns built above the old mines.

Wyoming has seven communities which lie completely or partially above abandoned coal mines. The communities vary in size from a few hundred people to over 20,000 people. Each community has had varying exposure to mine subsidence. Some communities have only seen subsidence events in open fields which have not adversely effected anybody. Other communities have witnessed entire homes being destroyed by mine subsidence. Those communities with a strong history of mine subsidence problems had an influence on the Wyoming AML Program. That influence led the Wyoming AML Program to pursue an active mine subsidence abatement program.

Wyoming's subsidence control program includes projects that range from stabilization of a single structure to 200 acres of residential area. Both grouting and hydraulic backfill techniques have been used. The design of the subsidence control technique requires various degrees of investigative work and research. Wyoming utilizes private engineering consulting firms to do the investigation, design and construction management of a subsidence control project. Each project that is conducted seems to present new problems as well as some reoccurring common problems. Some problems, such as, public inconvenience will occur in varying magnitudes dependent upon the size of the project.

During the administration of these projects, it has become apparent that not only is the design of vital importance, but also many "non-engineering" items play a key role in minimizing problems. "Non-engineering" items being defined as those items or tasks that are done in conjunction with the actual design but are not normally thought of as an engineering skill. In other words, there are areas associated with subsidence control which fall more into the administrative tasks. The administrative aspects have a tendency to fall between the cracks or are given a lesser priority as the design is compiled. Various administrative tasks and legal aspects will be identified as related to the investigation, design and construction management phases of a subsidence abatement project.

INVESTIGATION PHASE

As with most projects, the best way to proceed into the investigation phase is to gather the existing information. When dealing with mine subsidence the obvious information needed starts with mine maps. Mine maps can be found in a variety of locations. A good place to start is at governmental agencies. Agencies such as the Bureau of Mines, State Mine Inspectors, Department of Geology, universities, or regulatory agencies have provided maps in the past.

From governmental agencies the source of mine maps becomes more difficult and requires some ingenuity. The mining company may still be in existence. If not, a company may have bought the previous company and may have kept the records. The railroads may have had a subsidiary conduct the mining. Often times a request to the railroad company to go through their archived files can turn up information. It should be noted that this is easier said than done. More unique sources may need to be tapped. For example, a local historical society can provide not only mine maps, but also photographs of the old mines. The current mineral owner may have maps. Also, it is not uncommon for active mines in the areas to have maps. If names of people who worked in the mine can be obtained, it does not hurt to visit with them if they can be found.

An individual who worked in the mine can be an invaluable source of information. Generally this individual can be hard to find. A visit with a person familiar with the mine can provide many pieces of information that can help solve the puzzle. Many times maps will not show areas that were pillar robbed or areas that were mined but not mapped. Information such as ventilation closures, fault zones, poor quality coal areas, or poor roof conditions can aid the engineer in the design of a subsidence control project. A word of caution should be given to the person interviewing the old miners. Memories have a tendency to fade with time and some information should be taken with a "grain of salt".

Another source of information is the review of the surface above the mine. Past subsidence features can provide a good indication of the mine conditions below. Many times old surface subsidence features have been covered up by development or repair. Old aerial photographs or topographic maps may identify these features. Also, newspaper reports can help identify some structures damaged by subsidence events. For example, a local paper carried the story of a truck carrying a circus elephant falling into a subsidence sinkhole adjacent to the railroad where they were unloading the circus train. Likewise, owners of structures may be able to relate past subsidence experience near their property.

To culminate and refine the information obtained a subsurface investigation is recommended. The State of Wyoming generally utilizes drilling. However, with the recent development and refinement of other techniques, drilling is no longer the only option. Newer processes to define underground voids, such as resistivity, may be utilized. Drilling offers the best results, but generally comes with the highest price tag.

The subsidence control projects conducted in Wyoming have all had some investigative drilling done. I would encourage some type of subsurface investigation. The inhibiting factor associated with subsurface investigation is the cost. While considering the cost associated with a subsurface investigation one must also look at what information is needed to produce a quality design. The amount of unknowns associated with an underground mine can be substantial. By conducting a good comprehensive subsurface investigation the unknowns can be minimized. A drilling program will also help to identify present mine conditions. For example, the degree of roof collapse can be better predicted with the drilling data. This, in turn, will have a bearing on the design and method of subsidence abatement. In a similar fashion it will help define actual mining limits which can vary greatly from what is identified on mine maps.

As the investigation information is compiled into a report, the author should remember who will be the readers. If the report is going to be presented to the public, it should be written such that the average homeowner can understand the complex situation surrounding mine subsidence. The reader (public) needs to be made aware of what facts have a direct bearing on him. Both the pros and cons associated with subsidence control projects should be outlined. For example, the public should be made aware of the inconvenience associated with construction work of this type. Dust and traffic problems seem to be the inconveniences which cause most complaints.

Another factor which should be considered is how the information will be used. Because of the influence subsidence has on potential property buyers, the information may turn into a "real estate guide" for the city. Realtors will use the information as a guide to determine what areas are susceptible to mine subsidence. Likewise, appraisers may inflate or deflate the value of property based on its location with respect to the past mining. These individuals are generally not educated in the field of mining and may not be interpreting the report correctly. In the end it creates a problem which is usually dumped back into the hands of the reclamation agency.

Public input can be an important source of information. Obtaining public input can be a difficult task. The State of Wyoming generally holds public hearings. The attendance can vary from a few people to a packed room. I feel that a better approach is to address the town or city council. This ensures a fair size crowd and you are visiting with representatives of the community. The town officials also seem to have a better handle on what impacts the town more. For example, they may request that certain streets have work conducted only during hours which do no hamper traffic flow. Another factor which is helpful is the direct link town officials have to public input. Many times people are more apt to call a town official rather than the design engineer. Probably the most important consequence that can come from a public meeting is a source of new information. A new source of information not previously tapped can be brought forth by someone in the audience. With the input from the public the design phase can be initiated.

DESIGN

As design begins on a subsidence control project, most of the energy is focused on the engineering calculations and specification writing. The engineer should also incorporate some of the administrative and legal aspects in the specifications. The first area to examine and the most obvious is the actual surface constraints which may effect the implementation of the design. I suggest that a "walk-through" examination of the planned pipeline routes, mixing plant location and general working area be conducted. Many times as the engineer draws up the location maps he misses items because they are not shown on the base map.

An example of the above situation would be the utilities. Overhead power lines may limit drilling access. Extremely crowded utilities corridor may prevent locating an exploration hole in the preferred location. Buried pipelines may have to be ramped over. From the problems associated with utilities the next area to examine is associated with traffic.

Traffic flow should be examined on heavily traveled streets. Detours may be necessary. Also look at the inconvenience to homeowners. For example, if a slurry line blocks the access to a garage, the homeowner will more than likely complain. However, if this is discussed prior to actual construction, the homeowner may be willing to "live" with the inconvenience. Included with a traffic evaluation should be a visit with the city's engineer or public works director. They will be able to give the engineer some ideas for detours and the various requirements a city might have. At the same time it is good to find out where street construction will be occurring during the subsidence control project. This will minimize the chance for coincidental construction in one location and prevent delays to either contractor.

Street crossings should be reviewed with the city representative. Some cities prefer buried crossing to minimize the safety concerns while others prefer ramp type crossing. The ramp type crossings seem to create problems if not properly constructed. The long-term stability of a ramp crossing is poor and generally requires maintenance. However, ramp crossings can be easily cleaned up when no longer needed. The main drawback to buried crossings is the street repair needed following the extraction.

Traffic problems can also be minimized through the implementation of time constraints. Time constraints would limit the contractor's activities during a given period. An example would be to have the contractor shutdown his activities around a school when the children are leaving. This would serve two purposes. The first being the lack of traffic congestion due to construction, and secondly, the safety would be improved.

Time constraints can also minimize the nuisance complaints from residents. A limit on loud construction activities will help keep peace among the neighborhood. Drilling during early morning hours on Sunday is generally frowned upon.

Another item which can help eliminate inconveniences and nuisances to the public is the location of mixing plant or batch plant. The further away from the public the fewer the complaints will be. The more common problems associated with the plant site location are traffic, noise, and dust. It is easy to see why isolating the plant site will greatly reduce the complaints. Dust problems will generate the most complaints. The prevailing winds should be comsidered in determining the plant site location.

Dust control should be addressed in the specifications. The construction manager needs to have adequate language in the contract to require implementation of a dust control system. The dust control system requirements will vary depending upon what material is being pumped or processed. A sand will generally require less watering than a clayish material. The burden of adequate dust control should rest on the contractor's shoulders since he is the source and has the capability to correct the problem.

Anticipation of dust complaints or dust related problems is hard to accomplish during the design phase. A quick look at the project area can give the engineer an idea of what neighborhoods will require extra dust control. A neat and well kept neighborhood is more cognizant of dust. Traffic in alleyways may be enough to cause citizen complaints. An area which has paved roads will not create as many complaints.

CONSTRUCTION MANAGEMENT

As the mobilization for construction begins I would recommend the owner and engineer implement a preconstruction survey of structures to be affected. The preconstruction survey should be conducted in similar fashion to a preblasting survey. If a mine is going to conduct blasting operations in close proximity to homes or structures, a preblasting survey will be done to determine the existing status of that structure. The preconstruction survey serves the same purpose of identifying the existing conditions of the structure.

