COLORADO ROCKFALL SIMULATION PROGRAM

VERSION 4.0

For Windows 95, 98, and NT

Colorado Department of Transportation

Colorado School of Mines

Colorado Geological Survey

March 2000

REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
March 2000

3. REPORT TYPE AND DATES COVERED

4. AUTHOR(S)

Christopher L. Jones, Jerry D. Higgins, and Richard D Andrew

5. FUNDING NUMBERS
12-6-93
30.28

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(S)

Colorado Dept. of Trans.
4201 East Arkansas Avenue
Denver, CO 80222

Colorado Geol. Survey
1313 Sherman Street, #715
Denver, CO 80203

Colorado School of Mines
Golden, CO 80401

8. PERFORMING ORGANIZATION REPORT NUMBER
CDOT-SYMB-CGS-99-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESSES(S)

Colorado Department of Transportation
4201 East Arkansas Avenue
Denver, CO 80222

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

12.a. DISTRIBUTION/AVAILABILITY STATEMNET

No restrictions: this report is available to the public through the National Technical Information Service, Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This rockfall computer program, which simulates rocks tumbling down a slope, predicts the statistical distribution of speed and bounce height and can be used for locating and designing rockfall mitigation. The model takes into account slope profile, rebound and friction characteristics of the slope and rotational energy of the rocks. Spherical, cylindrical and disk shaped rocks can be simulated. At each impact, the slope angle is randomly varied from the nominal value input by the user within the limit set by the maximum probable variation in the slope. The model is recommended as a tool for the geologist and engineer responsible for analyzing and mitigating rockfall hazards.

14. SUBJECT TERMS

Rockfall, simulation, computer, slope profile, surface roughness.

15. NUMBER OF PAGES
127

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

COLORADO ROCKFALL SIMULATION PROGRAM
VERSION 4.0 (FOR WINDOWS)

By

Christopher L. Jones
Research Assistant
Colorado School of Mines

Jerry D. Higgins, Ph.D., P.G.
Associate Professor of Geological Engineering
Colorado School of Mines

Richard D. Andrew, P.G.
Engineering Geologist
Colorado Department of Transportation

Sponsored by

Colorado Department of Transportation

March 2000

For additional information or comments on the program, please contact Robert Beck, Department of Transportation, Geotechnical Section, 4340 Louisiana Avenue, Denver, CO 80246-3482, Phone 303-757-9749, Fax 303-757-9242, Email rob.beck@dot.state.co.us

ABOUT THE COVER

Oblique aerial photograph of the Missionary Ridge rock slide on the east wall of Animas Valley, three miles northeast of Durango, Colorado. On July 5, 1998 approximately 50,000 cubic yards of Dakota Sandstone cliff toppled and slid down into the Animas Valley. The slide occurred in a rural area 2,000 feet above the valley floor. There were no fatalities. Photo courtesy of the Low Altitude Large Scale Reconnaissance Group, Colorado Department of Transportation Geology Unit.

(For more information, see Carroll and others, 1999, Geologic Map of the Durango East Quadrangle, La Plata County, Colorado, Colorado Geological Survey Open-File Report 99-6)

CONTENTS

FIGURES

TABLES

SUPPLEMENTARY

FOREWORD

The Colorado Rockfall Simulation Program (CRSP) 4.0 and this technical report are the result of a Master of Engineering thesis project in Geological Engineering at the Colorado School of Mines (CSM). The project was conducted by Christopher L. Jones and supervised by Dr. Jerry D. Higgins, Associate Professor of Geological Engineering, and Richard D. Andrew, an engineering geologist for the Colorado Department of Transportation (CDOT). Dr. A. Keith Turner, Professor of Geological Engineering, served as a thesis committee member and was a valuable advisor on calibration issues. The project was funded by CDOT. Mr. Paul Burger assisted with final program modifications following testing and Pamela Miller assisted with manuscript preparation.

CRSP 4.0 is a Windows version of the original algorithm. The only modifications to earlier versions involve file editing, pop-up windows, graphics, and user friendliness.

The original CRSP version 1.0 was written by Timothy J. Pfeiffer for a Master of Engineering thesis in Geological Engineering at CSM in 1988. The project was supervised by Dr. Higgins. The research was partially funded by CDOT and was used originally on rockfall studies for the Glenwood Canyon I-70 project. Later versions included:

- Version 2.1 (1991) manual revised by Richard D. Andrew and program revised by Robert Beck (CDOT).
- Version 3.0 (1993) manual revised by Richard D. Andrew and Robert Beck and program revised by Richard J. Schultz, Timothy J. Pfeiffer, Richard D. Andrew, and Robert B. Beck (CDOT).
- Version 3.0a (1995) program revised by Richard D. Andrew (CDOT).

x

CHAPTER 1—INTRODUCTION

Disclaimer

The contents of this report reflect the view of the authors. The contents do not necessarily reflect the official views or policies of the Colorado Department of Transportation or the Colorado School of Mines. This report does not constitute a standard, specification, or regulation.

The Colorado Rockfall Simulation Program has been tested and is believed to be a reliable engineering tool. No responsibility is assumed by the authors for any errors, mistakes, or misrepresentations that may occur from any use of the program.

Problem Statement

Rockfall is a natural result of weathering on steep natural slopes or rock cuts. Rocks falling from steep slopes, natural cliffs, or rock cuts usually travel down the slope in a combination of free fall, bouncing, and rolling. In this report, rockfall refers to rocks traveling in a combination of these modes.

Rockfall presents a common hazard to transportation routes and structures in steep mountainous terrain. Until recently, it was common practice along transportation routes to provide little protection other than posting warning signs. As traffic has increased in rockfall areas, there has been more emphasis on mitigation of rockfall hazards, which has created a need for more understanding of rockfall behavior.

Tools that can accurately predict rockfall behavior are of great value in the design of mitigation schemes. Prior to the development of the Colorado Rockfall Simulation Program (CRSP), selection and design of rockfall protection measures were severely limited, as only Ritchie's (1963) ditch design criteria were widely used (although some other alternatives, including computer programs, existed). CRSP has been in use nearly ten years, but its accuracy has been limited by the quality of the required input coefficients (normal coefficient of restitution and tangential coefficient of frictional resistance), which were based on limited calibration efforts. As a result, the program is normally calibrated to sites using observational data.

Another weakness of CRSP has been that it was originally developed prior to the more "user-friendly" Windows operating environment, and it did not include subroutines that allowed iterative calibration runs to be conducted easily. In addition, the construction of input and output files was awkward.

Objectives and Purpose

The overall purpose of this project is the improvement of the Colorado Rockfall Simulation Program (currently Version 3.0a). Objectives to reach this purpose include: re-calibrating the program's input coefficients (normal coefficient of restitution and tangential coefficient of frictional resistance), producing a version of CRSP compatible with Windows 95 and Windows NT, and making minor modifications to the program (e.g., to the data input portion of the program) to increase "user-friendliness". The reprogramming was performed using Microsoft Visual Basic® (Version 4.0).

Scope of Research

The research included the re-calibration of input coefficients (normal coefficient of restitution and tangential coefficient of frictional resistance) for CRSP through the accumulation of rockfall data provided by Caltrans and the original CRSP calibration effort. The data was evaluated for accuracy and then used for input coefficient calibration. The data was chosen based on availability, slope forming materials, and slope angle to provide calibration information for varieties of slope properties not well represented by existing calibration data. In addition, CRSP was re-programmed using Visual Basic. In conjunction with the re-programming, the data input/text editor section of CRSP was modified to make the function easier to use. Finally, the CRSP statistical analysis section was evaluated.

The research has two products.

1. CRSP Version 4.0 based on the re-calibration of input coefficients, reprogramming using Visual Basic, and minor program modifications.

2. A new CRSP user's technical report that documents this research effort and includes a chapter on the use of the program (Chapter 8).

CHAPTER 2—PREVIOUS WORK AND BACKGROUND

The following information on the development and theory of the Colorado Rockfall Simulation Program is taken after Pfeiffer (1989) and Pfeiffer et al. (1991; 1995).

Program Development

The Colorado Rockfall Simulation Program (CRSP) was originally developed for use in conjunction with the construction of I-70 through Glenwood Canyon, Colorado. The program simulates rockfall events at a site from data describing slope irregularities, slope materials, slope profile, and rock size. The final product is a reasonably easy-to-use rockfall simulation program. Conventional design of rockfall protection using the ditch design criteria of Ritchie (1963) was often not applicable to the natural slopes of Glenwood Canyon or was aesthetically unacceptable. A reasonable estimate of probable bounce height and velocity of rockfall events was needed in order to design rockfall fences and alternative catch ditches in Glenwood Canyon. It was thus decided that a rockfall simulation program for PC-compatible style computers could best provide such data.

Development of CRSP took place between August of 1985 and May of 1989. Experimental verification and calibration of CRSP was conducted in conjunction with the testing of rockfall fences at a site near Rifle, Colorado. Videotapes recorded the motion of rocks traveling down a slope and impacting the test fence. Research conducted at the Colorado School of Mines added graphical data presentations to the program and analyzed the videotapes to verify and calibrate the simulation program.

