ENVIRONMENTAL GEOLOGY 7

POTENTIALLY SWELLING SOIL AND ROCK IN THE FRONT RANGE URBAN CORRIDOR, COLORADO

by Stephen S. Hart

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

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INTRODUCTION

Swelling soils are a nationwide problem, as shown by Jones and Holtz (1973):

> Each year, shrinking or swelling soils inflict at least $2.3 billion in damages to houses, buildings, roads, and pipelines--more than twice the damage from floods, hurricanes, tornadoes, and earthquakes!... Within the average American's lifetime, 14% of our land will be lashed by earthquakes, tornadoes and floods--but over 20% will be affected by expansive soil movements...Over 250,000 new homes are built on expansive soils each year. 60% will experience only minor damage during their useful lives, but 10% will experience significant damage--some beyond repair...One person in 10 is affected by floods; but one in five by expansive soils.

Swelling is generally caused by expansion due to wetting of certain clay minerals in dry soils. Therefore, arid or semiarid areas such as Colorado with seasonal changes in soil moisture, experience a much higher frequency of swelling problems than eastern states which have higher rain-fall.

Rocks containing swelling clay are generally softer and less resistant to weathering and erosion* than other rocks and, therefore, more often occur on the plains and along the sides of mountain valleys than in the high mountain areas. Because the population of Colorado is also concentrated on the plains and in mountain valleys, most of the homes, schools, public and commercial buildings, and roads in the state are located in areas of potentially swelling clay. In fact, most of Colorado's hard crystalline rock, which presents no swelling hazard, is located on public land--wilderness areas, national parks, and national forests.

The Front Range Urban Corridor includes the foothills and piedmont area of Colorado from Fort Collins and Greeley on the north to Pueblo and Canon City on the south (fig. 1). This area includes more than 80 percent of Colorado's population in less than 6 percent of the state's area. Although only half of the 30 sedimentary* bedrock formations* that are exposed in the Urban Corridor contain swelling clay, these swelling formations underlie all of the major cities. Swelling clays are, therefore, one of the most signigicant, widespread, and costly, but least publicized, geologic hazards in Colorado.

*Words with asterisk following are found in Appendix A--Glossary.

ACKNOWLEDGMENTS

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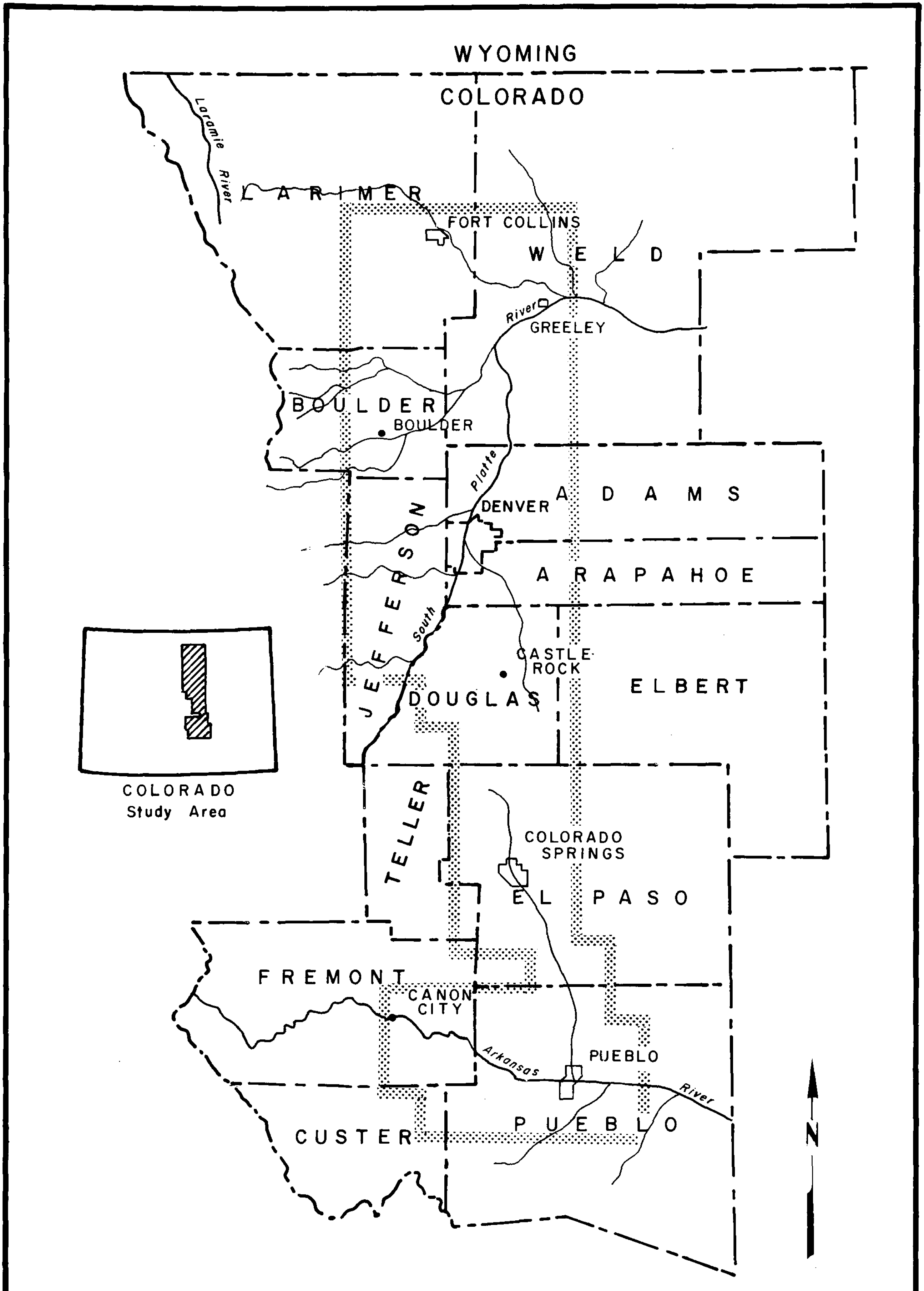


Project Area Location Map

Figure 1

WHAT IS SWELLING CLAY?

Sedimentary rocks* and surficial soils* are composed of gravel, sand, silt, and clay particles*. In order to visualize the relative grain sizes of these particles, an example using familiar objects can be given. Although the average diameter of a gravel particle is approximately 3/4 in., suppose that an average gravel particle were the size of a basketball. An average sand particle then would be the size of a baseball, and a silt particle the size of a pea. The average clay particle, however, would be almost invisible, with a pencil dot representing a large clay particle. These clay particles may consist of a variety of minerals--quartz, feldspar, gypsum, or clay minerals*. Common clay minerals in Colorado are montmorillonite, illite, and kaolinite. To return to the previous analogy, gravel, sand, silt, and some clay particles are often round, three-dimensional objects. Clay minerals, however, are generally flat, nearly two-dimensional plates just as the above-mentioned pencil dot is flat and two-dimensional.

The clay minerals in rocks and soils are responsible for their expansion, or "swell", as it is generally called. This swelling is caused by the chemical attraction of water to certain clay minerals. Layers of water molecules are incorporated between the flat, submicroscopic clay plates. As more water is made available to the clay, more layers of water are added between the plates, and adjacent clay plates are pushed farther apart, as shown below:

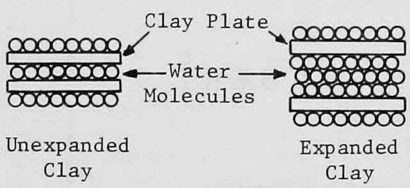


Figure 2. Diagrammatic sketch of a montmorillonite clay particle as it incorporates water within the clay structure.

This pushing apart, or swelling, occurs throughout the mass of soil that is being wetted, and causes increased volume and high swell pressures within the mass. The opposite effect, called shrinkage, may occur if a previously wet swelling clay is dried. Although no large pressures are exerted, shrinkage will cause a volume decrease of the soil mass. These processes of swelling and shrinkage may occur any number of times for a single soil mass. Either swell or shrinkage may cause damage to streets and buildings, but swell accounts for most of this damage in Colorado.

<u>Montmorillonite Clay (Bentonite)</u>. The clay mineral responsible for most swelling is montmorillonite *, often called"bentonite*". A sample of pure montmorillonite may swell up to 15 times its original volume. However, most natural soils contain considerably less than 100 percent montmorillonite, and few swell to more than 1 1/2 times their original volume (a 50 percent volume increase)(Jones and Holtz, 1973). A small load may decrease the actual swell to less than 1 1/4 times the original volume (25 percent volume increase). However, a 25 percent volume increase can be extremely destructive because volume increases of 3 percent or more are generally considered by engineers to be potentially damaging and require specially designed foundations.

<u>Gypsum and Alkali Salts</u>. Swelling minerals, other than clay, also accur widely in the Front Range Urban Corridor. Hydrated calcium sulfate, or gypsum*, and sodium sulfate, or white alkali*, may have moderate "swell potential" if they constitute more than 15 to 20 percent of a soil. This "swell potential" is not, however, caused by expansion of clay plates due to increased moisture content, but by the pressures developed during crystal growth.

Although there have been suspected cases of damage due to swelling sulfates, these minerals are more generally considered a hazard due to their corrosive properties (fig. 3). Corrosion* of concrete and metal by high sulfate concentrations is responsible for several million dollars in damage annually to sidewalks, driveways, roads, storm sewers, metal pipes, and buried utility cables. Such damage can be greatly minimized by recognition of the presence of sulfate. When recognized, proper engineering design procedures can be specified to minimize corrosion damage, e.g., Type II, air-entrained cement and cathodically protected metal pipes.

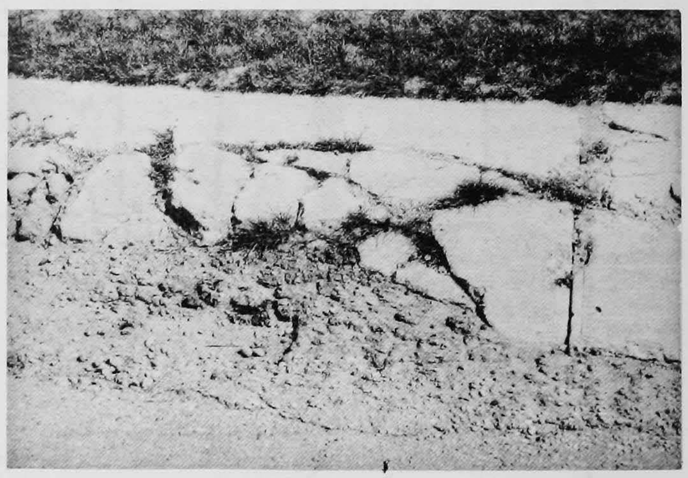


Figure 3. Destruction of curb and sidewalk by sulfate corrosion and swelling clay.

HOW CAN ONE RECOGNIZE SWELLING SOIL OR ROCK?