The preconstruction survey should include such items as the owner, the address, existing damage, photos, diagrams and potential problems. Any damage to walls, framing, foundations, and concrete slabs or sidewalks should be recorded. Photographs taken of existing damage with a measurement reference (i.e., ruler) provides a good record. Also, measurements of cracks should be recorded. This will allow for comparison if a complaint or concern is registered. The engineer can then go back and remeasure cracks to see if movement has occurred.

The preconstruction survey will serve many people in different ways. It will provide the contractor assurance that he will be held responsible for damage caused by his construction activities. For example, a piece of sidewalk may be fractured or cracked by drilling activities. The preconstruction survey should indicate if this condition existed before his operations and, therefore, answer the question of responsibility. The contractor can also use that same information to identify situations where protective measures will help minimize damage. The contractor may decide to use planking to bridge across the broken sidewalk in order to gain access without causing more damage. In a similar situation that homeowner may have installed new siding which should be protected. A tarp can be placed on the siding to eliminate damage from nearby drilling.

It is advisable to have the homeowner's input into the preconstruction survey. The homeowner will provide information that cannot be easily obtained by the engineer. The location of gas lines would be an example. At the same time the engineer should point out problems or potential problems to the homeowner. A common problem seen on most of the projects conducted by the State of Wyoming is poor drainage around the foundation. Many homes have rain gutters which direct the water into the foundation instead of away. Several homeowners have utilized the preconstruction survey as a "punch list" of items to repair around their home. The homeowner should also be asked if there are any particular items which should be avoided. It is surprising how many "prize" hedges or plants can exist in a person's yard.

Along with providing protection to the homeowner, contractor and the state, the preconstruction survey also provides an introduction mechanism to open up communication. During the survey the homeowner has the opportunity to ask questions about the grouting or slurry process being utilized. The question and answer session will give the homeowner a good idea of the construction process. When the construction begins the homeowner will generally be more receptive and will come out to view the operations. The public relations involved with operations around an individuals home should not be underestimated.

Another way to keep the people informed is to conduct "block meetings" prior to starting construction in an area. During the meeting people can be introduced to the on-site engineer and the contractor. This is a good time to explain the project and the construction process to be utilized. Photographs and visual aids are useful in explaining what is going to take place. One tool that has worked well is the use of video tapes of the mine workings and the construction process. For example, a video tape of the construction of a grouted gravel column taken with a down hole T.V. camera seems to work well. The people can see the process first hand without trying to visualize it themselves. Many people have commented that the mine did not look anything like what they had pictured.

Communication with the people affected by the project plays an important role in the construction. People should be notified when work is going to be done on or around their property. For example, if their driveway is going to be blocked for a period, that person should be notified so that the inconvenience can be minimized. In a similar fashion a notice in the paper can alert people if a street is going to be blocked off. If people can be notified prior to creating an inconvenience, that inconvenience will become less of a problem and fewer complaints are likely.

In conjunction with the public relations and communication tasks of a subsidence control project, a method for dealing with complaints should be established. The most common way to eliminate complaints is by having a quick response to a problem. The on-site engineer should be prepared to respond to complaints. Even if the complaints cannot be quickly remedied, a visit to and discussion with the complainant lets him know people are aware of the problem and something is being done.

Another area which should be monitored closely during construction is the safety of the operation. Not only should the contractor's operations be monitored but more specifically the safety of citizens in the area where work is being conducted. Most of the contractors working on Wyoming's subsidence abatement projects are not used to working in highly populated residential areas. Practices which do not create safety concerns in an isolated area may have to be modified to fit an urban setting. For example, drill casing laying on a street can be very inviting for children to play on. On one project children rolled a short piece of sixteen inch casing down an inclined street. Along this same line the contractor has many "spectators" around his equipment. Care should be taken to insure that people stay at a safe distance.

Traffic safety should also be monitored. Warning devices should be installed and maintained around hazardous areas. Nighttime traffic is especially dangerous when men and equipment are working in streets. Flashing warning lights and signs should be utilized. It will also be necessary to do periodic checks on the warning devices since they have a tendency to be moved by children. Generally the traffic control will be a site specific requirement but the engineer needs the ability to require the contractor to place warning devices when and where they are needed.

SUMMARY

As Wyoming's AML Program continues to administer subsidence abatement projects, the importance of the "non-engineering" aspects seem to increase. It has become evident that "non-engineering" tasks associated with a design need greater attention. Both the engineer and administrator of a subsidence control project need to do a full evaluation of the tasks described within this paper. Since each project seems to generate its site specific problems, the engineer and administrator must involve themselves in a guessing game to identify potential problems. Even if all problems can be foreseen, the early identification of the problem and the incorporation of a remedy into the design will greatly reduce the "headaches" associated with a subsidence control project.

MINE SUBSIDENCE INSURANCE FOR COLORADO: A RISK MANAGEMENT APPROACH

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ABSTRACT

The State of Colorado is in the final stages of developing a Subsidence Insurance Program which will be operated by one or more private insurance companies. The states involvement is necessitated by provisions in the federal enabling legislation for the program. Also, no specific subsidence risk insurance is available in the market place, today.

Last year during the federal budgetary process, PL 95-87 was amended to allow states with approved Abandoned Mine Reclamation Programs to develop "self-sustaining, state administered coal mine subsidence insurance programs. Our response to this opportunity has included the following efforts: Reviewing existing insurance programs in other states; meeting with the commissioner of insurance in Colorado to resolve programmatic and regulatory issues; coordinating with representatives from all segments of the insurance industry including individual insurers and their local and national trade associations; completing a land use evaluation and subsidence hazard data base for the major developed and undermined areas in the state; and, performing actuarial analyses of expected costs for insuring homeowners and developing insurance rates and a risk analysis of the potential for adverse development for this coverage.

Work to be completed in the near future includes finalization of actuarial work; submission of a grant application to obtain funds necessary to implement the program; negotiating and executing an agreement with a major insurance broker for full brokerage services; preparation of a detailed plan of operation for the program; obtaining

necessary approval from state regulatory officials; and, marketing the approved program. These activities are scheduled for completion by June, 1986.

This paper describes Colorado's Mine Subsidence Insurance Program Development process and provides an early view of its plan of operation.

INTRODUCTION

Mine subsidence has been recognized in this country for over two hundred years. Mine subsidence is the sinking or distortion of the ground surface as a result of the collapse of underground mine workings. A serious problem arises when structures not designed for the ground movements associated with subsidence are built on undermined areas. The damage to homes resulting from subsidence may involve major foundation and structural elements. Also, utilities such as natural gas lines may be broken during subsidence events resulting in significant hazards to public health and safety.

There are nearly 50,000 acres of undermined land in the rapidly developing front range urban corridor affecting more than 4,450 undermined structures in the Boulder-Weld Coal Field and over 3,000 structures in the Colorado Springs Coal Field. Approximately 25,000 people are directly affected by mine subsidence hazards along the Colorado Front Range.

No insurance coverages designed specifically to address the peril of mine subsidence are sold in Colorado. Homeowners are forced to bear the financial burden of whatever repairs are necessary. No Federal or State programs provide aid to homeowners whose residences are damaged by subsidence events.

SUBSIDENCE ABATEMENT

The problem of mine subsidence has been addressed in various ways over the years. These methods include abatement techniques, mitigation measures and structural repairs. Abatement techniques are those which have been developed to prevent or eliminate the occurrence of mine subsidence. Subsidence abatement measures are aimed at area-wide stabilization techniques including various types of mine backfilling activities using pneumatic or hydraulic methods to inject fill material such as coal waste, sand, fly ash or grout. In cases of shallow mine workings the possibilities of excavating the overburden to the floor of the mine and replacing the material as compacted fill is a possibility. Also, several attempts at blasting down the old mine workings have been attempted using explosives to collapse the mine roof to accomplish void filling.

Site-specific stabilization alternatives include grout columns which may be constructed to stabilize an individual surface structure or a small group of structures. This procedure results in a non-compressible cone of cemented fill between the floor and the ceiling of the void with a column of grout extending from the slab to the earth's surface. Providing deep foundations for structures using caissons from the foundation to the strata beneath the mine floor also may be used to stabilize specific structures.[1]

Abatement measures are costly when applied on an area-wide or site-specific basis. These methods are not 100 percent effective or guaranteed to eliminate future subsidence, but most observers agree that backfilling programs and structural stabilization procedures help to reduce the magnitude of future potential subsidence. Several subsidence events are thought to have been induced by backfilling programs.

Mitigation techniques have also been developed to provide new and existing structures with varying degrees of resistance to subsidence when it does occur. These methods include trenching around structures and backfilling with compressible materials, building sectioning to provide flexibility, taping to prevent safety hazards associated with breaking glass, shoring, reinforcing and jacking structures. Architectural measures to mitigate subsidence damages generally are aimed toward providing highly rigid or highly flexible foundations and structural elements. These measures are most effective when incorporated during construction of new buildings.[2]

Frequently, subsidence damage to structures is repaired by homeowners or structural contractors. These repairs may be quite costly. Repairs may involve foundation repairs, interior wall repairs, shoring and bracing and a myriad of interior finish repairs. Severe subsidence damage to homes may result in a total loss of the structure since the cost of repair can easily exceed a home's value.