Program Theory

The proper use of any computer-engineering tool requires an understanding of the basis of the program. Such comprehension helps the user of the program to choose appropriate input data and recognize reasonable results. While CRSP adds objectivity to the otherwise very subjective task of investigating rockfall, many aspects of using CRSP rely on the judgement of the investigator, and it is the investigator's responsibility to understand the applications and limitations of CRSP. The following presentation of the theory behind CRSP should help the investigator to understand the principles behind rockfall modeling and, hence, to make better decisions while using CRSP.

Rockfall Parameters

The behavior of rockfall is influenced by slope geometry, slope material properties, rock geometry, and rock material properties (Ritchie, 1963). Rockfall events originating from the same source location may behave very differently as a result of the interaction of these factors. Parameters that quantify slope geometry, slope material properties, rock geometry, and rock material properties (Table 1) are used to model rockfall behavior.

Table 1. Parameters determining behavior of rockfall.

Factor	Parameter
Slope Geometry	Slope Inclination
	Slope Length
	Surface Roughness
	Lateral Variability
Slope Material Properties	Slope Coefficients
	Rock Coefficients
Rock Geometry	Rock Size
	Rock Shape
Rock Material Properties	Rock Durability
	Rock Mass

Slope geometry parameters influencing the behavior of rockfall are slope inclination, slope length, surface roughness, and lateral variability of the slope surface. Slope inclination is critical because it partly defines zones of acceleration and deceleration of the rockfall. Slope length determines the distance over which the rock accelerates or decelerates. Slope inclination and length are input to CRSP by dividing the slope into straight-line segments called cells and entering the beginning and ending coordinates of each segment.

Apart from slope inclination and length, interaction of surface irregularities with the rock is perhaps the most important factor in determining the behavior of rockfall. Irregularities in the slope surface account for most of the variability observed among rockfall events originating from a single source location. These irregularities, referred to as surface roughness, alter the angle at which a rock impacts the slope surface. It is this impact angle that largely determines the character of the bounce (Wu, 1984). CRSP models surface irregularities by randomly varying the slope angle between limits defined by the rock size and surface roughness.

Slope material properties influence the behavior of a rock rebounding from a slope. Numerical representations of these properties are termed the normal coefficient of restitution (R_n) and the tangential coefficient of frictional resistance (R_t), where the normal direction is perpendicular to the slope surface, and the tangential direction is parallel to the slope surface (Piteau and Associates, 1980; Wu, 1984). The velocity components and coefficients are illustrated in Figure 1. In determining new velocity components for a rock following impact, separate normal and tangential coefficients are necessary due to the different mechanisms involved in resisting motion normal and tangent to the slope. When a rock bounces on a slope, kinetic energy is lost due to inelastic components of the collision and friction. While the primary mechanism in resisting motion parallel to the slope is sliding or rolling friction, the elasticity of the slope determines the motion normal to the slope. R_n is a measure of the degree of elasticity in a collision normal to the slope, and R_t is a measure of frictional resistance to movement parallel to the slope.

Because a larger rock has greater momentum and is less likely to lodge among irregularities, it will travel farther down a slope than a smaller rock (Ritchie, 1963). Rock size is thus critical in determining the degree to which surface roughness will affect rockfall

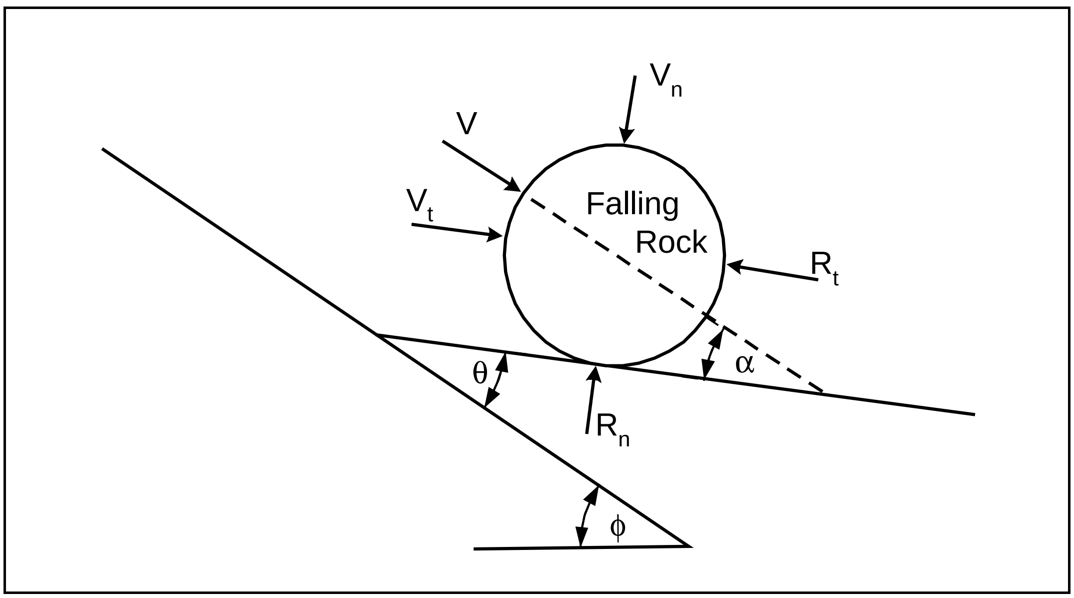


Figure 1. Impact angle (α) defined as a function of rock trajectory, slope angle (ϕ), and slope variation (θ). Rock velocity (V) is reduced into normal (V_n) and tangential (V_t) components. The tangential coefficient of frictional resistance (R_t) and the normal coefficient of restitution (R_n) act to decrease the falling rock's velocity (Pfeiffer, 1989; Pfeiffer et al., 1991; 1995).

behavior. Another important property of the rock is shape. Rock shape contributes to the randomness of rockfall behavior in a manner similar to that of slope surface roughness. Rock shape also influences the apportionment of translational and rotational energy through the moment of inertia.

A critical rock property is durability, which determines whether a rock will break apart upon impact. Rock fragmentation dissipates a large amount of energy and reduces individual rock size. Rock size has a direct relationship to kinetic energy and momentum, which are fundamental considerations in any impact. Two factors act to reduce the influence of rock durability and rock mass on a rockfall. First, the consistency of durability and mass minimizes their effect on the variability of the rock's behavior. Second, the variation of properties among rocks is considerably less than among slopes or even within a given slope.

Program Assumptions

On a natural slope, the parameters in Table 1 will have a wide range of values and would be cumbersome to analyze as independent variables. CRSP reduces the number of variables by means of the following simplifying assumptions:

The slope profile should follow the most probable rockfall path as established during field investigations. Therefore, all calculations may be in two dimensions.

Because the rock type does not change during a rockfall and the range of slope material properties is much greater than that of rock material properties, coefficients assigned to the slope material (R_n and R_t) can account for both the rock and slope properties.

The worst case scenario is generally that of the largest rock that remains intact while traveling down a slope. Therefore, it is assumed that the rock does not break apart in its fall.

Rock size and shape are assumed constant for analysis of rockfall from a given source. Values assigned to these parameters are determined by field study of the source area and slope materials.

For determination of a rock's volume and inertia, a sphere may be used because it yields a maximum volume for a given radius, which will tend toward a worst case. CRSP will also allow the use of discoidal or cylindrical rocks.

CRSP Algorithm

Rockfall simulation begins within a selected vertical zone representing the source location by assigning a rock nominal initial horizontal and vertical velocity components. The velocity components are acted upon by gravitational acceleration until the rock's trajectory intersects the slope below at resultant velocity V_1. At each impact, the incoming velocity, impact angle, and rotational velocity are used to calculate new velocity components and rate of rotation. At the point of impact, the slope angle (ϕ) is randomly varied up to the limit set by the maximum probable variation in the slope (θ_{max}). This limit is determined by field observation of the slope surface. The surface roughness (S) is defined as the perpendicular variation of the slope within a slope distance equal to the radius of the rock (Figure 2). This describes the slope angle experienced by the rock on impact. Surface roughness (S) and rock radius (R) are used in calculating the maximum allowable variation in slope angle (θ_{max}) by equation 1.