Although several visual methods for identification of potentially swelling clays exist, only a <u>competent, professional soil engineer and engineering geologist should be relied upon to identify this potential hazard</u>. Some warning signs for swell might include: a) soft, puffy, "popcorn" appearance of the surface soil when dry; b) surface soil that is very sticky when wet; c) open cracks (desiccation polygons) in dry surface soils; d) lack of vegetation due to heavy clay soils; e) soils that are very plastic and weak when wet but are "rock-hard" when dry.

Engineering soil tests include index tests and design tests. Rapid, simple index tests are used to determine whether more complex design tests are necessary. Some index properties that may aid in the identification of probable areas of swelling clay include Atterberg limits*, plasticity index*, grain size determination, activity ratio*, dry unit weight*, and moisture content (Asphalt Institute, 1964). The Potential Volume Change (PVC) test developed for the Federal Housing Administration (Lambe, 1960) has been widely used in the past but is now seldom used by Colorado soil engineers. The primary design tests for swelling soils are the consolidation-swell* test for buildings, and the California Bearing Ratio* (CBR) swell test for roads (Asphalt Institute, 1964).

EXAMPLES OF SWELLING CLAY DAMAGE

Damage from swelling soils can affect, to some extent, virtually every type of structure in the Front Range Urban Corridor. Some structures, such as downtown Denver's skyscrapers, generally have well engineered foundations that are too heavily loaded for swelling damage to occur. At the opposite extreme are public schools and single-family homes, which are generally constructed on a minimal budget and which may have under-designed lightly-loaded foundations that are particularly subject to damage from soil movements. Homeowners and public agencies who assume they cannot afford more costly foundations and floor systems often incur the highest percentage of damage and costly repairs from swelling clay. This has led many homeowners to make cheap, "cover-up" repairs and quickly place their homes on the resale market. This attitude of "cover-up and sell-out" has precluded extensive publicity in the media of swelling clay damage to homes. Schools and other public buildings, have, however, received both extensive swelling clay damage and extensive publicity by the media.

Pueblo. On May 27, 1974, local media announced that the Life Science Building at Southern Colorado State College (S.C.S.C.) in Pueblo would be closed pending repairs of swelling clay damage. Structural beams supporting the roof and floors of the 6-yr-old building were being pulled off of their supporting columns due to the uplift pressure on the foundation caused by wet "bentonite" soils (fig. 4). More than $100,000 in repairs will be necessary before the building can be reopened. Another building on the campus experienced 3 in. of heave in 5 months during the spring and summer of 1974 (fig. 5). Only a year earlier, $170,000 in repairs to swelling clay damage were required at the 7-yr-old library at the same school.

Denver. In 1970 repairs to damage from swelling clay were undertaken at Ridge Home, the state school for mentally retarded children, in Wheat Ridge. The $490,000 spent for repairs to cracked walls (fig. 6), floors, ceilings, doors, and windows represented nearly one third of the original cost of the 6-yr-old buildings. Another Denver metropolitan area school that has received damage was reported in Cervi's Rocky Mountain Journal on June 5, 1974. Issac Newton Junior High School in Littleton has received "...cracks where floors and walls had pulled away from support columns, bowed prestress concrete panels, floor cracks, and fallen ceiling tiles." Repairs to this swelling

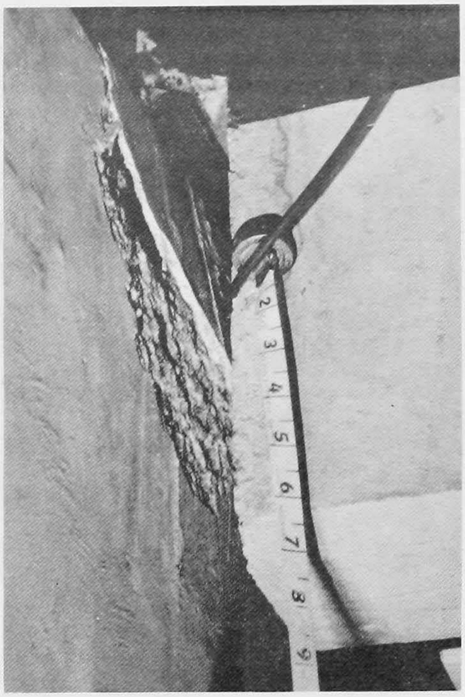


Figure 4. Beam being pulled off bearing wall by nearly 5 in. of swelling clay heave at college in Pueblo.

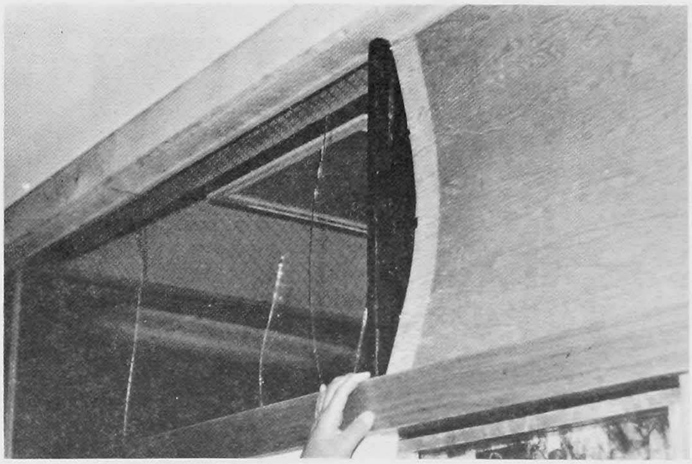


Figure 5. Plywood replacing broken glass caused by 3 in. of heave in 5 months at college in Pueblo.

clay-related damage have cost taxpayers nearly half of the initial construction cost of $1.5 million in a building only 12 yrs. old.

Figure 6. Cracked brick wall at Ridge Home caused by swelling clay.

Boulder. Another school district that has had a continual struggle with swelling clay damage is the Boulder Valley School District in Boulder (fig. 7).

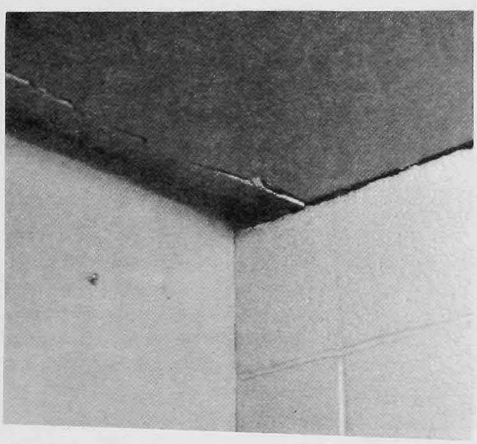


Figure 7. Cracked ceiling in Boulder school district building caused by 2 in. of uplift on left wall.

When the present director of planning and engineering began his job, the school district employed one full-time carpenter whose only job was to cut off the bottoms of doors (fig. 8). This was necessary because floor slabs, pushed upward by swelling clays, interfered with the closing of the doors. Damage from swelling clay has been so costly in Boulder schools that an average additional cost of $42,000 for structural floors is being spent on each new school in the eastern half of the school district.

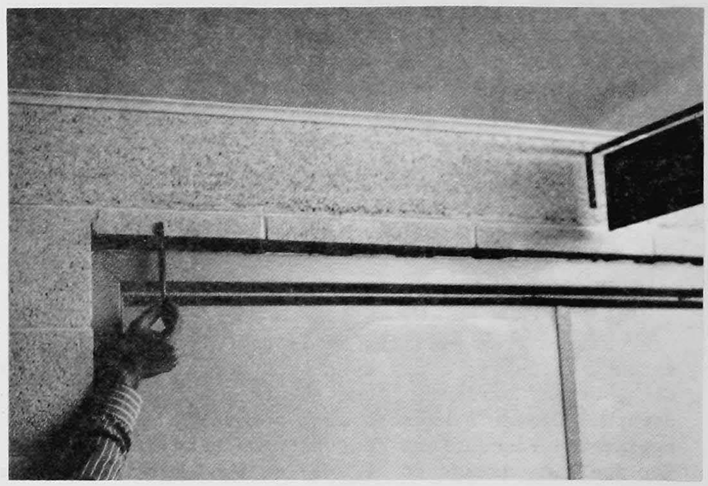


Figure 8. Heave of doorframe in Boulder school district building causes difficulty in closing door.

Urban Corridor Streets and Highways. Highways in some parts of the Front Range Urban Corridor have

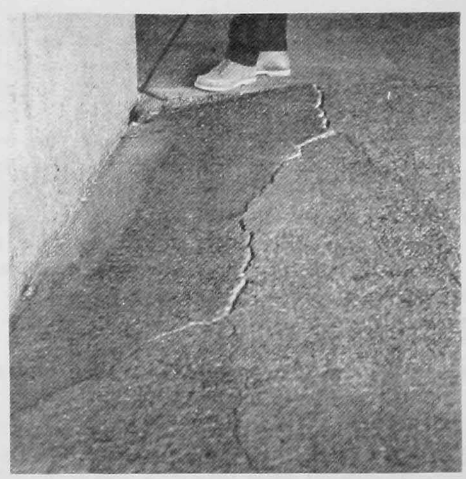


Figure 9. Patio slab broken by 3 in. of heave.

required frequent and expensive maintenance resulting from swelling damage. Part of the Boulder Turnpike (U.S. 36) near Louisville required extensive maintenance in the early 1950's. Pavement along the Turnpike heaved as much as 7 in. (Holtz, 1959) shortly after construction. Interstate Highway 25 has several sections of swelling damaged pavement both north and south of Denver. Heaved and cracked city streets, sidewalks, curbs, driveways, and patio slabs (fig. 9) are very common indicators of swelling soil and rock throughout the Urban Corridor.

POTENTIAL HAZARD AREAS IN THE URBAN CORRIDOR

Pierre Shale. Of the approximately 15 sedimentary bedrock formations that contain swelling clay, 4 underlie most of the Front Range Urban Corridor (fig. 10 and fig. 11). One of these, the Pierre Shale, contains some montmorillonitic shale and numerous white or yellow "bentonite" beds ranging in thickness from 1/4 in. to 6 in. This formation underlies the area from central Colorado Springs south through eastern Pueblo and from Canon City to Florence and Wetmore. North of Denver it extends from Roxborough Park to just west of Green Mountain, from Golden to Boulder west of Colorado 93, and from Boulder northeast to Longmont, Loveland, Fort Collins, and Windsor. In the Pierre, swell potential may range from low to very high, but the swell potential within specific parts of the formation is generally predictable.

Laramie Formation. A less predictable bedrock unit that underlies a large part of the Urban Corridor is the Laramie Formation. This formation is composed of thick, white to yellowish-gray sandstone beds alternating with greenish-gray claystone beds. Some of these claystone beds are montmorillonitic, particularly in the middle 1/3 of the unit. Other claystones in the Laramie, however, contain a high percentage of kaolinite, a clay mineral that does not swell significantly and is used locally in the manufacture of brick and tile (Gude, 1950). One of the best exposures of this formation is in the claypits immediately east of U. S. Highway 6 in Golden. Because the Laramie is also the principal coal-producing formation along the Front Range, areas underlain by outcropping or shallow Laramie beds are generally associated with coal mines and mining districts. One such district is the Boulder-Weld Coal Field, which runs from Leyden and Marshall on the southwest, through Lafayette, Louisville, Erie, Frederick, and Dacono, to Platteville and Hudson on the east. Another old Laramie coal-producing area lies in a narrow southeast-trending band located southwest of the Austin Bluffs and Palmer Park in Colorado Springs. The Laramie Formation forms the bedrock in the Eaton-Ault area north of Greeley but is generally covered by surficial deposits* including wind-blown sand and stream-deposited gravel and sand in the area.