INSURANCE ENABLING LEGISLATION

The heavy financial burden upon homeowners for providing repairs to subsidence damaged structures led to the development of several pioneer subsidence insurance programs. These programs offered a mechanism for managing the risk and financing the cost of repairing subsidence damages. Insurance appears to be a more cost effective response than abatement methods which have been developed to reduce or eliminate subsidence hazards because only a portion of undermined areas experience problems.

In 1985, Congress passed enabling legislation for mine subsidence insurance programs by amending section 401(c) of PL 95-87, the Surface Mining Control and Reclamation Act of 1977. The legislation authorizes the development of self-sustaining, State administrative programs to insure private property against damages associated with inactive coal mine subsidence. The State of Colorado has responded to this opportunity by carrying out community based mine subsidence hazard investigations along the Front Range, as well as insurance feasibility studies aimed at the development of a mine subsidence insurance program. The goal of State involvement has been to make it possible for the private industry to enter into this unfamiliar risk area by performing hazard assessments and actuarial studies which are required by underwriters prior to insuring a specific peril such as mine subsidence.

EXISTING SUBSIDENCE INSURANCE PROGRAMS

Colorado's effort toward developing a mine subsidence insurance program began with a review of existing programs in other states. There are three operating programs. A description of them follows.

Pennsylvania Mine Subsidence Insurance Program:[3] The Pennsylvania Mine Subsidence Insurance Program is by far the oldest program in the country. It was established in 1961. The Pennsylvania program is a public insurance program. The program is located administratively within the Department of Environmental Resources. All aspects of the program are handled by employees of the Department of Environmental Resources. These services include pre-policy inspections, policy sales, claim adjustment and special engineering evaluations for difficult and complex claims.

When a subsidence event occurs, a Department engineer determines the cause and origin of the damage and decides whether the loss is eligible for insurance. Then a Department adjuster estimates the cost of repairs for the damage. If the estimate is less than $4,000.00, the homeowner may select a contractor to provide the repairs. No bids are necessary in this case. A $500.00 deductible is attached to the settlement of the claim. If the estimate of the repair exceeds $4,000.00, then the homeowner must get at least three bids and select the low bidder for the repair project. However, the Department prepares the first bid or cost estimate. This policy has led to numerous disputes during claims/settlements. Up to 75 percent of the people who experience losses due to subsidence, repair their own damages after receiving the settlement check from the insurance program. In the past, a significant number of people took the money but did not perform any repairs. Now an agent checks to see that damage has been repaired. An estimated five million people live over abandoned mines in Pennsylvania. Even so, only 26,000 subsidence insurance policies have been sold in the state.

Presently, claims are coming in at the rate of 6-10 per month. During the last fiscal year over $800,000.00 in claims were made. Previously, $500,000.00 was the maximum level of claims in any one year. The upsurge in claims is attributed to increasing rates of subsidence in the bituminous region around Pittsburg.

Before issuing a policy, the Department does a thorough inspection of the property to determine any prior or existing damage. Extensive photographs of the property are taken. A letter is prepared for the homeowner which documents pre-existing damages with cost estimates for their repair and an exclusion from coverage for those damages. However, given an enrollment rate of 250-300 per month, pre-policy inspections are not always possible.

The Pennsylvania program issues subsidence insurance policies on a basis of extreme "adverse selection". Virtually everyone who has a subsidence insurance policy in Pennsylvania is subjected to a real risk from subsidence. Other states which are able to spread the risk for subsidence to a large population not really exposed to the hazard, have a greater ability to pay higher amounts for claims and to pay claims with less discrimination than does Pennsylvania. Even so, each existing program operates within the commonly accepted norms of the insurance industry. The philosophy in Pennsylvania is to put a structure back the way it was, but not to provide an improvement to the structure or the ground supporting the structure. Also, the premiums for coverage are higher than other states with subsidence insurance programs. For example, $100,000.00 coverage for a single family residence for one year costs $89.00. This is a rate of 9¢/$100.00 of coverage. The same coverage for a commercial building costs $354.00.

One feature of Pennsylvania's program is the fact that they often add a surcharge of 25 percent of the premium in areas which are scheduled for backfilling or flushing operations. It has been their experience that after backfilling (subsidence abatement) operations there is a noticeable increase in the incidence of subsidence events.

There is some difficulty in quantifying the cost of the Pennsylvania program over the long-term. While claims and losses are paid from the subsidence insurance fund, the administrative costs of the program are sometimes paid from the State's general fund. When there is a surplus in the insurance fund, the administrative costs are paid from it. In recent years the program has been self-supporting.

The Pennsylvania Mine Subsidence Insurance Program is comprised of a board which consists of the Secretary of the Department of Environmental Resources, the Treasurer and the Commissioner of Insurance. The Board meets twice a year to review the fund status, to make any needed change in rules and regulations and to approve the budget prepared by the staff. Otherwise, the State program manager is in charge of day-to-day operations.

<u>Illinois Mine Subsidence Insurance Program:</u>[4] The Illinois Mine Subsidence Insurance Program began in January of 1979. This program is best described as a private reinsurance mechanism for insurance companies which provide the primary subsidence insurance coverage to the public. The reinsurance program is connected to the Illinois Fair Plan. The Fair Plan was established in 1968 during the civil riots which ensued after the assassination of Martin Luther King. The Fair Plain provides a mechanism for placing high-risk home insurance policies for structures in areas which otherwise could not be insured. The Mine Subsidence Insurance Program is separate from the Fair Plan but reliant upon its administrative facilities. The Illinois program operates with a minimal staffing pattern, which

includes a part-time accountant and part-time secretary. The manager serves under the direction of the Mine Subsidence Insurance Board.

The membership of the Board consists of five representatives of the insurance industry which are nominated by the various insurance trade associations which operate in Illinois. The Governor then appoints four additional members to the Board which represent the various interest groups which are affected and concerned with the mine subsidence insurance program (e.g., banking and lending institutions, real estate agents, homeowners, consulting engineers, etc.). The Illinois program is run entirely by the insurance industry. The State Insurance Commissioner has oversight responsibilities for the subsidence insurance program as he does for all insurance activities in the State.

In Illinois, licensed insurance companies were given a mandate to sign reinsurance agreements with the Industry Placement Facilities' Mine Subsidence Insurance Board. Private insurance companies provide coverage to homeowners, but they are not responsible for any losses due to subsidence damages. The Industry Placement Facilities provides 100 percent reinsurance to the companies that issue subsidence insurance policies.

The Illinois program operates in the following manner. When a homeowner notices damage to his house which he thinks was caused by mine subsidence, he generally calls his insurance agent first. The agent then sends an adjuster to the home who makes a preliminary determination to the cause and origin of the damage. If the damage appears to be caused by subsidence, and the necessary repair is fairly obvious, the adjuster settles the claim with the homeowner. On a quarterly basis, the company reports its losses attributable to claims, and its income from premiums (less a 30 percent ceding commission). If a company owes money because premiums collected exceed losses paid, then it mails a check to the Mine Subsidence Insurance Fund. For subsidence events or ground movements that are difficult to interpret, a consulting adjuster whose specially trained by geologists and engineers may be called in to investigate the claim. An engineering firm may be called in to determine whether subsidence is the cause of a particular structural damage. Such specialists are available on retainer and their services are reimbursed from the Mine Subsidence Reinsurance Fund.

There is an incentive to properly settle claims since the Illinois program is operated entirely within the insurance industry. Claim settlements have been in line with the damages which have been observed and repairs have been well-targeted to abate the problems without creating undue enrichment to any homeowner. When compared with the Pennsylvania program, Illinois sells a high volume of mine subsidence insurance policies. This program is blessed with a very "favorable selection" of policy holders because the risk is spread to large numbers of homeowners who are not demonstrably at risk from mine subsidence. This is because subsidence insurance is automatically rolled on to homeowner policies in counties where at least one percent of the land surface has been undermined. It is estimated that less than 30,000 homes are directly at risk from mine subsidence, and yet almost 300,000 subsidence insurance policies have been sold. While mine subsidence insurance is not mandatory for homeowners (waiver forms are enclosed with the first premium), the insurance coverage is available at a low enough cost that few homeowners take advantage of the waiver, even though they are not at risk.

The maximum coverage is $50,000.00, which is available for a premium of $18.00. However, new legislation may raise the limit to $100,000.00 next year. Recently, the Illinois program had a $9 million premium surplus for a reserve against losses. The I.R.S. has ruled that this rapidly growing "private" fund is subject to taxation.

In Illinois, no pre-policy inspection of property to be insured is performed by the insurance company. If a claim is made, a determination of whether the damage is pre-policy or post-policy is made by a qualified adjuster or an engineer. The insurers in Illinois decided that pre-policy inspections were very expensive and that insurance premiums would have to be adjusted upward in order to do careful inspection before issuance of a policy. They found it cheaper to determine whether damage was pre or post-policy after a subsidence claim was filed. To date, there have been no law suits regarding their determinations of pre-existing damage. As the program has been in place for a longer period of time, the problem of pre-policy damage becomes minimal. Most insurance policies in Illinois were sold at the inception of the program, insurance coverage was automatically rolled on to existing homeowners policies.