$$\theta_{\max} = \tan^{-1}\left(\frac{S}{R}\right) \qquad \textbf{(1)}$$

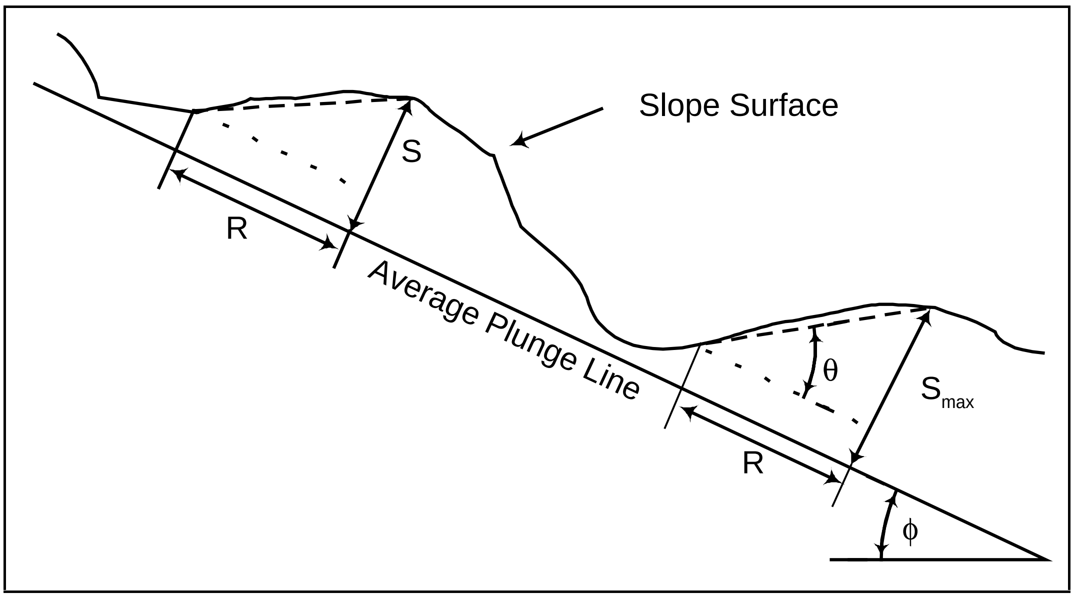


Figure 2. Surface roughness (S) established as the perpendicular variation from an average plunge line (defined by slope angle ϕ) over a distance equal to the radius of the rock (R). Maximum slope variation (θ_{max}) is defined by S and R (Pfeiffer, 1989; Pfeiffer et al., 1991; 1995).

The angle of variation (θ) is a randomly selected angle, less than θ_{max}, that determines the variation in the slope angle (ϕ). This random variation is largely responsible for the statistical variation of rockfall events modeled by CRSP. The impact angle (α), is used to resolve the incoming velocity (V_1) into velocity components tangential ($V_{t1} = V_1\cos\alpha$) and normal ($V_{n1} = V_1\sin\alpha$) to the slope surface (Figure 1).

A new tangential velocity is calculated from the conservation of energy considerations in equation 2.

$$\left(\frac{1}{2}I\omega_1^2 + \frac{1}{2}MV_{t_1}^2\right)f(F)SF = \frac{1}{2}I\omega_2^2 + \frac{1}{2}MV_{t_2}^2 \tag{2}$$

where:

M = rock mass

I = rock moment of inertia

$I = \dfrac{2MR^2}{5}$ (for a sphere)

$I = \dfrac{MR^2}{2}$ (for a disk)

$I = \dfrac{MR^2}{4} + \dfrac{ML^2}{12}$ (for a cylinder, L = length)

ω_1 = initial rotational velocity

ω_2 = final rotational velocity

V_{t1} = initial tangential velocity

V_{t2} = final tangential velocity

$f(F)$ = friction function

$$= R_t + \frac{1 - R_t}{\left(\dfrac{V_{t_1} - \omega_1 R}{20}\right)^2 + 1.2}$$

SF = scaling factor

$$= \frac{R_t}{\left(\dfrac{V_{n_1}}{250R_n}\right)^2 + 1}$$

In any non-perfectly elastic collision, kinetic energy is lost. In the case of a rock impacting a slope, the component of kinetic energy parallel to the slope and the rotational energy are attenuated by friction along the slope and collisions with features perpendicular to the slope. Friction is a function of the slope material, determined by the tangential coefficient and whether the rock is initially rolling over or sliding upon the surface. The friction function adjusts the tangential coefficient according to the velocity at the surface of the rock relative to the ground at the beginning of the impact. Figure 3 shows a graph of the friction function.

Another major influence on the loss of kinetic energy tangential to the slope is the velocity normal to the slope. An increase in velocity normal to the surface results in a greater normal force during impact. The scaling factor adjusts for the increased frictional resistances due to an increase in the normal force.

Equation 2 may be solved for the new tangential and rotational velocities by establishing the relationship between rotational velocity and tangential velocity shown by equation 3.

$$V_{t_2} = \omega_2 R \qquad \textbf{(3)}$$

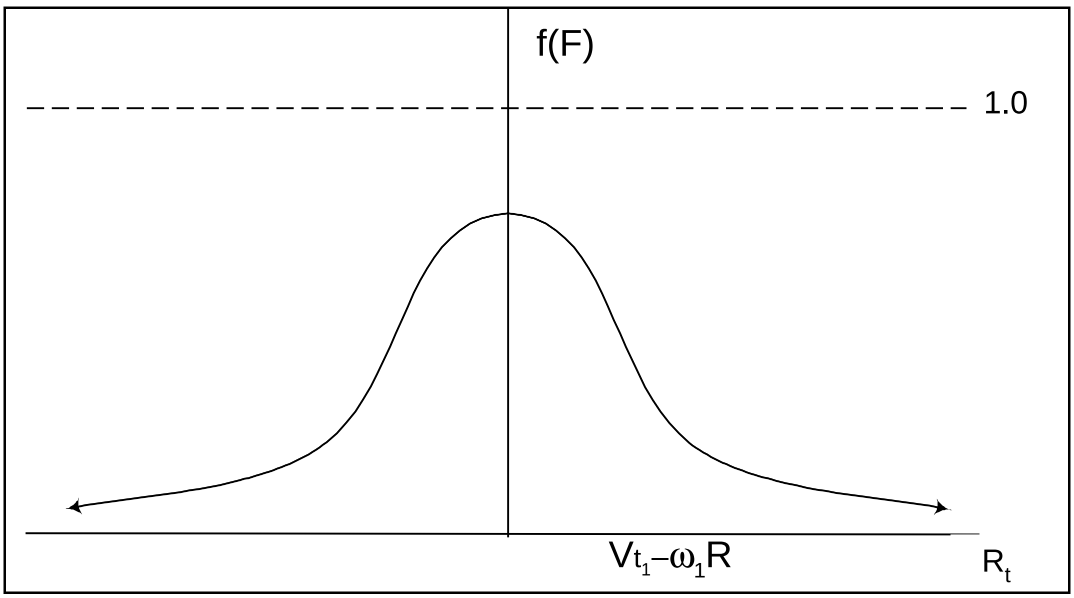


Figure 3. Friction function $f(R_t, V_{t1} - \omega_1 R)$ as a function of the difference between tangential and rotational velocities (Pfeiffer, 1989; Pfeiffer et al., 1991; 1995).

Equation 3 describes the situation where the rock rolls across the surface during impact rather than sliding. Observations of bouncing rocks show that regardless of the initial rotational velocity, rocks always leave the surface in the rolling mode. The relationship in equation 3 allows rotational energy to be applied to tangential velocity, or tangential velocity to be applied to rotational velocity. The energy lost during the bounce is determined from the difference between rotational and tangential velocities, the velocity normal to the slope, and the tangential coefficient. Constants used in the friction function and the scaling factor were determined by experiment. Solving equation 2 for the new tangential velocity yields equation 4.

$$V_{t_2} = \sqrt{\frac{R^2\left(I\omega_1^2 + MV_{t_1}^2\right)f(F)SF}{\left(I + MR^2\right)}} \tag{4}$$

A new normal velocity (V_{n2}) is established by equation 5.

$$V_{n_2} = \frac{V_{n_1} R_n}{1 + \left(\frac{V_{n_1}}{30}\right)^2} \tag{5}$$

This equation uses the coefficient of restitution (R_n) and a velocity-dependent scaling factor ($1/(1 + V_{n1}/30)^2$) to determine the new normal velocity (V_{n2}).

The normal scaling factor (B), graphically represented in Figure 4, adjusts for the decrease in normal coefficient of restitution as the impact velocity increases. This factor represents a transition from more elastic rebound at low velocities to much less elastic rebound caused by increased fracturing of the rock and cratering of the slope surface at higher impact velocities (Habib, 1976).

After each bounce, CRSP performs an iteration to find the time elapsed until the next bounce. Elapsed time is calculated from x- and y-velocity-components, gravitational acceleration, and the slope profile. After a new impact position is established, the next bounce is calculated as before. If the distance the rock travels between bounces is less than its radius, it is considered to be rolling and is given a new (x, y) position equal to a distance of one radius from its previous position. This models a rolling rock as a series of short bounces, much like an irregular rock rolls on an irregular surface.

Sensitivity to Input Parameters

With so many parameters affecting the simulation results in different ways, it becomes difficult to understand just how each parameter affects the results. When using a computer simulation model, an investigator usually performs several simulations with a range of possible input parameters. Therefore, it is often helpful when choosing a range of input parameters to know what effect each input parameter has on the results. By varying only one input parameter at a time for a site of interest, the effect of each parameter may be observed.