Dawson and Denver-Arapahoe Formations. The Dawson Arkose and Denver-Arapahoe Formation underlie most of the area from northern Colorado Springs on the south to Golden, Broomfield, and Brighton on the north. These formations consist of extremely variable beds of sandstone, conglomerate, siltstone, and claystone. In Colorado Springs the Dawson Arkose includes a potentially highly swelling zone that trends southeasterly from the Air Force Academy to Peterson Field, along the northeast side of Austin Bluffs. Other major areas underlain by swelling clays in the Dawson include the Parker and Cherry Creek Reservoir areas. The Denver-Arapahoe Formation is the principal bedrock unit underlying metropolitan Denver. Some parts of this unit contain very highly swelling clays that have caused millions of dollars in damage. The areas that have suffered the most costly damage include southeast Denver, Littleton, Aurora, Green Mountain, Applewood, Westminster, and Northglenn. However, no part of the Denver metropolitan area is completely free of potentially swelling soils. Other sedimentary bedrock units in the Urban Corridor, such as the Graneros, Carlile, and Smoky Hill Shales, Greenhorn Limestone, and Fox Hills Sandstone, normally contain some swelling clay. However, as these units generally underlie only small parts of the Urban Corridor, no specific areas of potential hazard are described (see pls. 1 through 4).

Surficial Geology. Surficial geologic units, such as stream gravel and wind-blown sand, often cover the sedimentary bedrock units mentioned earlier. Most of these units have little or no swell potential. However, some such units are overlain by potentially-swelling, clayey "subsoil" that is generally found only in the upper one to five feet of the unit. This clay-rich layer is formed by weathering of transported rock and is known as the "B horizon" by geologists. Wind-blown silt, termed loess* by geologists, will sometimes present a dual hazard when wetted due to the possible swell of this B horizon "subsoil" and possible collapse, or hydrocompaction*, of the underlying silt. Other surficial units that may locally contain swelling clay are colluvium* and residuum*. Both units are generally found where bedrock is near the surface, with colluvium found on slopes and residuum on flatter areas. They are formed from a mixture of weathered bedrock and debris from other surficial units. If the weathered bedrock is a swelling claystone or shale, the colluvium or residuum will also have some potential for swell. A third surficial unit that may be influenced by the character of the local bedrock is the Piney Creek Alluvium. This unit is a black, organic, micaceous silt or sand that is found along most small streams in the Urban Corridor. Where the local bedrock consists of Pierre Shale, Laramie Formation, or other potentially swelling bedrock formations, the Piney Creek Alluvium may contain swelling, montmorillonitic clay derived from erosion of the claystone bedrock.

No general statements, or even maps such as those accompanying this report, can determine the exact conditions that will be found on a specific building site. Therefore, all potential building sites in the Front Range Urban Corridor should be evaluated by a professional soil engineer and/or engineering geologist before construction.

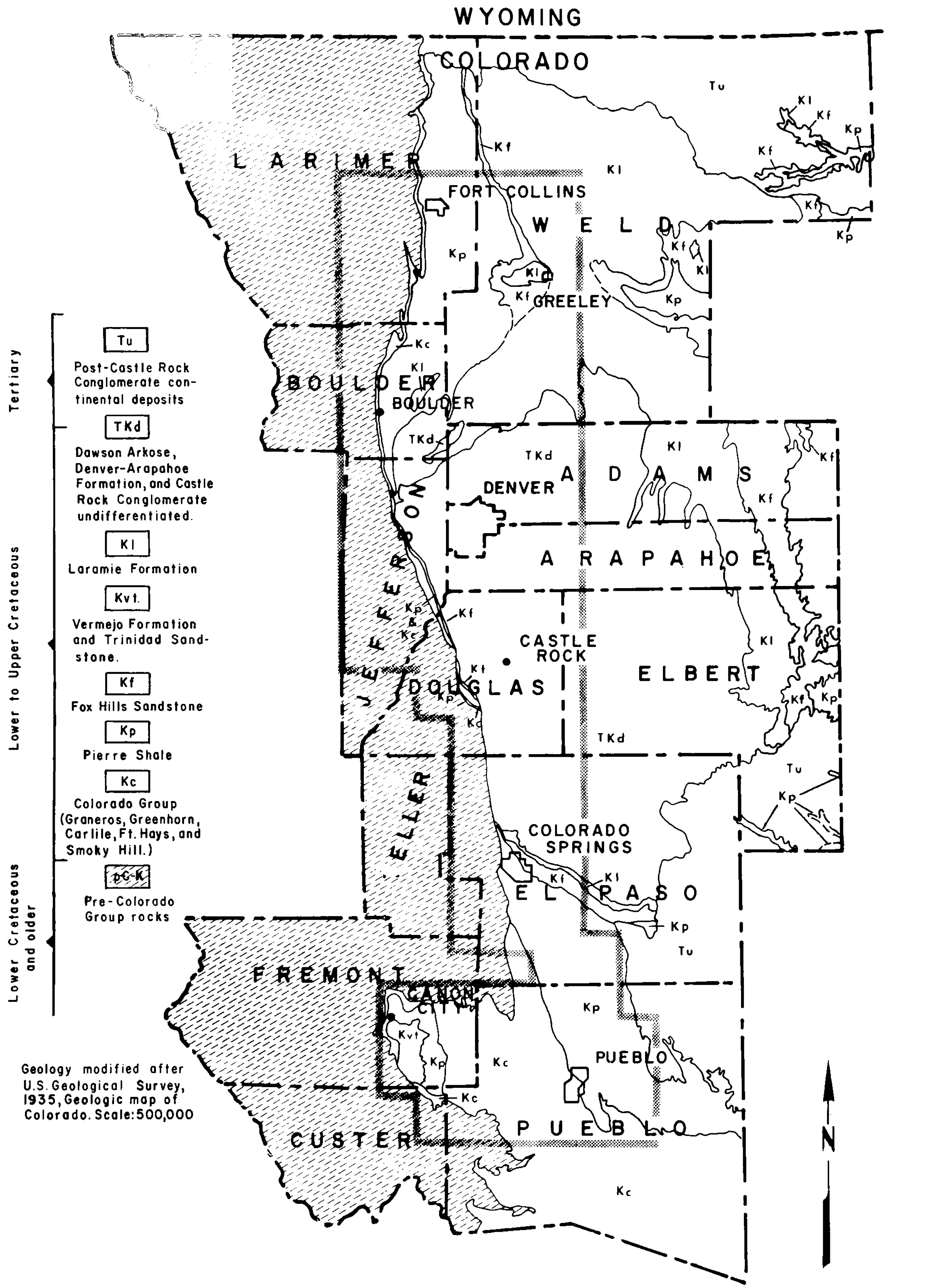
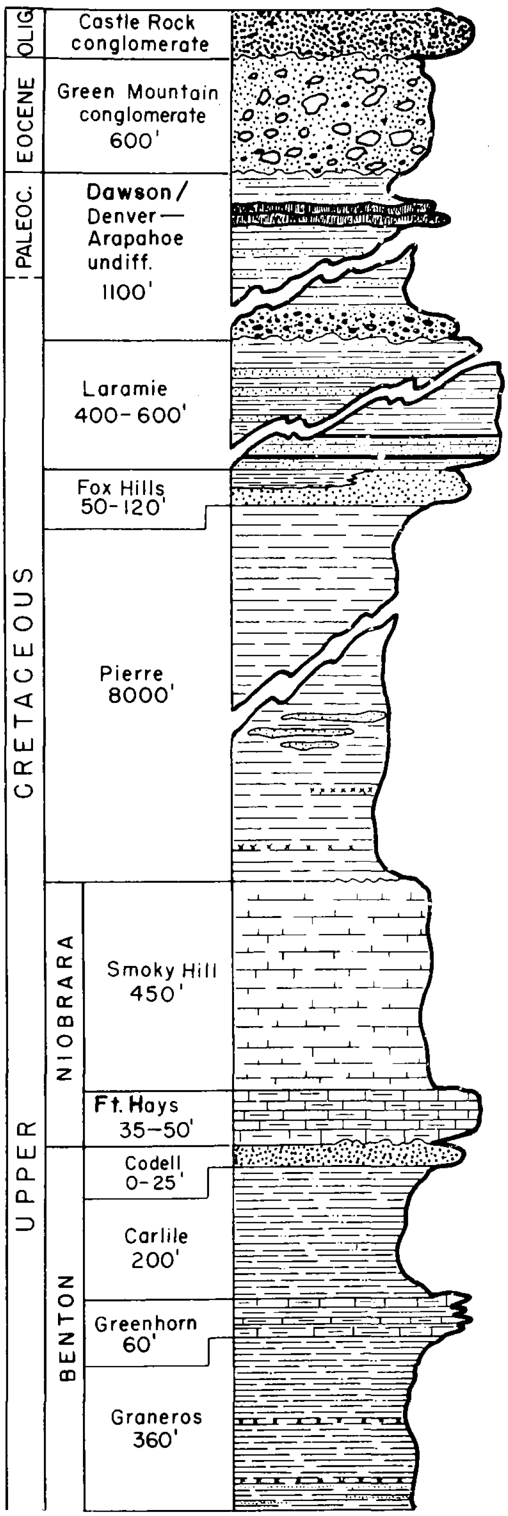


Figure 10. Generalized geologic map.

0 10 20 Miles

0 10 20 30 Kilometers

(Modified from Colorado School of Mines, Generalized composite stratigraphic section, Front Range of Colorado)



CONGLOMERATE AND GRAVEL: pebbles up to 2 feet; occasional lenses of tan to maroon siltstone; commonly forms escarpments; best developed near town of Castle Rock; generally low swell potential.

CONGLOMERATE: igneous and metamorphic boulders up to 3 feet, unconsolidated; lenses of tan, silty claystone containing leaf imprints; caps Green Mountain south of Golden; generally low swell potential; moderate to very high swell potential in some claystone.

SANDSTONE AND SILTSTONE: tan to light brown feldspathic, fine- to medium-grained sandstone, siltstone, and claystone; conglomerate at base; Table Mountain "basalt" flows in upper part; well exposed on west side of Green Mountain, below flows east of Golden, and in the Austin Bluffs near Colorado Springs; low to moderate swell potential in conglomerate and sandstone; moderate to very high swell potential in siltstone and claystone.

SANDSTONE AND CLAYSTONE: sandstones fine-grained, feldspathic to quartzose, white to light tan, compact; claystones dark gray, carbonaceous; thin lignitic coal beds in lower part; exposed in pits west of School of Mines campus; low swell potential in sandstone; moderate to very high swell potential in claystone.