The reinsurance facility providing mine subsidence insurance stays involved in the day-to-day processing of claims carried out by private companies only because it can be difficult to determine if a loss is due to subsidence. The facility has a right of recourse against the company in the case that it makes a "bad call". However, this right is rarely exercised, except where there is an appearance of fraud. Also, since the facility has a right of subrogation, it is in a position to recover losses if it can show that a coal company or anyone else has liability for the subsidence damage. One problem in Illinois is the fact that mineral rights convey broad and sweeping powers to those that possess them. The right to remove surface support and the right to build structures on the surface pursuant to the development of minerals, is often conveyed with mineral rights. This precludes many potential subrogation cases.

Currently, there is an average of one report of subsidence damage a day in Illinois. Of these reports, between 25 and 30 percent are determined to be related to mine subsidence. Where subsidence damages are apparent, many problems are determined to have occurred prior to the issuance of the policy. Like Colorado, Illinois has a significant swelling soils problem. In many cases, homes were not constructed properly given the soils conditions. Also, there are significant problems with soil piping and hydrocompaction. These factors can cause structural damages which appear to be very similar to the damages caused by mine subsidence. One phenomenon they have observed in responding to subsidence claims has been named "neighboritis". When one home sustains damage, all surrounding neighbors do careful examinations of their premises and notice problems too! The average amount per claim in Illinois is around $6,000.00. This compares to about $4,200.00 in Pennsylvania.

West Virginia Mine Subsidence Insurance Program:[5] West Virginia's Mine Subsidence Insurance Program was established in February, 1982. The West Virginia coal industry was apparently the motivating force behind the program.

The State Board of Risk and Insurance Management administers the Mine Subsidence Insurance Fund in West Virginia. This state agency provides reinsurance to private companies who actually sell subsidence insurance to homeowners. When the law was enacted, mine subsidence insurance was automatically rolled on to every homeowner insurance policy in the state. Waiver forms were provided with the first billing statement which allowed homeowners the option of waiving coverage. Subsequently, however, the law was amended so that mine subsidence insurance coverage was available only at the request of the insured. A dramatic decrease in the rate of enrollment and the amount of premiums collected occurred after the Act was amended. Indeed, the solvency of the program was jeopardized by the change in enrollment policy. Lobbyists for the insurance industry were responsible for the amendment. Apparently, insurance agents resented the state's entry into the insurance business. The amendment was counter productive because homeowners became confused and thought that they were covered when they were not. Accordingly, the Act was again amended in 1985 providing for a return to the original enrollment policy.

In West Virginia, subsidence claims are investigated by the State Department of energy and the Federal Office of Surface Mining. These agencies make the determination that damages are due to subsidence. If this is the finding the Administrator of the insurance program calls in a structural engineer to assess the damages and to recommend repairs. The claim is settled by the private insurance company on the basis of the engineer's report. Since the program was initiated a total of 128 claims have been submitted. Total incurred losses amount to 1.34 million.

West Virginia has a three member board for their subsidence insurance program. All three members are appointed by the Governor. The requirement for membership is five years of experience in the insurance business. The Board meets once a month to discuss program operations as well as the status of the Subsidence Insurance Fund. The Board hired a Risk Manager and Claims Manager to operate the program and to manage the fund on a day-to-day basis. The stipend for the board, the staff's salaries and the operating costs for the program are paid from the fund. claims for damages and claim adjustment costs are also paid from the fund. Subsidence insurance coverage is aimed at residential, owner occupied, single family dwellings in West virginia. The grounds surrounding the structure are not covered (i.e., sink holes in yards, damage to landscaping, etc.). It is a disaster or catastrophic type coverage which is not intended to restore the full retail value of the affected property.

Recently, coverage was extended to commercial structures and non-dwelling appurtenant structures. The premium rate schedule is \$10.00 for \$10,000.00 coverage and \$1.00 for each additional \$5,000.00 coverage up to \$23.00 for a maximum of $75,000.00 coverage. This is a rate of about 7¢/$100.00 coverage. The rate is not based on actuarial determinations, but rather an estimate of expected cost in the program. The ceding commission retained by agents for selling subsidence insurance coverage is 30 percent of the premium, or $13,000 per policy. If an independent adjustment company is used, the cost of claims adjustment can be passed on to the fund. The cost of in-house claims adjustment cannot be passed on. The West Virginia insurance program has a straight $250.00 deductible for all claims. Such a small deductible has led to numerous small claims for minor cosmetic repairs.

NEW AND DEVELOPING SUBSIDENCE INSURANCE PROGRAMS

Since Congress passed enabling legislation last year which provides financial incentives for states to develop subsidence insurance programs, a number of states have developed programs. The Commonwealth of Kentucky enacted legislation establishing a mine subsidence insurance program. The proposed Kentucky program is almost identical to West Virginia's program. The Mine Subsidence Insurance Fund will be housed in the State Treasury, and the State Board of Risk and Insurance Management will operate a reinsurance program which depends upon private companies to provide homeowner's policies and to settle claims.

The State of Ohio has enacted legislation which is a hybrid of the Illinois and Pennsylvania programs. Ohio will utilize their Fair plan to administer the program but a State Subsidence Insurance Board will control the program.[6] The states of Alabama, New Mexico and Wyoming have expressed an interest in developing subsidence insurance programs. The State of Colorado has been actively developing a mine subsidence insurance program.

SUBSIDENCE RISK ASSESSMENT

Over the past five years there has been a systematic and comprehensive effort under way in Colorado through the Inactive Mine Reclamation Program and Colorado Geological Survey, to identify and classify subsidence hazards throughout the state. This work has been based on several studies which were conducted in the middle-to-late 70's in response to state land use legislation passed earlier in the decade.[7,8] This subsidence hazard evaluation work has resulted in the development of a comprehensive bibliography of references pertaining to the mine subsidence in Colorado,[9] an Inactive Coal Mine Subsidence Resource document,[10] a complete set of land use maps at a scale of 1:50,000 or 1:24,000 which portray the actual extent of mining in each county with significant past coal mining activity, and detailed subsidence hazard evaluations for each undermined area along the front range urban corridor of Colorado.[11-14]

We are fortunate in this state to have a relatively complete set of underground mine maps for past coal mining operations. Certified mine maps were required of active coal mining operations as early as 1888 in Colorado. While inaccuracies exist on these mine maps, they do provide an excellent indication of the location and extent of most coal mining activity in the state. This knowledge of subsidence hazard areas presents a difficult problem for an insurance program, however. There is no legitimate way to spread the risk to homeowners not directly exposed to subsidence hazards. Colorado has an extreme adverse selection of potential insureds for its program.

The state's interest in developing a subsidence insurance program grew out of a volatile subsidence problem in the Foothills Coal Field in Jefferson County, Colorado. During the summer of 1981, the Jefferson County Geologist noticed commercial construction taking place in area known to be undermined. The construction was halted so that a proper subsidence hazard evaluation could be done. The county contracted with a geological consulting firm to evaluate the residential area adjacent to this construction area when local residents became concerned that their homes were also undermined. Examination of the underground mine map revealed this to be the case. The homeowners had not been informed when they purchased their lots or homes that any subsidence hazards existed. The State was called in to evaluate the threat of subsidence to these residents when it appeared that some of the structures were located over very shallow mine workings. At the same time, the homeowners organized and filed a major law suit against the county which had allowed development in this subsidence hazard area and against the developer.

The Virginia Mine Subsidence Hazard Investigation was undertaken in early 1982. The study showed that 44 homes were in a seven acre zone that could potentially be influenced by mine subsidence. Eleven homes were located in a relatively severe subsidence hazard area. The homeowners looked to the State to take abatement measures to eliminate the subsidence hazard to public health and safety. The State evaluated a number of abatement measures for the Virginia Mine. The option of backfilling the mine and substantially reducing the subsidence hazard was evaluated in detail. Backfilling was ruled out as a cost-effective abatement alternative given the high cost (e.g., 1.2 million dollars) and a lack of assurance of success. The Virginia Mine is filled with saturated mud and rubble. It would be very difficult to inject fill material into the mud filled voids encountered during the subsidence hazard investigation. Also, backfilling this mine would have set an undesirable precedent as far as the state-wide reclamation program is concerned. With over 50,000 acres of subsidence hazard areas along the Front Range, it would be impossible to use this abatement approach in an evenhanded fashion for all subsidence prone areas.

Another constraint the State faced in trying to address the subsidence problems over the Virginia Mine was found in the enabling legislation for the Inactive Mine Reclamation Program. (The Reclamation Fund can be used to repair foundation problems or problems in the ground supporting structures but not to repair buildings.) While there were no evident problems in the ground or severe foundation problems in the structures overlying the Virginia Mine, there was a significant potential for future subsidence. Because of this lack of existing subsidence, other abatement remedies including deep foundations and grout columns, were ruled out, as well. The end result of this prolonged subsidence hazard investigation process was the establishment of a subsidence monitoring system. The monitoring system allowed observation of the ground overlying the Virginia Mine to assess the development of subsidence features. No specific remedies to the affected homeowners were made available. This entire process was frustrating and unsatisfying to homeowners, local officials and State officials alike. It was the lack of specific remedies for affected homeowners that led to a finding by the Mined Land Reclamation Board that the State should pursue the development of a subsidence insurance program.