On a uniform slope, rock size will not affect rockfall behavior. However, natural slopes are not usually uniform, and thus the size of the rock does affect rockfall behavior. On portions of the slope where the rock's velocity is decreasing, a large rock having more momentum will require more distance to slow down than a relatively small rock. Another reason large rocks travel farther and faster than small rocks is the effect of surface roughness. While the surface roughness is proportional to the rock size, on most slopes the

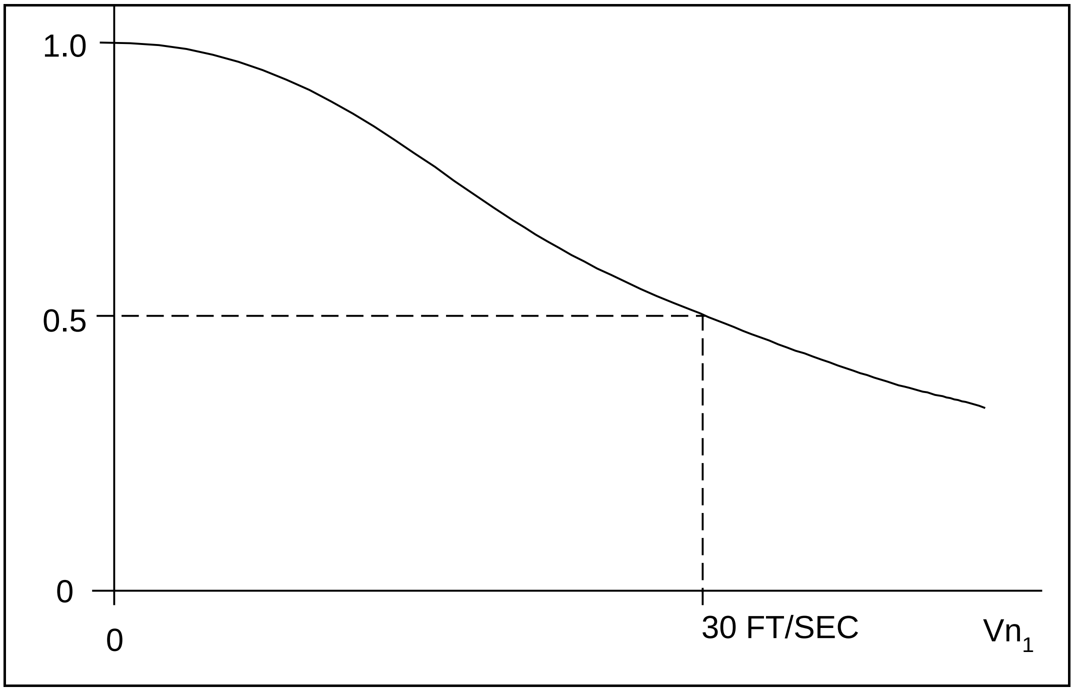


Figure 4. Normal coefficient scaling factor, $B = \dfrac{1}{1+\left(\dfrac{V_{n_1}}{30}\right)^2}$ **, as a function of the incoming normal velocity (Pfeiffer, 1989; Pfeiffer et al., 1991; 1995).**

surface roughness will increase the impact angle more for small rocks than for large rocks. The larger the impact angle, the more energy the rock will lose during impact. By itself, rock size does not affect the results, but it does affect the influence of changes in slope angle and surface roughness.

Simulation results from the area used for the original experimental testing of CRSP show a gradual increase in average velocity with increasing rock size (Pfeiffer, 1989; Pfeiffer et al., 1991; 1995). In addition, the simulation results from a site in Glenwood Canyon show many of the rocks stopping on the slope when a smaller rock size is used, whereas results for larger rocks show the rocks traveling into the Colorado River. This variation is consistent with observations of the stopping position of rocks on this slope (Pfeiffer, 1989; Pfeiffer et al., 1991; 1995).

As expected, slope angle is the most important factor in determining the behavior of rockfall. Falling rocks will tend to increase in velocity up to a maximum, depending on slope angle. A general pattern of increase followed by a leveling off is observed for both velocity and bounce height (Pfeiffer, 1989; Pfeiffer et al., 1991; 1995).

Second in importance in determining rockfall behavior is surface roughness. The effect of surface roughness changes with slope angle. An increase in surface roughness will have a greater effect on low angle slopes than on steep slopes. An increase in surface roughness will also generally result in a decrease in velocity and an increase in bounce height until the surface roughness decreases the velocity to the point where bounce height also begins to decrease. The surface roughness value where bounce height begins to decrease is lower for shallower slope angles.

Material coefficients affect rockfall behavior by determining the amount of energy absorbed during impact, with high coefficient values resulting in less energy loss during impact. Because the coefficients only act on impact, their effect on bounce height and velocity is dependent on the number of bounces. On steep slopes, where rocks impact the slope with less frequency, the effect of the coefficients on rockfall behavior becomes negligible. The effect of the coefficients on rockfall behavior is largest for low angle slopes, where the rockfall velocity is decreasing. On most slopes, changes in the coefficients, within reasonable limits for a specific slope material, will not produce a significant change in results.

Several factors act to reduce the effect of surface material properties on rockfall behavior. First, the effect of slope angle and surface roughness is so much greater than the effect of material properties that the results of changes in coefficients can be obscured. Second, the coefficients are modified by factors, discussed in the “CRSP Algorithm” section, that also tend to obscure the results of changes in the coefficients. The most important factor that modifies the coefficients is the velocity normal to the slope at impact. The normal velocity is dependent on the impact angle, which is determined by the slope angle and surface roughness. For these reasons, the effect of changes in coefficients is largely dependent on the slope configuration. Therefore, the recommended method of determining the sensitivity to changes in coefficients is to test the effect of changes in coefficients at the specific site of interest by varying the input parameters within a range consistent with properties reasonably attributable to the site of interest.

Original CRSP Verification and Calibration

During development of CRSP (Version 1.0), limited program verification and calibration were performed. A test site near Rifle, Colorado was used to collect rockfall data. Rocks were rolled down a 300-foot-high hillside consisting of thin desert soil with rocky ledges. The very sparse vegetation had little effect on rockfall behavior. A worst case slope profile was used to compare CRSP-predicted rock velocities and bounce heights with field data. The actual rock-rolling data was compared to CRSP output, and it was found that CRSP-predicted maximum bounce height closely matched field observations while the CRSP-predicted maximum velocity was substantially low. Thus, the Rifle experimental data was used to adjust the constants in the friction function and scaling factors until the simulation data fit the experimental values for travel time, number of bounces, and bounce height.

At this time, in an effort to determine the reliability of CRSP predictions, CRSP data was compared to field trials conducted by the California Department of Transportation (McCauley et al., 1985) and to Ritchie's (1963) rockfall ditch design criteria. It was found that CRSP predictions tend toward more of a worst case scenario than do the studied field tests, but the overall conclusions are similar.

More complete discussion of the original CRSP calibration and verification efforts can be found in Pfeiffer (1989) or Pfeiffer et al. (1991; 1995).

Literature Review

At the time of the development of CRSP, a literature review was conducted by Pfeiffer (1989), who found that published literature contains abundant studies dealing with slope stability and rockfall mitigation measures, but papers concerning the mechanics of rockfall motion are much less copious.

In the early 1960's, a rockfall study was conducted by the Washington Department of Transportation (Ritchie, 1963). By studying 16-mm films of rockfall, Ritchie observed the importance of angular momentum and bouncing ledges, or "ski jumps" in rockfall. From his observations, Ritchie developed criteria for designing cut slopes and ditches that are widely used (Nichol and Watters, 1983).

Piteau and Associates (1980) wrote and tested a computer rockfall simulation program designed for a mainframe computer. The program used a slope profile divided into straight-line segments, termed cells, and laws of motion to determine where a rock will impact the ground. At the point of impact, the velocity of the rock normal to the slope is attenuated by a normal coefficient of restitution, and similarly, motion parallel to the slope is attenuated by a tangential coefficient. The slope of each cell can be adjusted to account for the surface irregularities and angularity of the rock. The program produces velocity and bounce height distributions from the input coefficients, slope geometry, and probability of surface variations.

During the relocation of Interstate 40 in North Carolina, the North Carolina Department of Transportation produced a program to simulate rockfall and test the effectiveness of widening the roadway ditch to mitigate rockfall hazards (Wu, 1984). Rocks were dropped on an inclined wooden platform and a bedrock slope in order to determine coefficients of "restitution" for motion normal and tangential to the slope. The program randomly varied coefficients to achieve the statistical spread found among rockfall events at a given site. The tests indicated that the rock bounced less with higher impact angles, so the program reduced the coefficients for larger impact angles.

CRSP was developed to incorporate all of the concepts used by the preceding investigators to model the behavior of rockfall. CRSP models the effect of angular momentum noted by Ritchie (1963) by allowing kinetic energy to be transferred between rotational and translational velocity. All of the studies prior to CRSP's development noted a statistical variation of rockfall events caused by irregularities in the slope. CRSP approaches these irregularities by using field measurements of surface roughness. The effect of impact angle noted by Wu (1984) is advanced by CRSP, which reduces the coefficients according to the velocity normal to the slope. Additionally, CRSP makes adjustments for the difference in friction between rolling and sliding rocks. All of these concepts were incorporated into CRSP to produce a reasonably accurate and easy method of investigating and modeling rockfall hazards.