SANDSTONE: light tan, very fine-grained, arkosic, friable; upper part grades laterally into silty shales; boundaries gradational and interfingering; aquifer; low swell potential in sandstone; moderate to high swell potential in silty shale.

SHALE: dark gray, silty, carbonaceous, claystone, shale, and siltstone; frequent thin layers of bentonite; fine-grained sandstones in middle part; lower boundary gradational to unconformable; well exposed along I-25 from Colorado Springs to Pueblo; generally moderate to very high swell potential; low swell potential in sandstone and some siltstone.

CHALK AND SHALE: dark gray, weathers light tan, highly calcareous; lower boundary gradational; well exposed along Arkansas River between Florence and Pueblo; generally low swell potential; moderate swell potential in some upper shales.

LIMESTONE: light gray thin-bedded, argillaceous; numerous 1-inch layers of calcareous shale; commonly forms minor ridge east of Dakota hogback; well exposed along Arkansas River near Florence; low swell potential.

SANDSTONE: light gray, fine- to medium-grained, slightly calcareous, low swell potential.

SHALE: dark gray, sometimes silty; occasional calcareous concretions and thin layers of bentonite; well exposed in Canon City area; generally moderate to very high swell potential.

LIMESTONE AND SHALE: limestone light gray, argillaceous, dense, shale dark gray; well developed bentonite beds near base; lower boundary generally sharper than upper; well exposed in Canon City area; low swell potential in limestone; moderate to high swell potential in shale; very high swell potential in bentonite.

SHALE: dark gray, thin-bedded, occasional cone-in-cone concretions in lower part; bentonite beds (up to 6") throughout; occasional thin sandstones in lower part; well exposed in Canon City and Perry Park areas; moderate to very high swell potential.

Figure 11. Stratigraphic section of bedrock geologic units studied for swelling potential.

WHAT CAN BE DONE TO MINIMIZE DAMAGE?

Many methods of preventing or minimizing damage from swelling clays have been used in the Front Range Urban Corridor. Some of these methods should be included at the design stage of construction of any structure on potentially swelling soils. Other damage-reducing techniques should be utilized by the owner of the structure after the completion of construction. A technique that includes properly engineered and constructed foundations and proper lot drainage has become the most widely used and most successful method for coping with swelling soil conditions (table 1).

Foundation Design. To be considered properly engineered and constructed, a foundation must be designed and inspected by a registered professional soil and foundation engineer. The necessity for professional foundation design in areas of swelling clay was not widely accepted in the early 1950's. However, costly damage from swelling clay to the concrete slab foundations of many post-war homes in Denver rapidly changed this acceptance. Slab foundation* design was replaced with spread footing, bearing (footing) wall, and drilled pier and grade beam designs. Each of these foundations was designed to concentrate the weight of the structure on a much smaller area than was possible with the concrete slab. This concentration of weight was necessary to resist pressures developed when swelling clay was wetted.

In areas of relatively low swell potential, spread footings* are commonly used. In this design, the weight of the building is transmitted to the soil through walls supported on concrete strips, or footings, that are wider than the walls (see fig. 12A). For slightly higher swell pressures, extended bearing walls* (footing walls)(fig. 12B) or pads* may be used. Pads are generally used on large buildings rather than homes (fig. 12C) in the Urban Corridor. In areas containing moderately to highly swelling clay, drilled pier and grade beam* foundations are used (fig. 12D). With this foundation design, the weight of the building is transmitted through bearing walls to horizontal grade beams. The grade beam consists of specially-designed additional reinforcement of the lower part of the concrete bearing wall to allow bridging of building weight between individual piers. These beams rest on cylindrical, reinforced-concrete piers that concentrate the weight on very small area below the zone* of seasonal moisture change. The foundation is thereby founded upon soil that, because its moisture content remains constant throughout the year, should not experience a volume change.

With each of these special foundation designs, floating slabs* are commonly used for all on-grade floors (fig. 13). These interior concrete floor slabs are completely isolated by joints or void spaces from all structural components. Complete isolation from bearing walls, columns, nonbearing interior partitions, stairs, and utilities allows the slab to move freely without damaging the structural

Table 1. GEO-LOGIC - The Sensible Way to Build in Swelling Clay

DO	DON'T
1. Hire a registered professional soil engineer for foundation investigation.	1. Build without a foundation investigation and recommendation.
2. Utilize properly designed foundation (low swell potential--spread footing; moderate swell potential--bearing wall or pad; high swell potential--drilled pier and grade beam) with specific design by the soil engineer.	2. Use a foundation type based on the types used in other parts of the country.
3. Insist on careful inspection of all foundation construction.	3. Allow careless cleaning of foundation excavations or sloppy concrete work on piers, footings, grade beams, or floors.
4. Utilize procedures to provide maximum drainage around building and provide for positive drainage of entire lot.	4. Allow uncompacted backfill around foundations which may settle and pond water.
5. Surround building with 4-ft-wide or wider impermeable membrane (asphalt, concrete, or plastic sheeting).	5. Allow the surrounding impermeable membrane to slope toward the building.
6. Allow minimum separation of 5 ft between building and all grass, shrubs, and sprinkler systems.	6. Use so-called "foundation plantings" to hide the foundation.
7. Utilize floating floor slabs for all on-grade floors, and consider alternative of structural floor with crawl space.	7. Neglect to provide for freedom of movement.

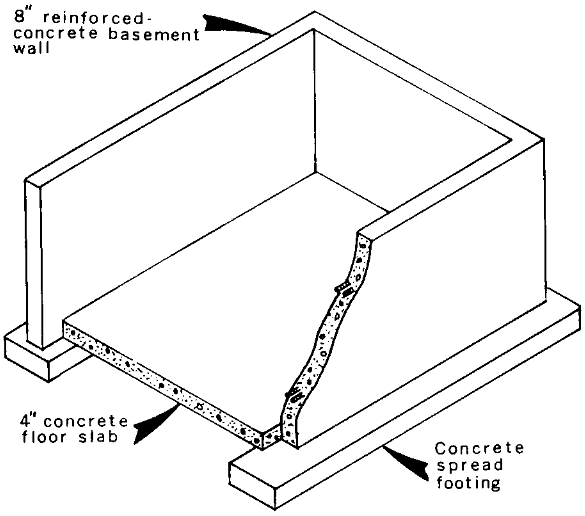


Figure 12a. Spread footing
foundation

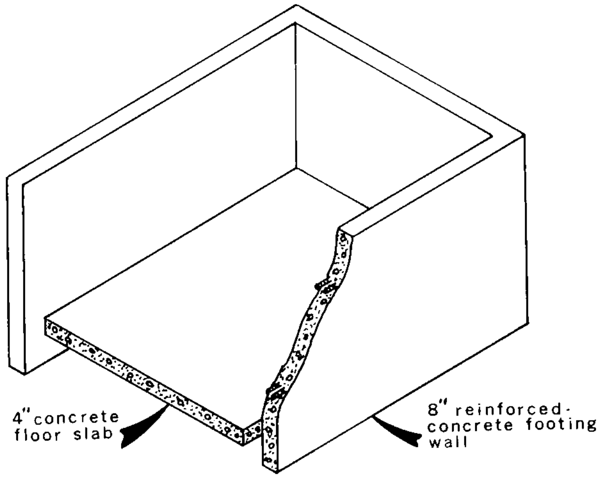


Figure 12b. Footing wall
foundation

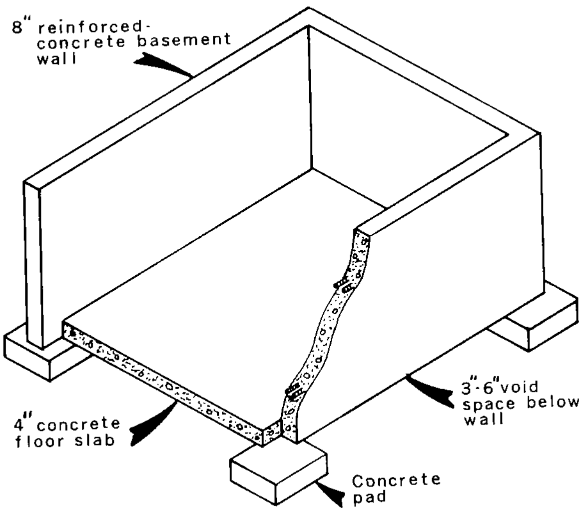


Figure 12c. Pad foundation

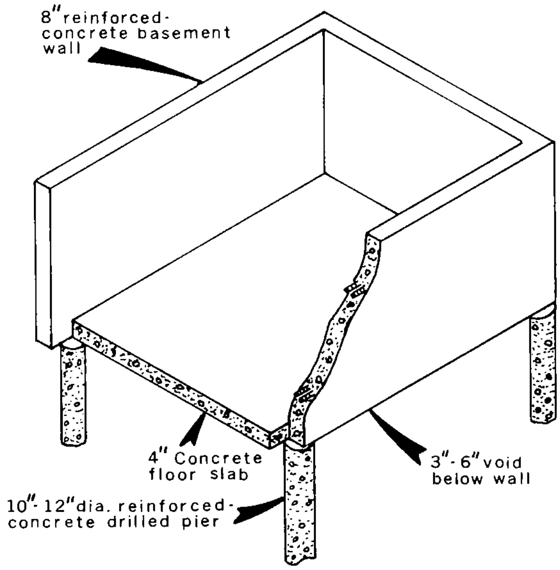


Figure 12d. Drilled pier and
grade beam
foundation

integrity of the building. Structural floors have been used extensively in large commercial buildings but have found only limited use in residential and school buildings owing to their high cost relative to slab floors. This type of floor system consists of flooring supported several feet above the ground by beams attached to bearing walls. The "crawl space" below the structural floor provides a large void between the floor and the swelling soil, preventing floor slab heave.

In the Denver area, swelling soil below the level of the proposed floor slab is sometimes excavated to a depth of several feet. The original swelling soil, placed slightly above optimum moisture content and 5 to 10 percent below maximum density, or imported, nonswelling soil is then backfilled into the excavation and compacted. This "over-excavation" method generally has been successful where slabs are poured immediately after compaction to prevent drying of the fill (Sealy, 1972).

In designing foundations for roads, the Colorado Division of Highways has tried various methods to offset the effects of swelling clay. The most commonly used method is excavation and recompaction of the subgrade soil. The depth of excavation is determined from the plasticity index*, e.g., 2 ft of soil is excavated if the plasticity index is between 10 and 20. The backfill is then recompacted at approximately the same moisture-density conditions mentioned above for floating floor slabs (Leo O'Conner, 1973, personal communication). Although not a preventive measure, the substitution of flexible pavements (asphalt) for rigid pavement (concrete) has reduced the costs of repairs to pavement heaved by moderately swelling clay. In recent years asphalt has also been used for membranes to seal water out of swelling subgrade soils. Because much of the water that causes swelling beneath pavements is formed in the porous subbase gravels below the asphalt pavement, nonporous asphalt subbases have been successfully used to prevent swell. Due to the expense of these methods and the continual excavation of city streets for utility lines, more economical and less easily-damaged solutions must be found to prevent swell of streets in urban and suburban areas.