INSURANCE PROGRAM DEVELOPMENT

Development work for a subsidence insurance began with the review of existing insurance programs in other states which was described earlier. Then, in February of 1984, a Subsidence Insurance Ad Hoc Committee was convened to consider the possibility of public/private sector cooperative effort to provide homeowners subsidence insurance coverage. The insurance industry representatives were generally not in favor of a joint venture. The Ad Hoc Committee formed a sub-committee comprised solely of industry representatives to pursue the development of a private subsidence insurance product to provide coverage to homeowners.

In April of 1984, the subcommittee announced the availability of two separate products which would cover subsidence. These products are certificates of insurance designed to cover perils not included on a homeowners all risk policy (i.e. HO-3 policy). These, so called, Differences in Conditions (DIC) policies are exclusionary in the sense that they cover all risks except those covered on a HO-3 policy, and those perils specifically excluded on the certificate. Since these were unveiled, very few homeowners have purchased these policies who are concerned specifically about subsidence hazards. One explanation for this observation may be that subsidence is implicitly rather than explicitly covered under the DIC Program. Another reason could be the price of the DIC coverage. Presently the rate schedule is about 22¢ per hundred dollars worth of coverage ($220.00 for a $100,000.00 home). Also, these policies cover numerous other perils such as landslide, flood and rockfall, which may not be of concern to most homeowners.

Because the Inactive Mine Reclamation Program is responsible for addressing the hazards arising from past coal mining activities (including subsidence) the low participation in the DIC Program is of concern. Subsidence insurance has been selected as the most appropriate response to the hazard, and yet, at-risk homeowners are not purchasing the only available coverage.

A pure public sector approach to providing mine subsidence insurance was evaluated, using an intergovernmental risk sharing pool mechanism. In late 1984, however, legal restrictions were encountered which apply to public sector pools limiting coverage strictly to public sector risks and liabilities.

In January, 1985, the State contracted with a risk management and actuarial consulting firm to carefully evaluate the subsidence hazards and the feasibility of subsidence insurance program for Colorado. Work completed to date includes:

- A review of statutory and regulatory limitations to program development;
- Meetings with regulatory officials in the Colorado Department of Insurance;
- Interviews with broker firms interested in providing services on a contractual basis;
- Actuarial analysis of expected costs for insuring homeowners. Expected costs include premium rates and a risk margin for potential adverse development (i.e., excessive losses) under this coverage.

For Colorado's proposed insurance program subsidence severity was modeled based upon engineering data concerning the predicted magnitudes of subsidence events and the structural characteristics of the property to be insured. The actuarial model for the program is based on an engineering analysis of 2400 subsidences over a 45 year time frame. The model provides a frequency analysis of expected subsidence given depth of overburden and time since mining. Subsidence frequency was based upon an actuarial analysis of historical and photographic records of occurrences. The premium rates are derived directly from the frequency and severity analysis.

The actuarial studies indicate that the State can expect subsidence events to occur at the rate of about 12 per year with an average claim of nearly $9,000.00.[15] However, a risk (confidence) analysis reveals substantial uncertainty in these figures. Therefore, a reserve against adverse development for this coverage is included in the expected costs for insuring homeowners.

At present, no legal or regulatory issues appear to constrain the development of a subsidence insurance program on a "contracted-out" basis in Colorado. The Commissioner of Insurance has been involved during the entire program development phase. It appears that a full service broker can be found through a competitive procurement process, to administer the program.

PROGRAM IMPLEMENTATION

Six major areas of activity must be addressed before an insurance program can be made available to homeowners in Colorado.

1. The State must receive the funds from a Subsidence Insurance Grant Application submitted to the Department of Interior. The grant application describes; how the program is State administered; how the

program will become self-sustaining; the specific coverages for private property; and a detailed projection of need and utilization.

2. The State must complete preliminary actuarial work which has been undertaken to refine expected cost projections, rates and deductible levels. Additional data from community wide subsidence hazard investigations will be available soon.
3. The State must select a broker who is capable of providing a full range of brokerage services and able to identify an underwriter or insurer to accept the program.
4. A plan of operation will be developed in conjunction with the broker so that all necessary insurance providers can be identified and a proposal can be submitted for approval to the State Commissioner of Insurance.
5. The program plan must be approved by the Commissioner of Insurance.
6. The program must be marketed to the general public.

PRIVATIZATION

A ten year financial projection of the program indicates it should become self sustaining within an eight year period.[16] If this is the case, a private insurance broker will have a strong incentive to take over the program at that time. The term "self-sustaining" means that the program is actuarially sound and the premiums paid by the insured parties are sufficient to cover losses and administrative expenses. The federal grant funds will cover program development costs and actual losses until the program becomes self-sustaining.

CONCLUSION

Mine subsidence insurance offers a mechanism for managing the risks and financing the costs associated with subsidence damages to property. Insurance is only part of an overall subsidence risk management program, however, it does not deal directly with the public health and safety hazards which exist in subsidence prone areas. These problems are best addressed prior to any development in mined areas. Detailed subsidence hazard investigations are needed prior to changes in land use in these areas. Building codes are necessary to insure buildings and utilities are constructed properly in undermined areas. Geologic hazard zoning can provide a powerful tool for controlling land use and corresponding public health and safety problems in subsidence areas.

Insurance approaches work well to protect against relatively rare, potentially catastrophic events, which occur at a predictable frequency. It can restore value to properties which become damaged by subsidence. The availability of insurance can also remove or lessen the stigma which can become attached to entire neighborhoods where subsidence events occur. Property casualty insurance provides the best protection against the most likely adverse effects of ground subsidence in developed areas. In undeveloped areas where subsidence is a concern, appropriate land use controls are the most effective means of reducing subsidence hazards.

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APPENDIX

GEOLOGIC ROAD LOG FROM DENVER FEDERAL CENTER TO MARSHALL, COLORADO

A Visit to the Boulder-Weld Coal Field and Some Considerations of Burning, Subsiding Coal Mines

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INTRODUCTION

The field trip goes to the southwest corner of the Boulder-Weld Coal Field, with accompanying description contained in this roadlog. The route originally was part of a field trip on geologic hazards in the Denver area, taken May 21, 1983, by the Colorado Scientific Society. The road log describes some of the general geology encountered along the route, but focuses principally on the hazards and problems of land use associated with abandoned underground coal mines with their potential for subsidence and spontaneous combustion.

The trip is about 52 miles in length and takes approximately one and one-half hours to drive, without stops, under normal conditions. The route goes through Golden to Marshall and Superior with return through the Leyden Coal Field. Optional side trips and short walks to example problem locations are mentioned in the text and discussion. Most of the sites for visit have been chosen for their public access on Boulder City parklands. Other specific problem areas that are on private land also have been identified along with the notation to seek permission prior to entry. The included photo of the Marshall area is labeled with the features discussed in the text, to facilitate location and visitation, and city parkland areas for public access.

Geologic maps and discussions of the geology in the Marshall area and along the route have been prepared by Van Horn (1972, 1976) and Spencer (1961). Additional discussions on the geology and geologic hazards of the Denver area can be found, respectively, in Hansen (1981) and in Costa and Bilodeau (1982). Also referenced is a report by Amuedo and Ivey (1975) on land use considerations in the Boulder-Weld Coal Field.

The Boulder-Weld Coal Field

The extent, nature, and development of the coalfield are discussed in detail by Herring et al. (this volume). The coal field begins at Marshall, where the first mining occurred, and extends northeast for approximately 25 miles. At Marshall the coal crops out and these exposures no doubt led to discovery of the field and early development as the coal market began and grew along the Front Range. Rocks in the field dip gently to the east, seldom more than 10 degrees, thus the coal seams become progressively deeper eastward. Depth to coal governs the ease of mining access, consequently mining began in the shallow seams of the western portion of the coalfield at Marshall and progressed to the northeast, where more expensive and technologically demanding deeper mines developed later. Mining in the field extends as far as Dacono and Firestone, a few miles east of Interstate 25. In its life the field has produced about 100 million tons of coal from approximately 100 underground mines. For comparison a large strip mine today may produce about 20 thousand tons per day or 10 million tons in a year. Some of the mines in the field, such as the Gorham Mine, are quite large, extending underground over a square mile. The coal is subbituminous B to C in rank, has a heat value of about 8,000 to 10,000 BTU/lb and averages about 0.4% by weight total sulfur both on as received basis. The usual method of mining was to mine out areas (rooms) of the coal seam, leaving supporting columns of coal (pillars) between the rooms. Further discussion of mining methods is included by Hart (this volume).

Six coal seams, named by number starting from the bottom upward, are identified in the coal field, although they seldom co-occur at a single location. Usually a single seam, commonly named the Gorham or Number 3 Seam, has been mined, although on occasion a second seam may be mined at the same locality. Multiple seam mining, for example, occurs in some mines near Louisville and Lafayette. Where mined, the Gorham Seam is commonly about 10 feet in thickness, although in places it is upwards of 20 feet thick but, also has been mined in places where it is as thin as 4 feet.