A literature review was also conducted at the time of the current study. Findings included a few papers that analyzed CRSP's accuracy and sensitivity and a case history of the CRSP-aided design of rockfall protective ditches.

Pearce (1994) performed the first known study of the accuracy of CRSP's maximum kinetic energy predictions. Using actual rockfall data collected by the California Department of Transportation, Pearce compared the total kinetic energy calculated for the field data with that predicted by CRSP. The findings were that CRSP consistently overestimates rockfall translational velocity by an average of 12 percent, while underestimating angular velocity by an average of 77 percent. Pearce stated that the overall effect of the combined misestimations, and their respective contributions to total kinetic energy, is that "CRSP calculates a very accurate total kinetic energy of rockfalls." However, it should be noted that for his study, Pearce used an early version of CRSP containing an error that prevented angular velocity from being included in energy calculations. This error has since been corrected and thus Pearce's findings concerning CRSP's underestimate of angular velocity are no longer applicable.

As part of a master's degree thesis, Larsen (1993) studied various rockfall models, including a concentration on CRSP. Larsen found CRSP to have practical applications to two-dimensional rockfall investigations. As part of his study, Larsen performed sensitivity analyses of CRSP's predicted rockfall run-out distance, bounce height, and velocity. Surface roughness was found to be extremely sensitive, while normal coefficient of restitution and rock size were also established to be important. Conversely, rock shape, initial velocity, and tangential coefficient of frictional resistance were found to have only minor influences on the output.

As part of a master's degree thesis study of designing catch bench geometry for open-pit mines, Evans (1989) compared several rockfall models and found that CRSP was consistent in predicting rockfall behavior on eight different test slopes. Evans thus recommended CRSP for use in designing catch bench geometry in surface mines. Evans also performed a sensitivity analysis of CRSP and found that the tangential coefficient of frictional resistance is not especially sensitive while the normal coefficient of restitution is somewhat sensitive. However, Evans asserts that surface roughness is CRSP's most sensitive input parameter.

Pierson et al. (1994) of the Oregon Department of Transportation used CRSP to aid in the planning of research for rockfall protective ditch design for 0.25 (horizontal): 1 (vertical) slopes. Field test results were compared with CRSP output to evaluate whether the model was reasonable for the given application. Once CRSP's reliability was established, the program provided a means to extrapolate velocity and bounce height information for slopes other than the 40- to 80-foot-high slopes tested and modeled with CRSP.

CHAPTER 3—METHODS

Visual Basic Programming

Microsoft Visual Basic® (Version 4.0) was employed to perform the re-programming of the Colorado Rockfall Simulation Program. The BASIC source code from CRSP Version 3.0a (a DOS application) was used as the basis for the new version, but the entire user interface was redeveloped in an effort to make the program easier to use. Additionally, Visual Basic creates the new version as a Microsoft Windows® application. The re-programming was performed using 32-bit technology so that it would be Windows 95 and NT.

The re-programming was initiated by creating several Visual Basic forms (or windows) to allow the user to enter CRSP input files and run the program by toggling between screens. Once the user interface of the program was complete, the next task was to write the code that would actually make the program perform. Hence, numerous sub-procedures were written to execute everything from toggling between screens to actually synthesizing the output. It was only for the data processing portion of the program that the code from CRSP Version 3.0a was used. The rest of the code was written especially for CRSP Version 4.0. Therefore, Version 4.0 will create the same output as Version 3.0a, but in a much more "user-friendly" environment.

Program Re-Calibration

The re-calibration of CRSP was enacted by comparing the results of actual rock-rolling experiments with output produced by CRSP. First, data was solicited from potential sources, such as users of CRSP, including several state departments of transportation. Available data was then compiled and reviewed for reliability and applicability to the CRSP calibration efforts. The useable data was compared with CRSP output to form a new set of suggested input coefficients for various slope types. The sources of data and the calibration process are described in more detail below.

Sources of Data

The California Department of Transportation (Caltrans) provided seven sets of data that were collected during the testing of rockfall fences. Six of the seven data sets are from tests performed on similar nearby slopes along California State Highway 1 in Monterey County, California (Duffy and Hoon, 1996; Duffy, 1996; Smith and Duffy, 1990). The other Caltrans data set was collected outside the town of Oberbuchsiten, Switzerland in the Jura Mountains (Duffy, 1992). Also, the rock-rolling data collected near Rifle, Colorado for the original CRSP calibration was utilized again (Pfeiffer, 1989; Pfeiffer et al., 1991).

Monterey County Data

Each of the slopes in Monterey County, California consisted of soil and rock fragments and was relatively smooth with occasional gullies and sparse vegetation. The gullies and vegetation were observed to have minimal effect on rockfall trajectories (Duffy and Hoon, 1996; Duffy, 1996; Smith and Duffy, 1990).

Smith and Duffy (1990) further describe one of the slopes, referred to here as the Caltrans Brugg/Industrial Enterprise slope, as consisting of clayey silt covered with 1-to-18-inch rock fragments. The slope was dry and hard, with occasional soft spots, during three sets of tests. The Caltrans Brugg/Industrial Enterprise slope is 130 feet high and 100 feet wide with an overall slope angle of 34° (Figure 5). The data from this slope is comprised of three individual experiments (each of which was performed under very similar condi-

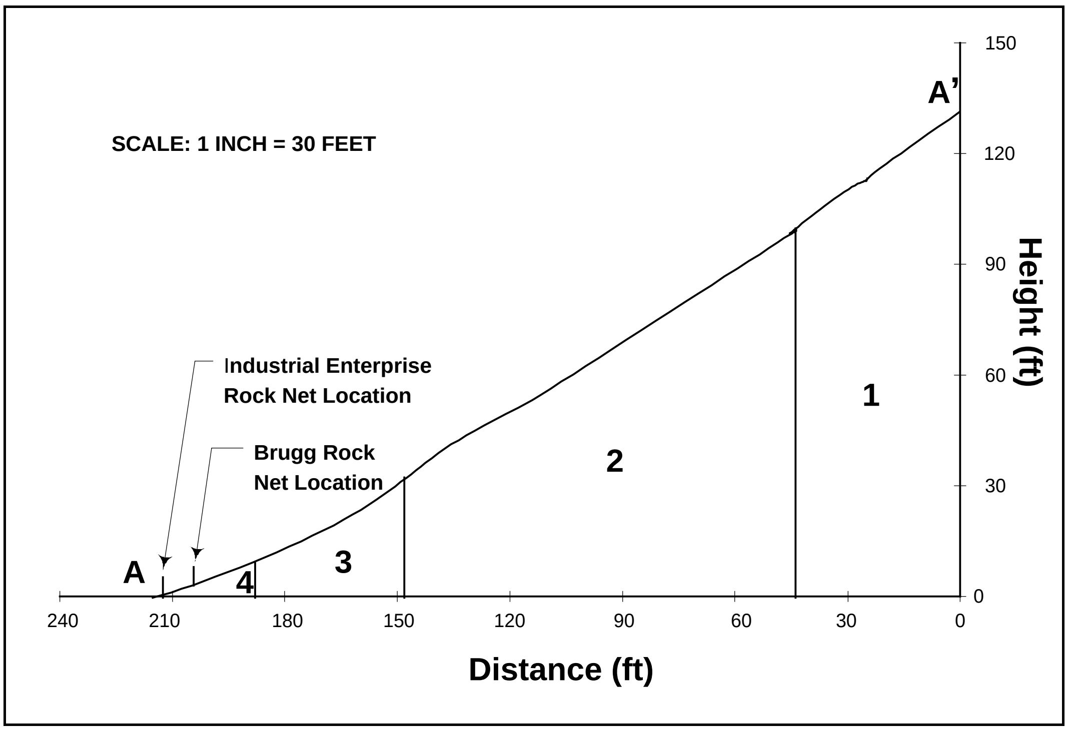


Figure 5. Slope profile for Caltrans Brugg/Industrial Enterprise tests (Smith and Duffy, 1990). Note that the slope profile is plotted with an origin on the right side of the figure while CRSP requires the profile to have an origin on the left side.

tions and is therefore treated as one large data set for CRSP calibration purposes). Overall, 61 dense greenstone boulders of 1.1- to 5.0-foot diameter were rolled during these three experiments.

The rest of the Monterey County tests are referred to here as the Hi-Tech 50/70 and Hi-Tech Low Energy tests. The location for each of these tests, as described by Duffy and Hoon (1996) and Duffy (1996), appears to be the same slope, with a length of 89 feet, a height of 66 feet, and an overall slope angle of 36-37° (Figure 6). The Hi-Tech 50/70 test used 32 meta-basalt and serpentinite rocks with diameters ranging from 1.2 to 4.4 feet (Duffy and Hoon, 1996). Similarly, the Hi-Tech Low Energy data involved 16 meta-basalt and serpentinite boulders of 1.2- to 3.6-foot diameter (Duffy, 1996).