Pre-construction chemical soil stabilization utilizing lime or organic compounds may reduce the potential of swelling soil damage more economically than the utilization of structural floors and special foundations. The chemical stabilization technique has a short history and limited use in Colorado. Where it has been used, it appears to have been successful for the period of time since application.

Drainage. The Federal Housing Administration recommends slopes of no less than 6 in. of vertical fall in 10 ft (12 in. in 10 ft is safer) around all buildings for drainage (Federal Housing Administration, 1966). These slopes must drain water into drainage swales, streets, or storm sewers. Water must not be allowed to stand near foundations in areas of swelling clay due to the potential for wetting foundation soils. All downspouts and splash blocks should be placed so that roof runoff will be carried at least 4 ft from the building. Interior drains for roof runoff are not recommended because an interior drain, cracked or broken by differential vertical movements, will immediately saturate the foundation. Peripheral drains* of clay tile or perforated plastic pipe are often used around the foundations of buildings to carry away extraneous subsurface water (fig. 13). In areas of heavy lawn irrigation, these drains have proven effective in helping to prevent the formation of perched* water tables and the resulting downward seepage of surface water (Sealy, 1972).

Landscaping. Proper design and construction will not solve all swelling-clay problems. The owner of a structure is responsible for maintaining proper drainage by careful landscaping and maintenance. Backfill around foundations is often not properly compacted. Therefore, additional soil may be required on the slope around the structure in order to compensate for settlement of the backfill. This prevents "ponding" and percolation of water around the foundation. Although not esthetically pleasing to many persons, asphalt, concrete, or gravel-covered plastic sheeting should be placed around the entire foundation (fig. 13). These 4-ft or wider strips prevent surface moisture penetration and excessive dessication cracking near the building. Grass, shrubs, and sprinkler systems should be kept a minimum of 4 to 5 ft from the foundation. Trees should be planted no nearer than 15 ft to a building. The most critical aspect of landscaping in swelling clay areas is not to flatten a properly designed slope.

Interior finishing. One of the most costly mistakes a homeowner or careless contractor can make is to defeat the design purpose of a floating floor slab. A floating garage or basement floor slab is designed to move freely. Therefore, any furring, paneling, dry wall, or interior partitions added to a basement or garage must maintain this freedom of vertical movement. Any added walls or wall coverings should be suspended from the existing walls or ceiling, and should not be attached to the floor slab. A minimum void space of 3 in. should then be provided just above the floor slab. This void space may be covered with flexible molding or with inflexible molding attached to the floor rather than the wall. Although these recommendations provide 3 in. of upward swell of the soil beneath the floor slab, more void space may be necessary in areas of highly swelling clay.

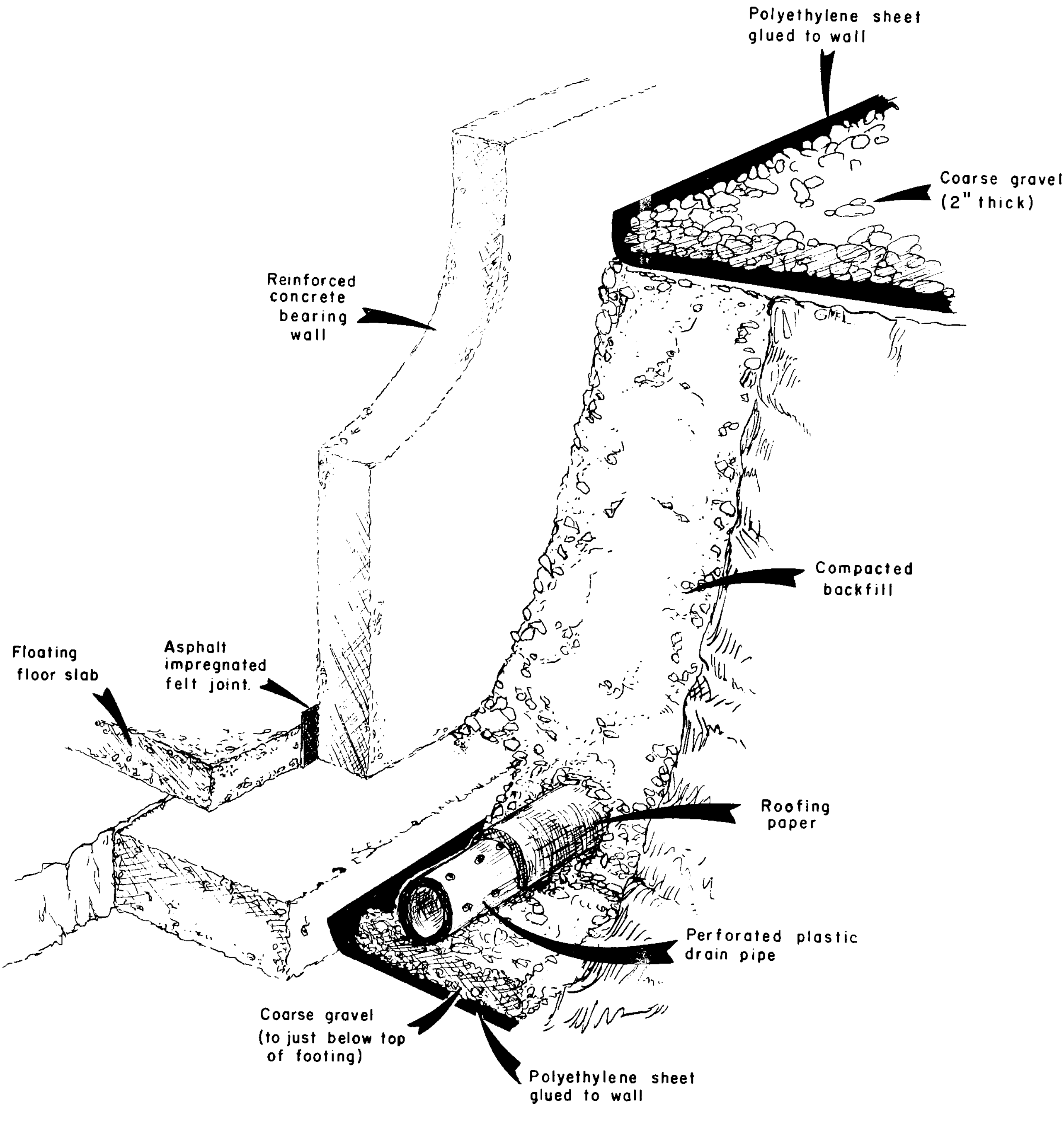


Figure 13. Details of a typical floating floor slab, peripheral drain, and surface moisture barrier, showing specific components but not intended as a model for a specific foundation design (modified from Federal Housing Administration, 1966, p. 91).

SUGGESTIONS FOR FURTHER STUDY

For more information on swelling soils, the reader is referred to "Expansive Soils and Housing Development" by D. Earl Jones, Jr., and "The Current Practice of Building Lightly Loaded Structures on Expansive Soils in the Denver Metropolitan area" by Curtis O. Sealy. Both of these papers are contained in the Workshop on Expansive Clays and Shales in Highway Design and Construction Proceedings (May, 1973) prepared for the Federal Highway Administration.

Topographic, geologic, and sand and gravel resource maps for the Front Range Urban Corridor are currently available, or will soon be available, at a scale of 1:100,000 from the U. S. Geological Survey, Distribution Section, Bldg. 41, Denver Federal Center, Denver, Colorado 80225. Larger-scale geologic maps of many parts of the Urban Corridor are also available from the U.S.G.S.

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APPENDIX A - GLOSSARY

Activity ratio - the ratio of the plasticity index to the percentage of clay (particles less than 0.002 mm in diam) in a soil sample.

Alkali - an accumulation of soluble chloride and sulfate salts, such as sodium chloride (table salt), calcium sulfate (gypsum), or sodium sulfate (white alkali), on or near the surface of the soil in arid regions due to upward movement of soil moisture during drying periods; potentially harmful to concrete.

Atterberg limits - certain properties of clay soils that are dependent upon water content. The three most common limits are: The liquid limit, the plastic limit, and the shrinkage limit. These represent the water content as a percent of dry soil weight at transitions from liquid to plastic behavior from plastic to solid, and the water content below which further loss of water by evaporation does not result in a reduction in volume of the soil. These soil parameters are determined by standard laboratory tests.

Bearing wall - a wall which transmits part of the weight of a roof or upper floor to the foundation; may be extended below frost line for use as the foundation, and may then be called a "footing wall."

Bentonite - a common name for layers of white or yellow clay containing a mineral called "montmorillonite" and formed from weathering of volcanic dust; may be highly swelling if exposed to water while dry.

California bearing ratio (CBR) test - the ratio of the pressure required to penetrate a soil mass with a 2-in. diam, circular piston at the rate of 0.05 in./min to the pressure required for corresponding penetration of a standard material.

Clay mineral - a group of generally flat, platy, silicate minerals that form by chemical weathering of primary rock-forming minerals such as feldspar and mica.

Clay particle - the finest particle size among those normally measured sedimentary particles from gravel to sand, silt, and clay; any particle less than 0.002 mm in diameter.

Colluvium - any loose, poorly-sorted mass of soil or rock material deposited by rapid, water-deficient processes such as landslides, rockfalls, and mudflows; usually formed at the base of a steep slope; the soil or rock may range in size from clay to boulders.

Consolidation-swell - a test in which a thin cylindrical soil sample, confined by a brass ring, but with free access to water, is loaded axially to determine percentage consolidation or swell under load.

Corrosion - the disintegration of concrete in foundations, basement floors, porches, sidewalks, and driveways due to the chemical action of sulfate salts; may be alleviated by use of Type II or Type V cement with air blown into the mixer to form small bubbles ("air-entrainment").

Drilled pier and grade beam - a type of foundation in which the weight of the building is transmitted to the soil through walls resting on horizontal, reinforced-concrete beams (grade beams), which are in turn resting on vertical reinforced-concrete posts (drilled piers or "caissons") placed in drilled holes; more suitable for highly swelling clays than spread footing, bearing wall, or pad foundations because loads can be concentrated on the small bottom end of the drilled piers.

Dry unit weight - the ratio of the oven-dried weight of a soil sample to its original wet volume; also called "dry density".

Erosion - the wearing away of rock or soil and the movement of the resulting particles by wind, water, ice, or gravity.

Floating slab - a type of interior concrete floor slab commonly used for basements and garages in which the slab is poured separately from bearing walls and is isolated with joints or void spaces from all bearing walls, columns, stairs, utility lines, and interior partitions; the slab is isolated to allow movement of the slab without damaging the structural components of the building.

Formation - (geologic) - the ordinary unit of geologic mapping, recognizable by field mapping, consisting of a large and persistent stratum of predominatley one kind of rock.

Gypsum - hydrated calcium sulfate, the most common sulfate mineral found in Colorado soils; corrosive to ordinary concrete.

Hydrocompaction - a property of some dry, unconsolidated deposits to undergo after wetting, spontaneous consolidation, settling, and cracking. Commonly this occurs in areas that are normally dry, but are subjected to abnormal wetting resulting from activities such as sewage disposal systems, irrigation systems, or water carrier breakage.