The coal seams occur in the basal 75 feet of the late Cretaceous Laramie Formation. The Laramie Formation is a nonmarine unit overlying the Fox Hills Formation, a transitional unit between the late Cretaceous marine shale (Pierre

Shale) below and nonmarine units above. The Laramie Formation varies in thickness from 100 to 500 feet and is overlain by the Arapahoe Formation, also late Cretaceous. The lithology of the two formations is difficult to define. This, along with the lateral and vertical inhomogeneity of lithology in the Laramie Formation, makes detailed stratigraphic correlation or structural interpretation most difficult in the Boulder-Weld Coal Field.

Subsidence in the coal field is discussed in detail by Herring, et al. (this volume). In summary, subsidence is an on-going process in the Boulder-Weld Coal Field and likely will continue for many decades, if not centuries or longer. Above the mine-out room, the roof rock eventually fails and stopes (falls) into the void of the room, occupying slightly more volume than before it fell (bulking). This process repeats and the cavity, in a sense, migrates upward, while progressively reducing in volume due to bulking of the collapsed rock. Eventually, the cavity will breach the ground surface if the overburden rock is sufficiently thin such that progressive bulking has not first filled it. Many other factors, such as pillar collapse, the presence of water, or the type of rock, can complicate the nature and extent of subsidence, hence the prediction of time and extent of subsidence becomes extremely difficult. What is known about the Boulder-Weld Coal Field, however, is that vast areas are undermined, including parts of many towns, and these areas will have to contend with a threat of subsidence for many years to come. Also, there is a relationship between fire and subsidence and it should be pointed out that mine fire accelerates subsidence, while subsidence opens additional airways to support combustion, thus the two processes are synergistic. Recommendations for reclamation of specific problems in the Marshall area are mentioned by Herring et al. (this volume).

Coal in the Boulder-Weld Coal Field is susceptible to spontaneous ignition, especially where it has been freshly worked and has ready access to air while in the mine or in waste dumps. The actual mechanisms of spontaneous ignition are unknown, but it seems that the presence of water enhances the tendency for spontaneous ignition. At outcrop the coal slakes and oxidizes too slowly for ignition. Thus, few burned outcrops exist in this coal field, in contrast to other coal-producing areas, for example the Powder River Basin in Wyoming. On this trip, however, we will pass by the single example of natural combustion of a large coal outcrop in the coal field.

The intent of this field trip is to illustrate some of the potential hazards associated with burning, subsiding coal mines. While only a few mines will be viewed on the trip, it should be remembered that there are approximately 100 coal mines in the Boulder-Weld Coal Field and about 10,000 abandoned coal and mineral mines in Colorado, thus the impact of mine subsidence on society from this problem is potentially immense. Remember, also, that Colorado is only one of the several states in the U.S. with this problem, consequently the dimensions of the problem are nationwide in scope and significance. In addition, many other countries in the world share this problem; mine subsidence indeed is a nontrivial problem of immense size and potential cost.

TRIP ROAD LOG

Incremental and total distances in miles

Increment, Total

0.0 0.0 Start from Cold Spring Park-n-Ride lot at Union Avenue and Highway 6. Head west on Highway 6, notice over the next 3 miles the spreading urbanization that has expanded westward. This was an undeveloped area only a few years past. The development is progressing higher up the flanks of Green Mountain, thus more and more buildings will be subjected to the foundation problems associated with slumpage and swelling clays in this area. Concern about coal mine subsidence has occurred over the mines located 10 miles southeast of here, at Kipling and Coal Mine Road, while coal mine fires, with fatalities, have occurred in mines 5 miles southwest along Rooney Road.

4.6 4.6 Highway 93 and 10th Street intersection with Highway 6 approaching Golden. Vertically-dipping Dakota sandstone lies on west side of highway with clay pit excavations, while the also vertically-dipping sandstone on east side is Fox Hills Formation, also with clay pit excavations. Several thousand feet of section of the interlying Pierre Shale have been removed here by the Golden Fault, a high-angle reverse fault. Note occasional small excavation pits on the west side of the highway. These are exploration pits dug in conjunction with clay mining in the area.

1.4 6.0 19th St., Golden. Clay mine pits still visible, particularly on east side of highway. Building over poorly consolidated soil filling in the pits has occasionally posed subsidence problems for student housing buildings at the Colorado School of Mines. Red soil in roadcut on west side is erosional wash from the Fountain Formation.

0.4 6.4 Abandoned, flooded coal mines in Golden lie east of here. These mines were worked in the 1870's using deep, vertical shafts to descend the length of steeply dipping beds to where the dip flattens out east of tight-radius folds in the Laramie. The beds have near-vertical dip for approximately 700 feet, depth, then in a tight-radius fold of a few hundred feet become nearly horizontal. The location of the mines will be visited on the return portion of the trip.

0.2 6.6 Approximately 1/4 mile east of Clear Creek. Contact exposed up canyon to west is between pre-Cambrian crystalline basement and basal part of the sedimentary section, here the arkosic sandstone of the Permian-Pennsylvania Fountain Formation. Over a billion years of history are missing in this nonconformity.

0.2 6.8 Crossing Clear Creek. Turn onto Highway 58 eastbound and exit at the first offramp, Washington Street. Old newspaper accounts of floods on Clear Creek recount stories of damage in Golden, including washout of bridges over the creek. These remind us that most of the large canyons along the Front Range can become disasters when hundred-year storm events occur as it did with Big Thompson Canyon. The downcutting and erosion of Clear Creek has bisected Table Mountain into North and South halves. On the outskirts of Golden note more excavation pits to the west, here searching for evidence of Holocene fault movement from evidence of disturbed alluvium. The Holocene movement along the Golden Fault is controversially argued. If such recent movement indeed has occurred then the possible seismic risk to Denver, Golden and Rocky Flats plant will have to be re-evaluated. Turn left (north) onto Highway 93, which here follows the trace of Golden Fault, out of town.

1.8 8.6 Hogback of Dakota sandstone occurs at 12 o'clock and low, reddish nub of Fountain Formation is in the foreground at 11 o'clock.

0.7 9.3 Pine Ridge Road intersection. North Table Mountain, comprised of Tertiary age extrusive mafic latite, lies to the east. Notice the well-developed columnar jointing at the top of the mountain. Clay strip mine scars are in the Dakota Formation to the west. The areas of dark soil also to the west, between the highway and the Dakota hogback, are loadout areas for coal mines that were worked here in the 1880's.

1.0 10.3 Overturned sandstone hogback of Fox Hills in foreground to west.

0.9 11.2 Highway proceeds uphill by dairy. Location and nature of the Golden Fault here is debated, with some interpretations contending that there is an overthrust salient exposed around the toe of this hill to the east.

0.5 11.7 Slides in colluvium are exposed in road cut at top of hill.

0.6 12.3 Hairpin in old highway can be seen at 12 o'clock across valley. The hairpin was added to the original highway to help smooth out the grade, but reworking of the switchback in 1959 reactivated slippage and the route was abandoned. Even today the road in this stretch is continually in need of maintenance.

1.2 13.5 Overturned hogback of Fox Hills Formation visible ahead at 10 o'clock.

0.7 14.2 Entrance to Leyden Coal Field on right through Leyden Gulch stream gap in the hogback.

0.9 15.1 Entrance to Jefferson County Landfill is on right. The pit is dug in Arapahoe and Laramie formations. At present this is the only active landfill for the county and necessitates long haulage distances with commensurately high costs. Pierre Shale (with slumpage) is visible in road cut north of the landfill entrance.

2.1 17.2 Entrance to Rocky Flats plant on right. Eastward, steeply-dipping beds in this area are obscured by pediment gravels but have been exposed and excavated to the east where the Fox Hills has been worked for clay. Most of the clay pits are now water filled. The projected outcrop of the Fox Hills in this area can be followed by the occurrence of occasional pine trees, which probably locate there because of improved drainage, parallel to the highway and to the east about 1/4 mile. The Cap Rock Coal Mine in the Laramie Formation, east of the highway and about 1/4 mile north of Rocky Flats Lake, was located in 45°, east-dipping rocks.

1.0 18.2 Rockwell wind energy research station can be seen at 2 o'clock. Straight ahead is the abandoned Ideal aggregate plant, which was kilning light-weight aggregate of the Pierre Shale taken from the excavation pit across the highway to the west. The supports of the rotary kiln are still visible.

1.2 19.4 Crossing Coal Creek. Fox Hills Formation lies to the east and here dips about 70° east. In the next two miles ahead, the Fox Hills is covered by pediment gravel, but when the formation emerges, the dip will have decreased to just a few degrees eastward, as we will have crossed the southward plunging axis of the tight-radius fold that occurs in the rocks along much of the Front Range.