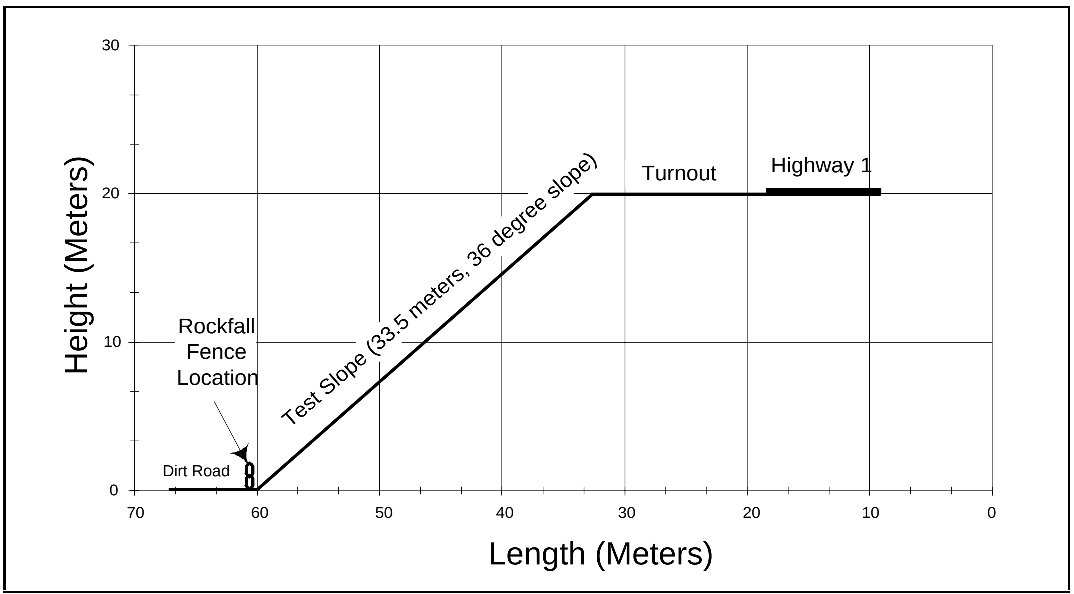


Figure 6. Slope profile for Hi-Tech 50/70 and Hi-Tech Low Energy tests (Duffy, 1996; Duffy and Hoon, 1996). Note that the slope profile is plotted with an origin on the right side of the figure while CRSP requires the profile to have an origin on the left side.

Swiss Data

The test slope in Switzerland consists of an exposed limestone rock face. The limestone is of the Jura Formation and is described as very hard, competent, and dark gray. The slope is 460 feet long, 328 feet high, and has an overall slope angle of 45° (Figure 7).

The Swiss experiment involved the rolling of 58 limestone and granite boulders, ranging in diameter from 1.2 to 4.2 feet, from two starting locations on the slope (Duffy, 1992).

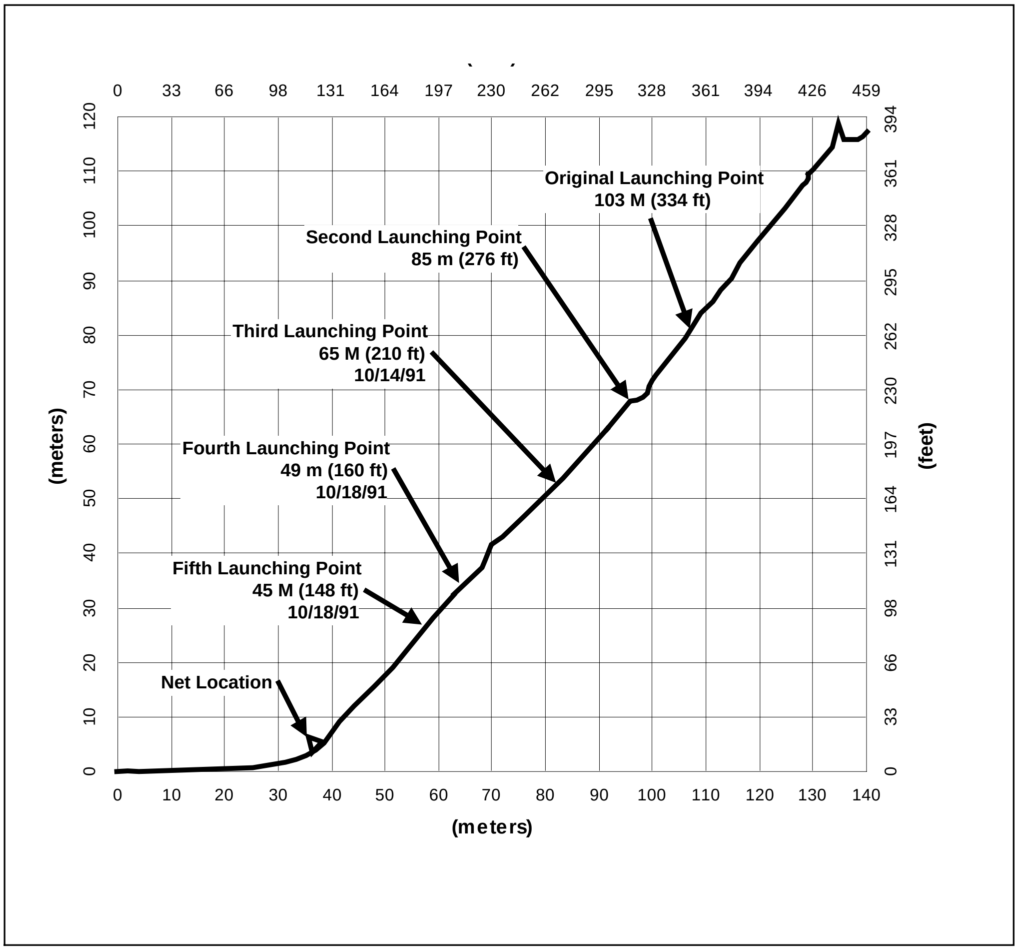


Figure 7. Slope profile for the Swiss test (Duffy, 1993). Note that the slope profile is plotted with an origin on the right side of the figure while CRSP requires the profile to have an origin on the left side.

Rifle Data

The slope used for the Rifle, Colorado experiment is 400 feet long, 300 feet high, and has an overall slope angle of approximately 30° (Figure 8). The slope material is formed by Wasatch formation of very weathered claystone and rock ledges of sandstone and siltstone beds. The climate is arid so only very sparse vegetation is present. It was observed that vegetation had little effect on rockfall behavior. For the Rifle test, data on 36 rock rolls were obtained. Rocks were basalt with an assumed unit weight of 165 lb/ft^3.

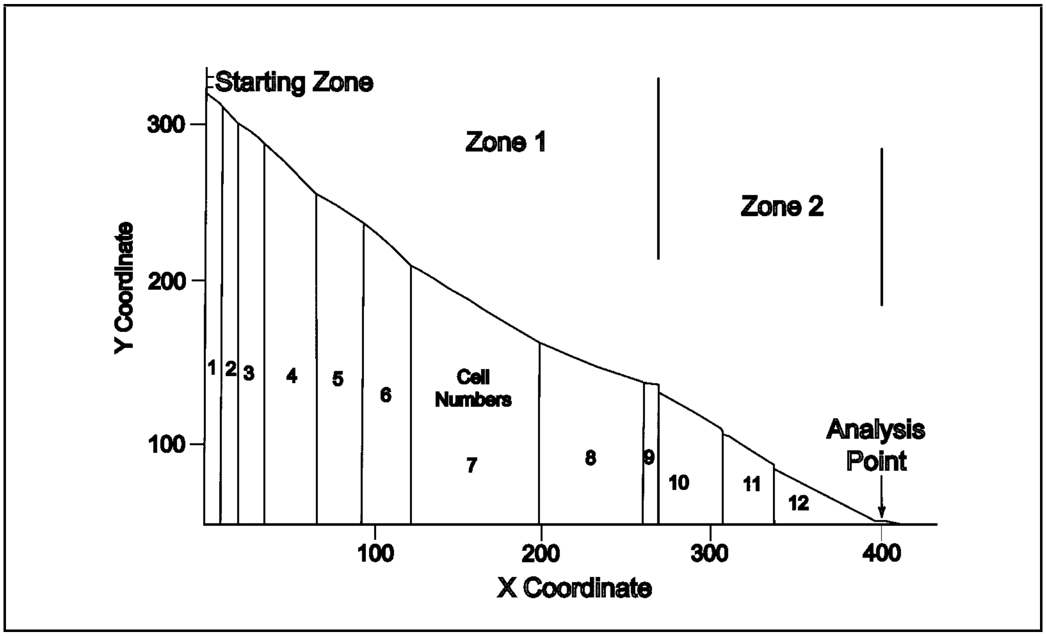


Figure 8. Slope profile for the Rifle test (Pfeiffer, 1989; Pfeiffer et al., 1991).

Treatment of Data

In order to calibrate the program, each set of distinct data was modeled using CRSP. Data sets that corresponded to the same slope under very similar conditions were compiled into a single data set. Thus, the Caltrans Brugg/Industrial Enterprise data was treated as a single data set and the Hi-Tech 50/70 data was merged with the Hi-Tech Low Energy data to form another set. In addition, the Swiss data was reduced into two different data sets, corresponding to two rock-release points on the slope.