Loess - a wind-deposited, unstratified, unconsolidated, blanket-like surficial deposit consisting primarily of silt and generally yellowish-brown in color. It is generally found as a mantle, as thick as 25 or 30 ft, covering gentle hill-slopes and uplands. Undisturbed loess may stand unsupported in very steep or vertical faces.

Montmorillonite - a clay mineral composed of loosely bonded silica layers that may be expanded by the absorption of water molecules; the most highly swelling of the clay minerals; often locally called "bentonite."

Pad - a type of foundation in which the weight of the building is transmitted to the soil through bearing walls resting on columns or grade beams which are in turn resting on flat, rectangular, reinforced-concrete pads; generally used in large buildings rather than single-family residences.

Perched water table - a water-saturated zone that is separated from the underlying water table by a zone of tight (impermeable) rock through which water cannot flow.

Peripheral drain - also called a "footing drain"; open-jointed clay tile or perforated plastic pipe laid in a trench beside the foundation of a structure and covered with coarse gravel back-fill; aids in preventing swell or settlement by collecting water near the foundation and draining the water away through "French drains" (gravel fill) or by "daylighted drains" (tile or pipe discharging onto a slope below the level of the peripheral drain).

Plasticity index - the difference in water content between the liquid limit and the plastic limit (see Atterberg limits).

Residuum - also called "residual deposits"; unconsolidated and partly weathered material that is presumed to have developed in place from weathering of the consolidated rock on which it lies.

Sedimentary - earth materials formed by the deposition of particles (gravel, sand, silt, or clay) or precipitation of chemicals (calcium carbonate-"lime", sodium chloride--"salt", etc.) by water, wind, or ice, e.g., sandstone, shale, limestone.

Slab foundation - a type of foundation without a basement or crawl space in which the weight of the building is supported by a concrete slab poured directly on the soil; not recommended in areas of swelling, settlement, hydrocompaction, or high water table; used in Colorado primarily for driveways and porches.

Soil - in engineering work a soil is any earthen material, excluding hard bedrock, composed of (1) loosely bound mineral and organic particles, (2) water, and (3) gases. In agriculture, a soil is the loose surface material capable of supporting plant growth, and having properties resulting from the integrated effect of climate and living matter.

Spread footing - a type of foundation in which the weight of the building is transmitted to the soil through bearing walls supported on concrete strips which are wider than the bearing wall; may be "continuous" or "discontinuous", with discontinuous being similar to pads.

Surficial deposits - unconsolidated deposits of gravel, sand, silt, or clay that are formed by the action of water, wind, ice, or gravity and overlie bedrock or other surficial deposits; some examples of surficial deposits are stream terraces, sand dunes, and glacial moraines.

Zone of seasonal moisture change - the upper portion of an engineering soil in which the moisture content varies with the season, i.e., high moisture content during a wet spring, lower moisture content during a dry summer.

APPENDIX B - SOURCES OF PROJECT DATA

The data for the Colorado Geological Survey swelling clay project represented a variety of testing methods and sources. Each of these sources, however, attempted to measure some of the factors influencing swelling mentioned in Appendix C--clay mineralogy, density, moisture content, time, soil structure, pore fluid, and loading conditions.

Colorado Geological Survey. Approximately 425 samples were tested specifically for the swelling clay project in the laboratories of the Colorado School of Mines and Kal Zeff & Associates. Clay mineralogy was determined for all samples using X-ray diffraction. All of the samples were also tested for grain size distribution and clay content (ASTM D421, D422 and D2217), liquid limit (ASTM D423), plastic limit (ASTM D424), shrinkage limit (ASTM D427), and natural moisture content (ASTM D2216). Other tests that were run on selected samples included dry unit weight (ASTM D2937), specific gravity (ASTM D 854), consolidation-swell under 1 psi surcharge (a modification of ASTM D2435), swell pressure (a combination of ASTM D2435 and D2166), and potential volume change (Lambe, 1960). Some standard penetration tests (ASTM D1586) were also run during the collection of the samples. From the results of these tests, index properties and soil classifications were determined, e.g., plasticity index (ASTM D424), shrinkage ratio (ASTM D427), activity ratio (Skempton, 1953), Unified Soil Classification (ASTM D2487), and the American Association of State Highway Officials (AASHO) Soil Classification (AASHO M145).

Several other sources of data were present within the Colorado Geological Survey. The Windsor Environmental Geology Project provided data for 15 samples from the Fort Collins-Greeley area. Liquid limit, plasticity index, grain size distribution (sieve analysis only), optimum moisture content and maximum density (ASTM D698), consolidation-swell (remolded sample) at 1000 psf surcharge, Unified Soil Classification, and ASHO Soil Classification were obtained for each of these samples. From the subdivision review files, data was obtained for approximately 200 samples run by various geological and soil engineering consultants (for types of tests, see section below on "Data from consultants and school districts").

Colorado Division of Highways. Before construction of highways, the Colorado Division of Highways prepares a preliminary "soil profile" along the proposed alignment. Sampling stations along this profile range from 100 to 3000 apart, with an average interval of 1000 ft. At each station one soil sample is generally collected at a depth of 2 or 3 ft. If more detailed investigation is necessary, more samples may be collected at depths ranging from several inches to 20 ft or more. These samples are then tested for grain size distribution (sieve analysis only, AASHO T27), liquid limit (AASHO T89), plastic limit (AASHO T90), moisture content, specific gravity (AASHO T100), and R-value (stabilometer test, AASHO T173, T174, T175). Additional data determined for the soil profile includes the plasticity index (AASHO T91) and the AASHO Soil Classification. Before 1967, the Division of Highways ran California Bearing Ratio (CBR)(ASTM D1883) instead of R-value, and often ran clay content (AASHO T88) and shrinkage limit (AASHO T92). Data from more than 800 samples were collected from Division of Highways file.

U. S. Geological Survey. As part of its cooperative projects with the Denver Regional Council of Governments, the U. S. Geological Survey (U.S.G.S.) tested soil samples from several 1:24,000 quadrangles in the western and southern Denver metropolitan areas. Results from tests on approximately 1300 samples were collected from this source. The tests performed on all of these samples were approximately the same as those used by the Colorado Geological Survey--grain size distribution, clay content, liquid limit, plastic limit, shrinkage limit, moisture content, and potential volume change. Other properties determined by the U.S.G.S. included plasticity index, activity ratio, Unified Soil Classification, and AASHO Soil Classification.

Data from consultants and school districts. The engineers, architects, and school districts listed in the acknowledgements section of this paper provided data for approximately 700 selected samples from throughout the Urban Corridor. This data generally included moisture content, dry unit weight ("dry density"), standard penetration test blow count, and some type of test for swell. In most cases the swell test was the consolidation-swell test run at surcharge pressures ranging from 144 psf (1 psi) to 3000 psf, with the majority at 600 psf to 1000 psf. However, some firms do not run standard consolidation-swell tests, preferring instead the "free" swell test (surcharge of 100 psf or less) or the potential volume change test. Other data obtained from some of these firms included liquid limit, plastic limit, plasticity index, shrinkage limit, unconfined compressive strength (ASTM D2166), grain size distribution (often just the total percentage of silt and clay), and the Unified Soil Classification.

APPENDIX C - FACTORS INFLUENCING SWELLING OF NATURAL CLAY SOILS

The potential volume change of a swelling clay depends on the following factors (Holtz, 1959; Johnson, 1969; Lambe and Whitman, 1959):

1. Clay mineralogy. Includes the following:
   a. Type of clay minerals--montmorillonite swells more than illite, while illite may swell more than kaolinite; generally determined by X-ray diffraction, electron microscopy (EM), or differential thermal analysis (DTA).
   b. Amount of clay minerals--a sample containing 50% montmorillonite generally swells more than one containing 10% montmorillonite; generally determined by X-ray diffraction or DTA.
   c. Exchangeable cation--sodium montmorillonite has greater potential for volume change than has calcium montmorillonite; cation exchange capacity is determined by infrared absorption spectroscopy.
   d. Clay particle size--small clay particles provide more surface area, therefore more water absorption per unit volume of clay, than larger particles; determined by centrifuge fractionation.
2. Density. Because there are more clay particles per unit volume in a dense soil than in a loose, low density soil, more swell is possible in the dense soil. Density is determined in the field by the sand-cone method (ASTM D 1556), the rubber-balloon. method (ASTM D 2167), or the nuclear moisture-density meter method, or in the laboratory by the drive-cylinder method (ASTM D 2937).
3. Moisture content. Dry clay has a greater swell potential than wet clay because more layers of water molecules can be adsorbed between the clay platelets of the dry clay. This is determined by oven drying in the laboratory (ASTM D 2216) or with the nuclear moisture-density meter in the field.
4. Soil structure. Remolded clays swell more than undisturbed clays under similar moisture-density conditions owing to preferred orientation of the clay platelets. The bonding of the clay particles in a cemented clay prevents swell pressures as high as those in a non-cemented clay. Preconsolidated clays may swell more than normal clays because of the addition of strain relief to the actual clay swelling. Electron microscopy is the preferred method to determine clay structure, while the consolidation test (ASTM D 2435) is used to determine preconsolidation.
5. Time. High plasticity clays have low permeabilities, and often become self-sealing when wetted, requiring from weeks to years to become saturated. Lower plasticity clays that have higher permeability may, therefore, swell more rapidly and cause more damage than do some high plasticity clays.
6. Pore fluid. The presence of calcium or sodium carbonate, calcium sulfate, or other salts in the pore fluid may lower water adsorption between the clay plates and, consequently, lower swell. Pore fluid chemistry is generally determined by chemical analysis.
7. Loading conditions. If the weight per unit area of a structure built on swelling soil is equal to the internal swelling pressure of the soil, volume change can be held to zero. This is the principle that governs the selection of a foundation design for a structure. Also, the allowance of a small amount of volume change, e.g , providing a void space below grade beams, will substantially reduce swell pressure. Proper load conditions can be determined by the consolidation-swell test (a modification of ASTM D 2435).

APPENDIX D - METHODS FOR ESTIMATING SWELL POTENTIAL FROM SOIL INDEX PROPERTIES

The data utilized in the production of the swelling clay map of the Urban Corridor were obtained from a variety of sources and testing methods, as explained in Appendix B. Because of this variety, four different swell classifications were evaluated. Each of these classifications grouped swell potential into four categories--low, medium, high, and very high--based on selected soil index properties. In order to evaluate the accuracy of these index classifications, a complete battery of index tests was run on several hundred samples. For each of these samples, the swell category indicated by the index classification was compared to a swell category derived from consolidation-swell test data for the sample. The index classification was also compared to the clay mineralogy of the sample as determined by X-ray diffraction spectrometry. These comparisons were necessary for this project because consolidation-swell tests and X-ray mineralogy are expensive and exceedingly time-consuming tests, whereas index tests are cheap and simple. Inexpensive tests were requisite because sufficient data were necessary to provide at least a "pseudo-statistical" approach to the mapping of areas of swelling clay. If statistics were to be utilized, scores of samples had to be taken from locations spaced as closely, both geographically and stratigraphically, as was possible within time and economic constraints. Only through primary reliance on index testing could this be accomplished.