0.9 20.3 Intersection of Highway 128 from east. Proceed northward to top of hill and overlook of Boulder. Notice the immense thickness of Pierre Shale which forms the nondescript valley between here and the flatirons in Eldorado Springs Canyon to the west. Much of this thickness was removed by the Golden Fault in the rocks to the south near Golden. The Laramie Formation is exposed in roadcuts as we proceed downhill. In the roadcuts notice the mixture and rapid alternation of thin beds of sandstone, shale, claystone, and coal, along with iron-rich concretions. Coal slack in the soil on hill to right identifies the load-out area of the Premier Mine.

0.2 21.5 Cross the Community Ditch. Look for Pine Ridge Fault between the Fox Hills and Laramie exposed in roadcut. This fault trends northeast and offsets the upthrown eastern block about 250 feet vertically from the western block. The fault offsets the mined coal seam from underground in the valley on the downthrown block nearly up to the top of tree-covered Pine Ridge to the northeast. The Community Ditch is the inflow to Marshall Lake, on top of the mesa a mile east.

0.4 21.9 Cross Davidson Ditch. Look 50 feet to east at the shutoff valve of the 800-psi high pressure gasline and notice the coal mine subsidence crater that lies only a few feet away to the north. The pipeline is undermined for 1/2 mile to the east by the Marshall No. 3 Mine. There is a concern that regional subsidence over this mine could lead to breaching of the pipe. From here to the liquor store the surface recently has had fill added as part of a reclamation project sponsored by the Office of Surface Mining. The reclamation is an attempt to seal off the access of air to a smoldering part of the Marshall No. 3 mine and halt the advance of the mine fire progressing toward the highway.

0.2 22.1 Turn into second driveway of liquor store and drive to the rear of the dirt lot in back of the store, facing Pine Ridge. Pause on the ripple-marked sandstone (sometimes referred to as the "C" sandstone of the Laramie Formation), which is an occasional marker bed above the Gorham coal seam. Just on the other side of the fence are several vertical, PVC pipes drilled into the workings. The pipes have been used to sample gases in the mine in conjunction with a gas tracer experiment (see Herring, et al., this volume). On Pine Ridge notice the exposed gradational contact between the Laramie at the top of the ridge and the buff-colored massive sandstone of the lower Fox Hills about half-way down. The mined coal seam on the upthrown block of Pine Ridge is about 4 feet in thickness, while in the valley, on the downthrown block the seam is up to 20 feet thick. The valley between here and Pine Ridge is completely undermined at depths ranging from 10 to 100 feet. Most of this end of the parking lot is undermined and the mine in places is smoldering, as evidenced by the issuance of steam from test holes drilled into the mine and the acceleration of snowmelt of this area. See the notes on side trips to the El Dorado Mine and Marshall No. 5. Take the additional side trips from this point, mentioned in the discussion at the end of the report, or continue out the driveway at the north end of lot, noticing the Gorham coal seam exposed in the cut for the driveway. Take the short north-trending stretch of Highway 170, turning to the east to continue. From the driveway northward notice the red, rubblized area on the right. This is burned, subsided rock overlying the Marshall No. 1 Mine, the original mine of the Boulder-Weld Coal Field. After turning east, the highway in the roadcut and for the next 1/4 mile lies on the abandoned Colorado and Southern railway bed constructed for haulage of the mined coal into Denver. The continuation of the abandoned railway roadbed can be seen in the valley ahead. Note the exposure of the Gorham seam in the southern roadcut and places in the northern cut where the coal has burned and baked the overlying rocks, indicated by red rock. The highway is completely undermined along this stretch.

0.6 22.7 Turn left (north) onto Cherryvale Road, noticing the disrupted asphalt north of the intersection. The road here was on fire in the early 1970's, ignited from the burning coal mine to the northeast, which has burned most of the exposed hillside.

0.1 22.8 Stop at the load-out area of the Peerless and Lewis Mines. Park on the west side of the road, across from the old winch, and, after obtaining owners permission, walk eastward up the hillside on the private land. New house here is located on the trace of the Fox Fault (see Herring et al., this volume for discussion). The Davidson Ditch has a history of subsidence here and has been rebuilt this year by the State Abandoned Mine Reclamation Project. The reclamation technique combines reinforced concrete lining with rock bolting to stabilize the ditch against future subsidence. The Fox Mine extends to the north, where it is accessible via city parkland, and the Peerless (also named Lewis) Mine was worked to the south. The winch of the Peerless is still in place and indicates that the main haulageway ran to the south in the direction that cable would spool from the winch. The main haulage way for the mine extends 1400 feet south to the foot of Pine ridge at a pitch of 8°. The Peerless Mine is comparatively shallow on this hillside, probably no deeper than 35 feet, and this shallowness has allowed the subsiding ground to exactly outline the underground room and pillar nature of the mines. To the south the mined area extends under Highway 170, across the valley, and to the foot of Pine Ridge. This mine was worked up until 1943 and since that time the mine periodically has been on fire. It is this part of the coal field that has received notoriety for burning and parts of it still smolder. Gas explosions, incandescent melted rock, and melted highways have been some of the more dramatic effects of the mine fire. For example, in 1977 a local resident stuck a wagon axle down into one of the flaming pits. When the axle was removed it was incandescent white hot and sparking, indicating a temperature in excess of 1000° C. Many times the local fire department has been called in response to explosions or fire plumes in the sky. This area is discussed in more detail by Herring et al. (this volume).

The area seems relatively uninhabited, thus the potential for adverse effects from fire and subsidence may appear rather minimal. However, keep in mind that this area is simply an example of what can happen over an abandoned coal mine and then remember that this coal field extends for miles under gaslines, major highways, parts of several cities like Louisville and Erie, and undermines the Marshall Lake Dam. Thus, the potential for widespread and serious hazard is considerable. Multiply this by all of the abandoned coal fields in the state and suddenly the dimensions of the problem increase tremendously. Return to vehicles and continue northward along Cherryvale Road. Notice the thick, massive sandstone lens in the Laramie Formation. Holes cut in this sandstone layer were used as storage rooms for blasting powder. Proceed along Cherryvale road northbound. Where the stretch of Cherryvale Road runs east-west note the new houses in the valley to the north. Some of these dwellings are located over or near old mine workings.

1.2 24.0 Abandoned mine operation buildings visible to west.

0.6 24.5 Cross over Denver-Boulder Turnpike.

0.8 25.3 Stop sign. Turn right (east) onto South Boulder Road (County Road 60). To north you can see Baseline Reservoir, Valmont Powerplant and Valmont Dike. As you continue eastward you cross fault-block alternations of Laramie and Fox Hills Formations. Mine workings and dump 1/2 mile to south are the Cracker Jack Mine.

1.0 26.3 (Private land) Quarry in clinker is visible at 11 o'clock and can be reached by parking at the end of Crannel Road to the east. Clinker is the rock that is baked during combustion of the underlying coal seam. Coal combustion alters the overlying rock and produces a variety of high-temperature, metamorphic minerals in the baked rock. Temperatures in the rocks here have reached as much as 1100° C, sufficiently high to produce anatexis of the sedimentary rocks and resulting in production of an iron-rich slag sweated from the sedimentary rocks. Notice that the hill of clinker is isolated from the surrounding erosional valley. The clinker is extremely resistant to erosion and has allowed the burned locality to remain intact while the surrounding softer rocks have eroded around it. While clinker and natural combustion are quite common to many other coal fields, this locality is the only occurrence of natural combustion in the Boulder-Weld Coal Field. The meter-thick soil above the clinker is unbaked, hence the soil age, here about 150,000 years, places a minimum age on the coal burn.

1.4 27.3 Turn right (south) onto 80th Street. This ridge is Davidson Mesa and is an uplifted fault block of Fox Hills sandstone, visible in the roadcut just before the top of the hill.

1.0 28.7 Burned coal dump of the Matchless Mine is visible about 1/4 mile to the east.

1.2 29.9 Superior interchange with the turnpike. Cross over turnpike and follow signs towards Superior (McCaslin Blvd.).

0.5	30.4	Coal dump of Industrial Mine visible on ridge to west. Continue southward, traveling upsection in the Laramie from the coal-containing section of the lower Laramie.
3.1	33.5	Intersection with Highway 128. Turn left (east).
0.3	33.8	Turn right (south) onto Indiana Street. Notice the pediment gravels for the next few miles. Rocky Flats Alluvium is Nebraskan (Early Pleistocene).
1.3	35.1	East entrance to Rocky Flats plant.
2.9	38.0	Stop sign intersection with Highway 72. Turn left (south) and cross underpass under railroad tracks.
0.3	38.3	Turn right (west) toward Leyden. Notice the flat dip of the Laramie Formation here. As you continue along Leyden Gulch you will go upsection into the Arapahoe Formation and then downsection into the Laramie and Fox Hills before reaching Highway 93.
0.6	38.9	Gas injection plant is on right. This is where natural gas is injected into the abandoned Leyden Number 3 Coal Mine for storage. Tower visible 1/2 mile to north a bit farther along the road is the Tosco Corp. experimental oil shale plant. The Leyden Number 3 Coal Mine was started in 1905 and last worked in 1950. In 1959, after considerable testing, the abandoned mine began to be used to store natural gas to provide storage for peak demand times in nearby Denver during the winter.
1.0	39.9	Burned coal dumps on left from the Leyden Mine.
2.2	42.1	Hogback of Fox Hills sandstone, here mined for clay, coal, and uranium.
0.1	42.3	Turn left (carefully) onto Highway 93, southbound.
1.2	43.4	Stretch of repaired highway.