For the calibration, all rocks were assumed to be spherical and were modeled using CRSP as such. Each of the data sets used for the calibration appeared to be reasonably consistent with this assumption. Thus, the results of similar calibration efforts using other shapes, including cylinders and disks (as available within CRSP), would be uncertain. However, spherical rocks generally represent a worst-case scenario because they comprise the greatest amount of rock mass for a given radius.

Known slope profiles, rock densities, surface roughnesses, and rock sizes corresponding to each data set were input into CRSP to produce output which could be compared with the actual rock-rolling data. All parameters were kept constant, except for the tangential coefficient of frictional resistance (R_t) and the normal coefficient of restitution (R_n), which were varied individually. Thus, R_t was held constant while R_n was varied and vice-versa. This way, one independent variable could be analyzed at a time. The values used for R_t were 0.65, 0.80, and 0.95 while R_n varied among 0.10, 0.15, 0.20, 0.30, 0.45, 0.60, and 0.80.

Next, graphs were prepared to allow for the visual comparison of the CRSP output with the actual data. For each data set, four types of graphs were compiled:

- actual rock velocity versus CRSP predicted maximum velocity
- actual rock velocity versus CRSP predicted average velocity
- actual kinetic energy versus CRSP predicted maximum kinetic energy
- actual kinetic energy versus CRSP predicted average kinetic energy .

Each graph employed rock diameter as the abscissa and either velocity or kinetic energy as the ordinate. Several graphs of each type were prepared for each data set. Each graph held either R_t or R_n constant while the non-constant coefficient varied. For example, one graph might show how CRSP predicted average velocity would vary (among a range of rock sizes) for R_n equaling 0.10, 0.20, 0.30, 0.45, or 0.60 when R_t equaled 0.80. Actual observed velocity values would be plotted on the same graph to allow for comparison with the CRSP output. Selected graphs are presented in Appendix A.

Once the graphs were prepared, combinations of R_t and R_n that produced output falling in the middle to upper end of actual observed values were sought. Output corresponding to the middle to upper end of actual data is desirable because it represents a somewhat conservative yet reasonable model. This analysis was performed for each of the four graph types and for each set of data. For a single set of data, ranges of R_t and R_n that corresponded to the middle to upper end of actual observed values for all different graph types was compiled. CRSP predicted average and maximum velocities were compared with actual observed velocities, and CRSP predicted average and maximum kinetic energies were compared with actual observed kinetic energies. The results from data sets with similar slope material types, such as the medium-hard soil and rock fragments of each of the Caltrans Monterey County data sets, were compared and compiled to form a larger set of R_t and R_n ranges. Thus, a complete set of suggested input coefficients was prepared.

Given the hard bare rock slope of the Swiss data, the thin soil over hard rock slope of the Rifle data, and the medium-hard soil and rock fragment slopes of the Monterey County data, three distinct types of slopes were covered by the new set of suggested coefficients. Suggested coefficients for the remaining gaps in slope type were therefore extrapolated from the three slope types already established. This yielded a complete set of suggested input coefficients, which are presented and discussed in Chapter 5.

CHAPTER 4—RESULTS

Calibration Results

The results of the Colorado Rockfall Simulation Program re-calibration are presented as graphs in Appendix A and Tables 2, 4, and 5 in Chapter 5. For each of the four data sets used in the calibration (Caltrans Brugg/Industrial Enterprise, Hi-Tech, Swiss, and Rifle tests), the following graphs were constructed to illustrate the effects of selected tangential and normal coefficients on kinetic energy and velocity (due to limited field data, only velocity information is presented for the Rifle tests):

1. Envelope of actual velocity and trends of CRSP predicted maximum velocity at R_t of 0.95 and various values of R_n (Appendix A, Figures A-1, A-9, A-17, A-25)

2. Envelope of actual velocity and trends of CRSP predicted maximum velocity at R_t of 0.65 and various values of R_n (Appendix A, Figures A-2, A-10, A-18, A-26)

3. Envelope of actual velocity and trends of CRSP predicted average velocity at R_t of 0.95 and various values of R_n (Appendix A, Figures A-3, A-11, A-19, A-27)

4. Envelope of actual velocity and trends of CRSP predicted average velocity at R_t of 0.65 and various values of R_n (Appendix A, Figures A-4, A-12, A-20, A-28)

5. Envelope of actual kinetic energy and trends of CRSP predicted maximum kinetic energy at R_t of 0.95 and various values of R_n (Appendix A, Figures A-5, A-13, A-21)

6. Envelope of actual kinetic energy and trends of CRSP predicted maximum kinetic energy at R_t of 0.65 and various values of R_n (Appendix A, Figures A-6, A-14, A-22)

7. Envelope of actual kinetic energy and trends of CRSP predicted average kinetic energy at R_t of 0.95 and various values of R_n (Appendix A, Figures A-7, A-15, A-23)

8. Envelope of actual kinetic energy and trends of CRSP predicted average kinetic energy at R_t of 0.65 and various values of R_n (Appendix A, Figures A-8, A-16, A-24).

Each of the graphs listed above used a constant surface roughness of 0.5 feet. Although no field measurements of surface roughness were performed on any of the slopes used for the calibration, a surface roughness of 0.5 feet appears to be reasonable for each of the slopes based on the slope descriptions and pictures provided by the investigators supplying the data. During the analysis of the calibration data, many graphs in addition to those presented in Appendix A were generated and used to aid in the formation of the observations discussed in Chapter 5.

In addition, a new set of suggested normal and tangential coefficients was produced for four general slope types:

1. Smooth hard surfaces and paving
2. Most bedrock and boulder fields
3. Talus and firm soil slopes
4. Soft soil slopes.

The new set of suggested coefficients is presented in Tables 2, 4, and 5 of Chapter 5.

Programming Results

The product of the Visual Basic programming is the Colorado Rockfall Simulation Program, Version 4.0. Diskettes 1 through 3 are the installation media for the program.

.

CHAPTER 5—DISCUSSION OF RESULTS

Calibration Results

The plots presented in Appendix A were evaluated to determine new sets of suggested normal coefficients of restitution (R_n) and tangential coefficients of frictional resistance (R_t) for use with CRSP. The sets of suggested coefficients were selected by evaluating combinations of R_t and R_n that yielded output corresponding to the middle to upper range of actual observed values of velocity and kinetic energy, as described in the "Treatment of Data" section of Chapter 3. Output falling within the middle to upper range of actual data is advantageous because it represents a moderately conservative yet reasonable model.

The Caltrans Brugg/Industrial Enterprise test data (Appendix A, Figures A-1 through A-8) and the Hi-Tech test data (Appendix A, Figures A-9 through A-16) were analyzed to generate a range of suggested normal and tangential coefficients for talus and firm soil slopes. By comparing Figures A-1, A-3, A-5, and A-7, which use a constant tangential coefficient of 0.95, with Figures A-2, A-4, A-6, and A-8, which keep the tangential coefficient constant at 0.65, for the Caltrans Brugg/Industrial Enterprise data and comparing Figures A-9, A-11, A-13, and A-15 (tangential coefficient of 0.95) with Figures A-10, A-12, A-14, A-16 (tangential coefficient of 0.65) for the Hi-Tech data, it is apparent that normal coefficients of approximately 0.12-0.20 generally fall within approximately the upper half of observed values for both velocity and kinetic energy. Additionally, tangential coefficients closer to the 0.95 value (Figures A-1, A-3, A-5, A-7, A-9, A-11, A-13, and A-15) produce output close to the upper end of observed values while tangential coefficients closer to the 0.65 value (Figures A-2, A-4, A-6, A-8, A-10, A-12, A-14, and A-16) generate results close to the middle of observed values using normal coefficients of 0.12-20, as proposed above. In contrast, it was surmised that normal coefficients lower than approximately 0.12 and tangential coefficients lower than approximately 0.65 do not consistently reach the upper half of observed values in these sets of data. Thus, for modeling talus and firm soil slopes, normal coefficients of approximately 0.12-0.20 in combination with tangential coefficients of approximately 0.65 to 0.95 (Table 2) should produce reasonable results.

The suggested ranges of normal and tangential coefficients for smooth hard surfaces and paving were produced by analyzing the Swiss data shown in Appendix A, Figures A-17 through A-24. By comparing Figures A-17, A-19, A-21, and A-23, which use a constant tangential coefficient of 0.95, with Figures A-18, A-20, A-22, and A-24, which keep the tangential coefficient constant at 0.65, it is evident that normal coefficients of approximately 0.60-1.0 (with 1.0 theoretically representing complete conservation of energy in the normal direction) generally correspond to approximately the upper half of observed values for both velocity and kinetic energy. Also, tangential coefficients closer to the 0.95 value (Figures A-17, A-19, A-21, and A-23) than the 0.65 value (Figures A-18, A-20, A-22, and A-24) better approximate the upper half of observed values using normal

Table 2. Comparison of New Suggested CRSP Input Coefficients with Prior Values.