Potential Volume Change. One index classification evaluated by the C.G.S. was the Potential Volume Change (PVC) test developed for the Federal Housing Administration in 1959 (Lambe, 1960). The apparatus utilized in this test consisted of a modified floating ring consolidometer in a loading frame with a proving ring between the consolidometer and loading frame. An air-dried sample of soil finer than the #10 sieve was compacted into the consolidometer in three layers with seven blows per layer from a 5.5 lb hammer dropped 12 in. The sample was then flooded with water and the sample allowed to swell against the proving ring. The dial, (calibrated in 0.0001 in. units), on the proving rings was read after two hours and converted to a "swell index" in pounds per square foot (psf). This index value was converted to a swell classification as follows:

PVC No.	Swell Potential
0-2	Noncritical
2-4	Marginal
4-6	Critical
> 6	Very Critical

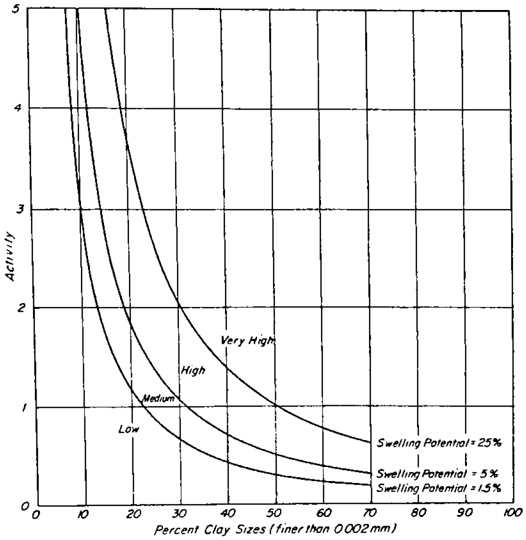
This classification system probably approximated the maximum potential swell which could have been exerted by each sample under air-dried, recompacted conditions. It was, therefore, not surprising that the swell potential categories determined from the PVC for more than 200 Urban Corridor project samples exceeded those determined by the other swell classifications for 40 percent of the samples. An interesting sidelight, however, was that the PVC test generally indicated "noncritical" whenever a gypsiferous or highly plastic kaolinitic soil was tested. The index classifications based, in part, on Atterberg Limits generally indicated "moderate" or "high" swell potential for these same soils.

Chen Classification. In 1965, a Denver soil engineer (Chen, 1965) introduced an index classification system for swelling soils based on three standard AASHO tests. This system compared the percentage of swell from the consolidation-swell test (1000 psf surcharge) to the liquid limit, the percentage of the sample finer than the #200 sieve (0.074 mm), and the standard penetration test blow count. This system classified swell as follows:

% < #200 sieve	Liquid limit (%)	Standard Penetration (blows/ft)	Consolidation swell (%)	Swell Category
> 95	> 60	> 30	> 10	Very high
60-95	40-60	20-30	3-10	High
30-60	30-40	10-20	1-5	Medium
< 30	< 30	< 10	< 1	Low

Utilizing test data from approximately 100 samples, the Chen classification was evaluated as part of the Urban Corridor project. This evaluation indicated that this system classified 22 percent of the samples higher than, and 10 percent of the samples lower than they were classified by their respective consolidation-swell tests.

Seed-Woodward-Lundgren Classification. In 1962 several San Francisco Bay area soil engineers (Seed, Woodward, and Lundgren, 1962) presented an index classification for swell based on studies of recompacted clays. However, the system was assumed by its originators to be applicable to natural clays as well as recompacted samples. The index parameters utilized in this system included the percentage of the sample finer than 0.002 mm and the activity ratio (Skempton, 1953). The activity ratio is a ratio of the plasticity index to the percentage of the sample finer than 0.002 mm. These index values were compared to the percentage swell of a dry sample at 144 psf surcharge in the following graph:



The evaluation of data for the Urban Corridor project indicated that this system provided values higher than consolidation-swell for 13 percent and lower than consolidation-swell for 17 percent of the samples.

Holtz-Gibbs Classification. One of the first, and still on of the best, index classifications for swell was developed by the Bureau of Reclamation in Denver in the early 1950's (Holtz and Gibbs, 1956; Holtz, 1959). This system compared the plasticity index, the shrinkage limit, and the percentage of the sample finer than 0.001 mm to the Bureau of Reclamation swell test at 144 psf surcharge, as shown below:

% < 0.001 mm	Plasticity Index (%)	Shrinkage limit (%)	% swell (USBR)	Swell Category
> 28	> 35	> 11	> 30	Very high
20-31	25-41	7-12	20-30	High
13-23	15-28	10-16	10-20	Medium
< 15	< 18	< 15	< 10	Low

This system more nearly approximated the results of the consolidation-swell test in the Urban Corridor project than did any other system. Only 3 percent of the samples evaluated were higher, and 14 percent lower, than the results of the consolidation-swell tests.

Other Classifications. Many other types of swelling classifications have been developed in the United States, South Africa, Israel, India, and other countries that have serious swelling soil problems. Several of these were studied, but not extensively evaluated, for the Urban Corridor project. A system developed by consulting engineers (Vijayvergiya and Sullivan, 1972) in Houston, Texas, correlated dry unit weight, liquid limit, and percentage swell at 200 psf surcharge for the Pleistocene Beaumont Clay. In Israel a system comparing dry unit weight, moisture content, and liquid limit to swell pressure was developed by Komornik and David (1969). Jennings (1969) developed the "double oedometer" test (two simultaneous consolidation-swell tests on the same sample) for measuring potential swell in South Africa. In India, a system comparing the shrinkage index (liquid limit minus shrinkage limit) to swelling potential was developed for recompacted clays (Ranganatham and Satyanarayana, 1965). Many attempts have also been made by researchers in Australia, South Africa, Oklahoma, Texas, and other areas to correlate the Thornthwaite climatic index with expected ranges of potential swell.

Conclusions and Recommendations. The Holtz-Gibbs Classification most closely approximated consolidation-swell test results for the Urban Corridor samples. The Chen and Potential Volume Change Classifications generally indicated the maximum potential swell for any particular sample. The Seed-Woodward-Lundgren Classification was intermediate between these two extremes. Further evaluation of these, and the other classification systems mentioned above, and application of these systems to Colorado, is needed before any single system is chosen as best for Colorado soils. Government, university, and industry research projects in the study of index classification systems for swelling soils are urgently needed in Colorado. Funding for such research may be arranged through the American Society of Civil Engineers Research Council on the Behavior of Expansive Earth Materials.

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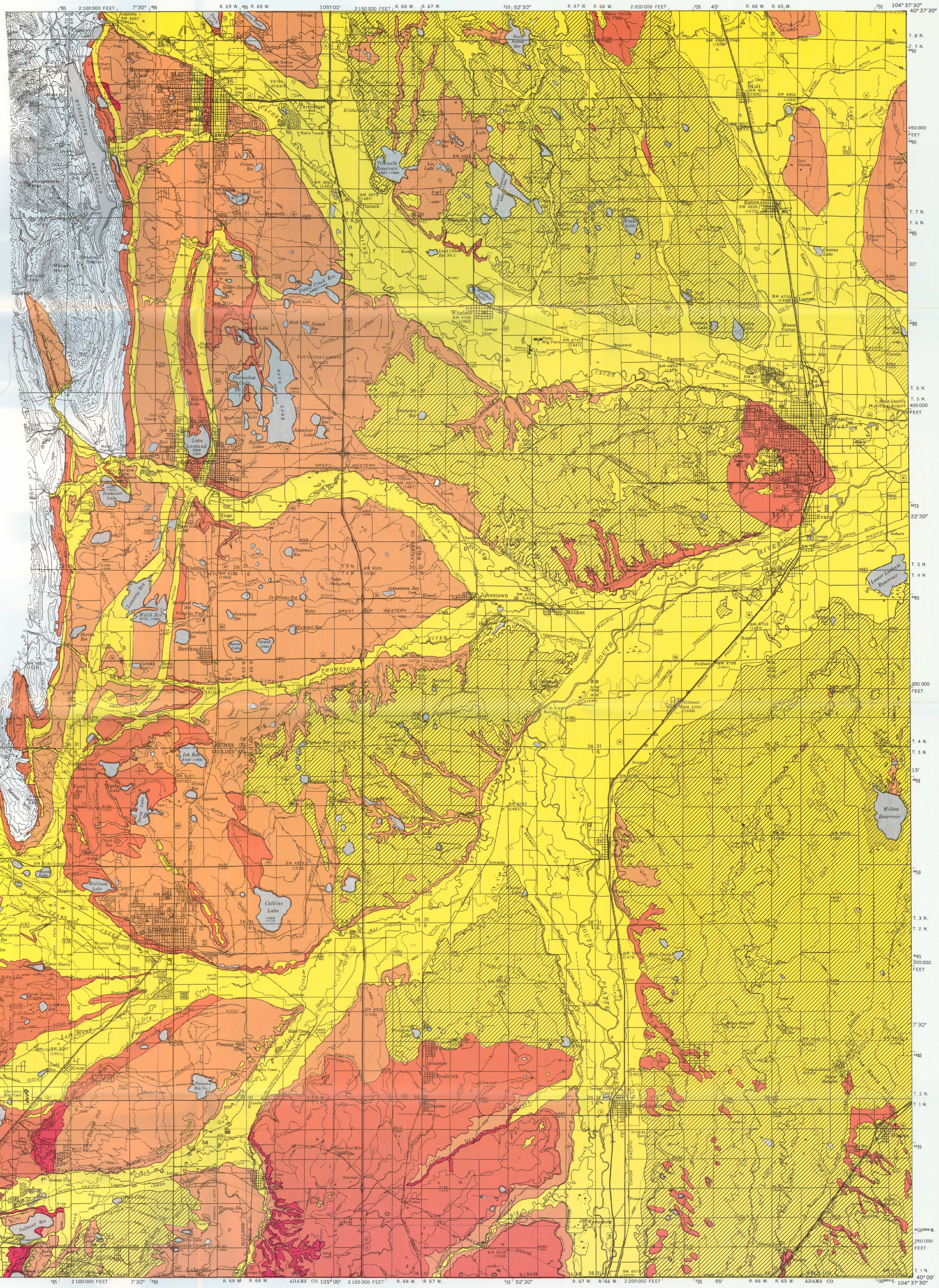
BOULDER - FORT COLLINS - GREELEY AREA
COLORADO



EXPLANATION

NOTE: *The swell potential categories shown below generally apply to the upper 10 ft of soil or rock. However, local variations in thickness of surficial deposits should be expected. Therefore, this information should not be considered adequate for an individual building site. A registered professional soil engineer should be utilized for site investigation and foundation design for every building site in the Front Range Urban Corridor.*