1.3 44.7 Interpreted fault salient heads out to east. The entrance on the right is to the rock quarry in the Ralston Dike. This Tertiary monzonite intrusive body is related to the Table Mountain volcanics.

1.1 45.8 Entrance to north end of Pine Ridge Road is on right. This is a good 3-mile sidetrip to see the Dakota in cross section up close. The section from Dakota to basement rock is also visible along the Pine Ridge Road valley, with especially good exposures of hogbacks composed of Lyons sandstone. The Lyons Formation overlies the Fountain, which in turn overlies the crystalline basement rock. The road to the Schwartzwalder Uranium Mine begins at the west end of this part of Pine Ridge Road.

1.4 47.2 Southern entrance to Pine Ridge Road.

1.6 48.8 Washington Street intersection with Highway 58. Continue straight ahead on Washington Street into Golden. Turn right onto 12th Street and go 5 blocks to the turnaround at the east end of the CSM athletic field. Here, the clay pits in the Fox Hills can be examined. Notice, also, the commemorative plaque about the White Ash Coal Mine disaster, in honor of the 10 men who were killed on September 9, 1889, and are still entombed. The depth to the mine workings is 730 feet. The two scenarios reported about this disaster involve breaking into flooded old workings or mining into the flooded Golden Fault zone. In both cases the mine rapidly filled with water, drowning those remaining in the mine. Several men escaped who were on the lift hoist, which was being raised at full speed and even then the lift was at several times under water. Return to vehicles and turn right on Maple Street, passing by the excellent geology museum of the Colorado School of Mines. Jog right then left over to 19th Street. Turn right.

1.0 50.6 Turn left onto Highway 6 and return to Federal Center, 6 miles. However, for an interesting sidetrip with a spectacular view, proceed straight ahead across the 19th Street intersection and continue uphill to Lookout Mountain. Along the way you will see fresh, excellent exposures of the pre-Cambrian metamorphic rocks of the Front Range.

SIDE TRIPS FROM THE PARKING LOT

1. From the store parking lot look southeast down in the valley towards Pine Ridge. The small spoil pile in the middle of the valley was the tipple location for the Marshall No. 3 Mine and can be seen in the old photos taken when mining was active in the area (see Figure 1 of Herring et al., this volume). The mine entrance has subsided open occasionally, allowing access into the mine where it is extremely dangerous. The entrance was last backfilled in 1982. Both regional and local subsidence have occurred over this area.

   Walk south along highway right-of-way to the Davidson Ditch. The area immediately south of the liquor store, along the west side of the Marshall No. 3 Mine, was reclaimed by the Office of Surface Mining in 1982 by adding 2 feet of fill dirt to cap soil overlying the smoldering mines to try and suffocate the fire. Regional subsidence has occurred just east of the reclaimed area and south of the parking lot. Just before reaching the Davidson Ditch note the high pressure gasline shutoff valve to the east 100 feet. This gasline heads eastward and for the next 1/2 mile is underlain by the Marshall No. 3 Mine, which poses a regional subsidence threat to the pipeline.

   From the Davidson Ditch south along the east side of Highway 93 the land is accessible city open space (parkland). This stretch along the highway, uphill nearly to the level of the Community Ditch, is undermined on the eastern highway right-of-way up to the asphalt, but it is unknown if mining extends westward under the roadbed. East of the highway about 150 feet and south of the ditch 300 feet in the entrance to the Eldorado Mine. This mine as shown on the mine maps appears local in extent, but from the drilling and tracer gas experiments discussed by Herring et al. (this volume) extends well up the valley south of the entrance. The entrance has subsided periodically and was most recently backfilled in 1982. Another subsidence crater is visible 200 feet southeast of the entrance.

   Walk along the south side of the Davidson Ditch towards Pine Ridge. Pine Ridge Mine and waste dump are visible along skyline to the south. Before reaching Pine Ridge walk up the valley to the southwest, where the Marshall No. 5 Mine entrance is located. The tipple from this mine can be seen in the old photos mentioned previously. The mine is one of the few in the state with water flowing from the entrance. A reclamation project was recently completed. This facility can be seen just downstream from the mine entrance. A hike up Pine Ridge allows examination of the rocks in the lower section of the Laramie Formation. Note especially the lithologic variation, with coal beds alternating with sandstone, siltstone, and shale.

2. In vehicles, proceed east along Highway 170 1 1/2 miles intersecting with road heading south to landfill. Proceed south. The dam to Marshall Lake is visible from this section of road and the lake can be viewed from the road along the south side of the landfill. The lake is approximately 7,000 acre-feet in volume, depending on seasonal water storage. Natural drainage from the dam is to the community of Marshall and eventually to South Boulder Creek. The north quarter of the dam is undermined by the Gorham Mine. Of concern is that possible failure of the dam could occur from subsidence into the mine workings or from hydraulic breaching of the dam through the mine workings leading to undermining of the dam.

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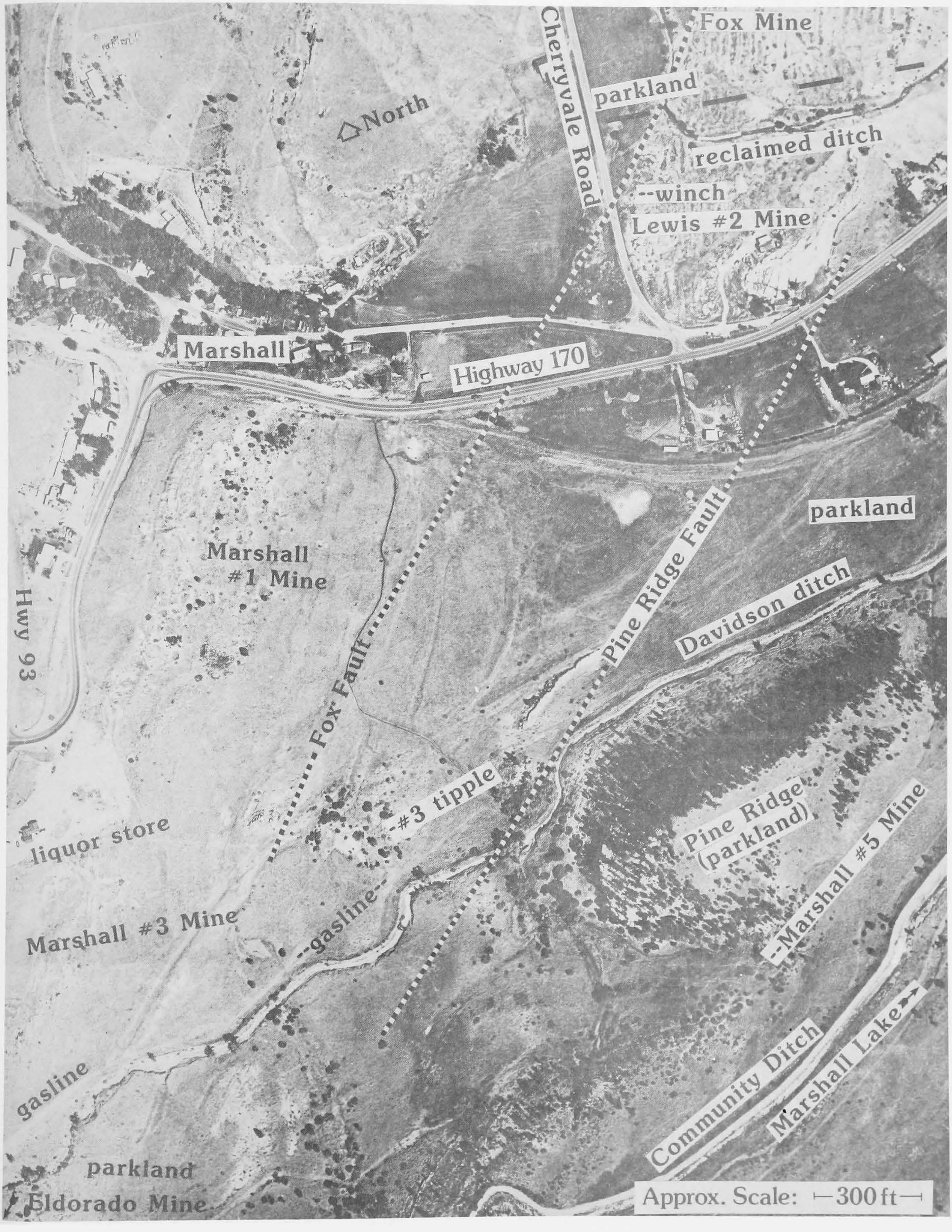

Fox Mine
Cherryvale Road
parkland
North
reclaimed ditch
--winch
Lewis #2 Mine
Marshall
Highway 170
parkland
Marshall
#1 Mine
Pine Ridge Fault
Davidson ditch
Hwy 93
Fox Fault
-#3 tipple
Pine Ridge
(parkland)
liquor store
-Marshall #5 Mine
Marshall #3 Mine
--gasline--
gasline
Community Ditch
Marshall Lake
parkland
Eldorado Mine
Approx. Scale: 300 ft