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13½°
TRUE NORTH
MAGNETIC NORTH
DECLINATION AT CENTER OF SHEET

Map edited and published by the Colorado Geological Survey, 1973–1974

Base map from U. S. Geological Survey, 1972

CARTOGRAPHICS: JAMES A. BARNES

POTENTIALLY SWELLING SOIL AND ROCK IN THE FRONT RANGE URBAN CORRIDOR, COLORADO

BY
Stephen S. Hart

INDEX TO USGS 7.5' QUADRANGLES

BUCKHORN MTN 1962	HORSETOOTH RESERVOIR 1962-REV 71	FORT COLLINS 1960-REV 69	TIMNATH 1960-REV 71	SEVERANCE 1960-REV 71	EATON 1960-REV 71
DRAKE 1962	MASONVILLE 1962-REV 71	LOVELAND 1960-REV 69	WINDSOR 1950-REV 69	BRACEWELL 1950-REV 69	GREELEY 1949-REV 71
PINEWOOD LAKE 1962	CARTER LAKE RESERVOIR 1962-REV 71	BERTHOUD 1960-REV 69	JOHNSTOWN 1950-REV 69	MILLIKEN 1950-REV 69	LA SALLE 1950-REV 69
LYONS 1957-REV 66	HYGIENE 1950-REV 71	LONGMONT 1950-REV 71	GOWANDA 1949-REV 69	PLATTEVILLE 1949-REV 69	MILTON RESERVOIR 1950-REV 71
BOULDER 1957-REV 71	NIWOT 1950-REV 71	ERIE 1950-REV 71	FREDERICK 1950-REV 69	FORT LUPTON 1949-REV 69	HUDSON 1949-REV 71

FRONT RANGE URBAN CORRIDOR
SHEET 1 OF 4

SCALE 1:100,000

CONTOUR INTERVAL 100 FEET
DOTTED LINES REPRESENT 50-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL

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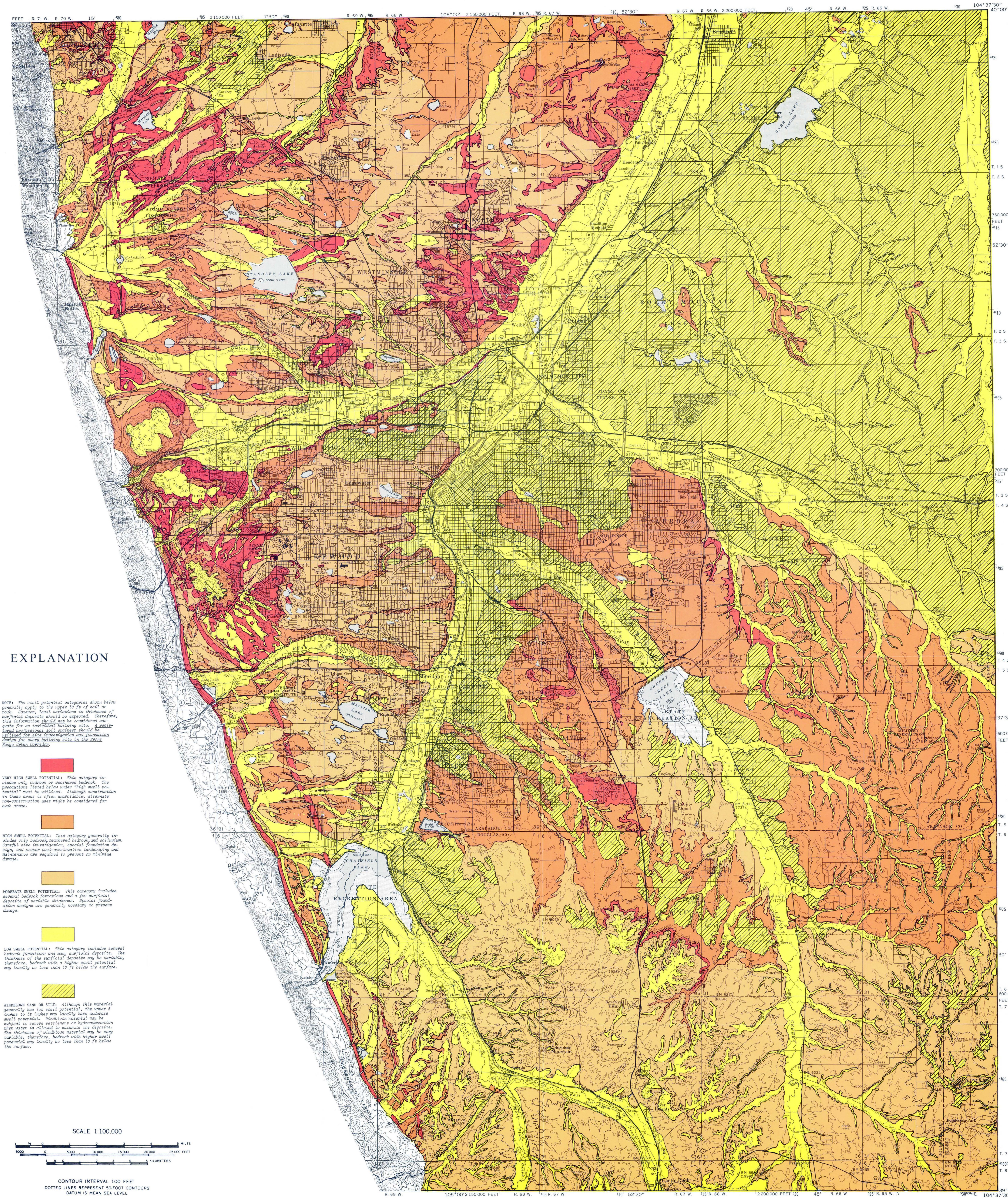
GREATER DENVER AREA
COLORADO



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SCALE 1:100,000

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DOTTED LINES REPRESENT 50-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL

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DECLINATION AT CENTER OF SHEET

POTENTIALLY SWELLING SOIL AND ROCK IN THE FRONT RANGE URBAN CORRIDOR, COLORADO

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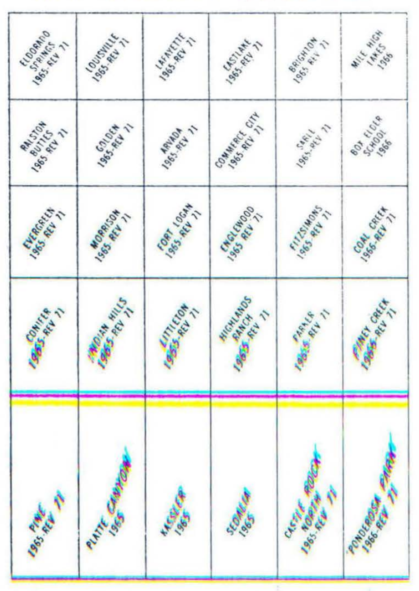
INDEX TO USGS 7.5' QUADRANGLES



FRONT RANGE URBAN CORRIDOR
SHEET 2 OF 4

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EXPLANATION

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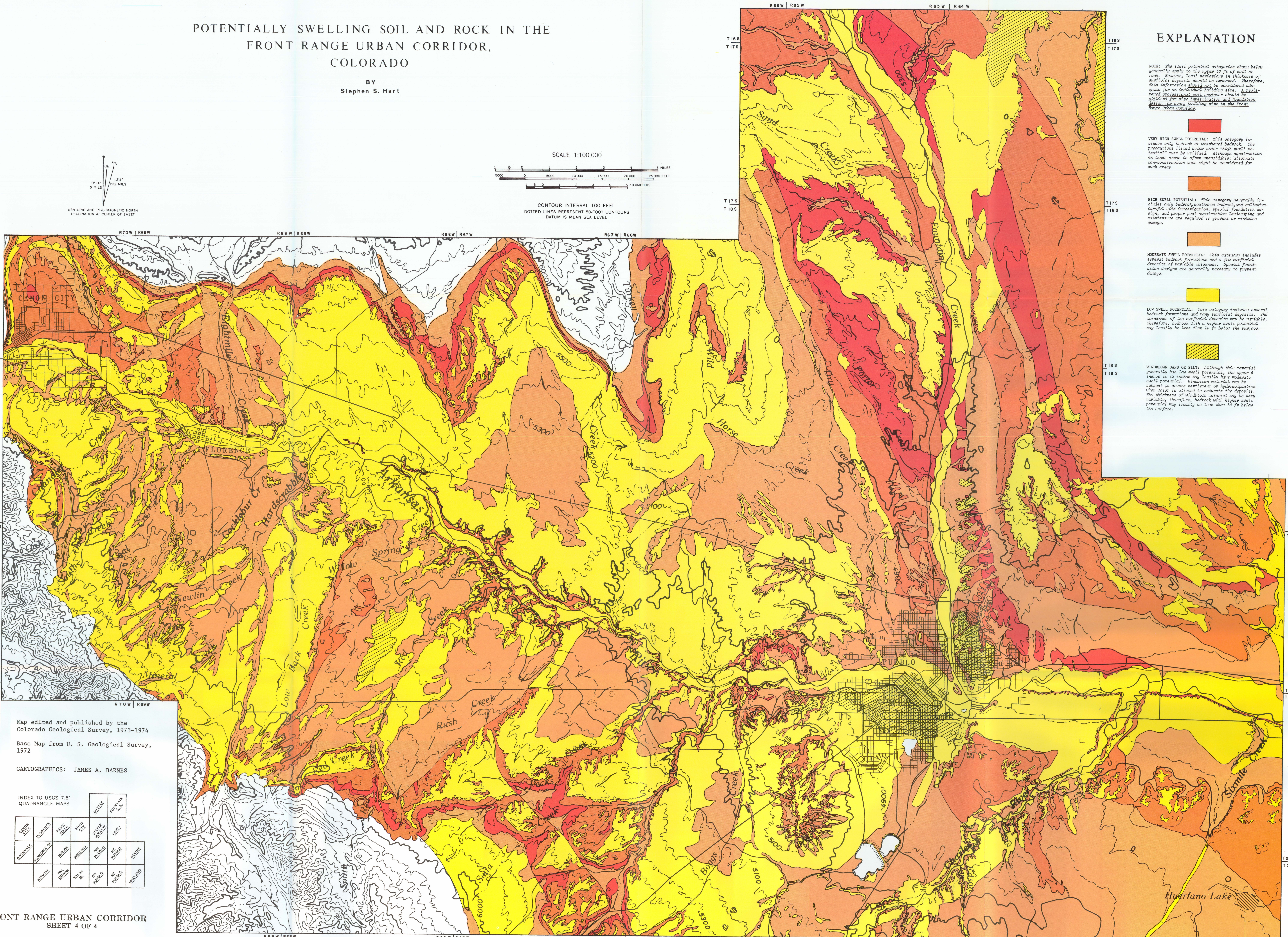
PUEBLO - CANON CITY AREA
COLORADO

POTENTIALLY SWELLING SOIL AND ROCK IN THE FRONT RANGE URBAN CORRIDOR, COLORADO

BY
Stephen S. Hart



SCALE 1:100,000

CONTOUR INTERVAL 100 FEET
DOTTED LINES REPRESENT 50-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL

UTM GRID AND 1970 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

EXPLANATION

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