Slope Type	Soft Soil*	Caltrans (talus, firm soil)	Rifle (bedrock, boulders)	Swiss (smooth, hard)	Prior CRSP Versions **
R_t range	0.50-0.80	0.65-0.95	0.75-0.95	0.90-1.0	0.78-0.92
R_n range	0.10-0.20	0.12-0.20	0.15-0.30	0.60-1.0	0.28-0.42

*Soft soil slope coefficients were extrapolated from other slope types due to lack of data.

**Covers all slope types.

coefficients of 0.60-1.0, as proposed above. In contrast, it was assessed that normal coefficients lower than approximately 0.60 and tangential coefficients lower than approximately 0.90 do not consistently reach the upper half of observed values in this set of data. Thus, for modeling smooth hard surfaces and paving, normal coefficients of approximately 0.60-1.0 in combination with tangential coefficients of approximately 0.90 to 1.0 (Table 2) should produce reasonable results.

The Rifle test data (Appendix A, Figures A-25 through A-28) were analyzed to create a range of suggested normal and tangential coefficients for most bedrock and boulder fields. By comparing Figures A-25 and A-27, which use a constant tangential coefficient of 0.95, with Figures A-26 and A-28, which keep the tangential coefficient constant at 0.65, it is discernible that normal coefficients of approximately 0.15-0.30 generally fall within approximately the upper half of observed values for both velocity and kinetic energy. In addition, tangential coefficients somewhat closer to the 0.95 value (Figures A-25 and A-27) than the 0.65 value (Figures A-26 and A-28) better approximate the upper half of observed values using normal coefficients of 0.15-30, as proposed above. In contrast, it was surmised that normal coefficients lower than approximately 0.15 and tangential coefficients lower than approximately 0.75 do not consistently reach the upper half of observed values in this set of data. Thus, for modeling most bedrock and boulder fields, normal coefficients of approximately 0.15-0.30 in combination with tangential coefficients of approximately 0.75 to 0.95 (Table 2) should produce rational results.

Due to a lack of test data for soft soil slopes, the suggested ranges of normal and tangential coefficients for this slope type were extrapolated based on the suggested ranges of coefficients derived for the other slope types. A description of this extrapolation process follows. The size of the suggested range of normal coefficient values is considerably larger for smooth hard surfaces and paving (0.60-1.0) than for the somewhat softer slope types (0.15-0.30 for most bedrock and boulder fields and 0.12-0.20 for talus and firm soil slopes). Conversely, the size of the suggested range of tangential coefficient values is smaller for smooth hard surfaces and paving (0.90-1.0) than for the relatively softer slope types (0.75-0.95 for most bedrock and boulder fields and 0.65-0.95 for talus and firm soil slopes). The upper bound of the suggested range of normal coefficients for smooth hard surfaces and paving (1.0) is much higher than the upper bounds for most bedrock and boulder fields (0.30) and talus and firm soil slopes (0.20). Conversely, the upper bound of the suggested range of tangential coefficients for smooth hard surfaces and paving (1.0) is close to the upper bounds for most bedrock and boulder fields and talus and firm soil slopes (0.95 for each). However, a significant decrease from the relatively low normal coefficient range of 0.12-0.20 for talus and firm soil slopes to the suggested normal coefficient range for soft soil slopes is probably unreasonable because values resulting from such a decrease would yield very little conservation of energy in the normal direction. Thus, a range of normal coefficients for soft soil slopes, 0.10-0.20, that is very similar to the suggested normal coefficient range for talus and firm soil slopes (0.12-0.20) and a tangential coefficient range, 0.50-0.80, somewhat lower than the suggested tangential coefficient range for talus and firm soil slopes (0.65-0.95) are proposed (Table 2).

Knowing that the suggested tangential and normal coefficients were developed by selecting combinations of R_t and R_n that corresponded to the middle to upper end of actual data on the graphs presented in Appendix A, the user may evaluate where input coefficient combinations other than those suggested would fall on the graphs. In this manner, the user can judge the sensitivity of the coefficients and determine values that may be more appropriate with respect to the goals of specific projects.

The new sets of suggested normal and tangential coefficients are significantly different from the sets of suggested coefficients presented in previous versions of the CRSP users' manual (Pfeiffer et al., 1991; 1995). For instance, as Table 2 illustrates, prior CRSP users' manuals suggested tangential coefficients ranging from 0.78 to 0.92 (across all slope types) while the new suggested values range from 0.50 to 1.0. Similarly, prior versions of the CRSP users' manual suggested normal coefficients ranging from 0.28 to 0.42 while the new suggested values range from 0.10 to 1.0. Thus, a limitation of the previous CRSP calibration effort (that produced the earlier sets of suggested coefficients) is the indication that the values appropriate for the two coefficients fall within relatively small ranges (across all slope types). In fact, Table 2 shows that the ranges of both tangential and normal coefficients covering all slope types suggested by prior CRSP versions are smaller than many of the ranges now suggested for individual slope types. In contrast, the current calibration effort suggests that much wider ranges in coefficient values are suitable and, hence, that differences in slope type are more important to CRSP modeling than previously believed. Presumably, the earlier calibration effort yielded smaller ranges of suggested coefficients than the current calibration because the earlier calibration utilized data from less diverse slope types than the current calibration, as described in the "Original CRSP Verification and Calibration" section of Chapter 2.

Although the upper bound of both suggested tangential and normal coefficients for smooth hard surfaces and paving is 1.0, which theoretically represents a complete conservation of energy in the respective direction, this value does not correspond to a complete conservation of energy in practice. Rather, 1.0 is merely a convenient upper boundary that is observed to generate CRSP predicted velocities and kinetic energies along the upper end of observed data. Since the observed data clearly did not involve complete energy conservation, using a coefficient of 1.0 for CRSP does not represent complete energy conservation, but rather, it generates output consistent with the field observations.

Figures A-1 through A-28 (Appendix A) illustrate several observations. For a given slope type, using a suggested combination of tangential and normal coefficients tends to yield CRSP predicted maximum velocities and kinetic energies that may be greater than velocities and kinetic energies observed in the field. Correspondingly, the same set of coefficients with the same slope may yield CRSP predicted average velocities and kinetic energies that may fall within the upper range of field-observed values. Thus, determining whether CRSP predicted maximum or average values will be used for design is important. If the user intends to use as design criteria CRSP predicted maximum velocity and kinetic energy, normal and tangential coefficients within the lower ends of the suggested ranges for a given slope type should be applied, as they tend to produce CRSP predicted maximum velocities and kinetic energies representing the middle to upper range of actual rock velocities and kinetic energies. Alternatively, if the user intends to use CRSP predicted average velocity and kinetic energy as design criteria, coefficients within the upper ends of the suggested ranges should be used.

Another observation is that the normal coefficient is much more sensitive than the tangential coefficient. Thus, more attention should be paid to R_n than R_t in the coefficient selection process (as described in the "Tangential Coefficient" and "Normal Coefficient" sections of Chapter 8) and site-specific calibration efforts (as discussed in the "Site-Specific Calibration" section of Chapter 8). However, the tangential coefficient is observed to be important for hard slopes, presumably because the rock does not embed into hard slopes, while some degree of embedment is likely for softer slopes. Also, the tangential coefficient is known to be important for slopes where vegetation can impede a falling rock.

The shape of the CRSP predicted velocity curves in Appendix A Figures A-1 through A-4, A-9 through A-12, and A-25 through A-28 may be somewhat attributed to decreasing effects of rock size as rock diameter increases. In each of these figures, it is generally apparent that as rock diameter increases, the trend lines for each set of CRSP predicted velocities with a given R_t and R_n becomes flatter. Thus, it appears that rocks reach a "terminal" velocity for each given slope and set of input coefficients. For example, Figure A-1 illustrates that along the slope used for the Caltrans Brugg/Industrial Enterprise tests, rocks five feet in diameter do not travel appreciably faster than rocks four feet in diameter. Similar observations can be made for each of the CRSP predicted velocity graphs referenced above.

However, Appendix A Figures A-17 through A-20, which present the CRSP predicted velocity curves from the Swiss data, do not show a curve flattening as rock diameter increases. Rather, the curves in these graphs are relatively flat throughout the range of rock diameters represented. So, at least for the slope used in the Swiss test, it appears that the influence of rock size on velocities along smooth hard surfaces may be minimal. However, this is probably only the case on slopes that have few breaks in slope. As the “Sensitivity to Input Parameters” section of Chapter 2 describes, rock momentum, which is directly related to rock size, is an important variable when breaks in slope cause deceleration of falling rocks. Also, if a hard slope is not smooth, rock size may be important because surface roughness affects small rocks more than large rocks.

The appearance that rock size generally affects velocity less as rock diameter increases and may have a minimal affect on velocity on hard slopes may be due to a condition of rock embedment into an underlying slope having a smaller effect on the velocity of large rocks than small ones and, clearly, no effect where embedment does not occur. Thus, relatively larger rocks would have a smaller proportion of their energy dissipated by embedment into slopes compared to relatively smaller rocks and rock size would be less important for smooth hard slopes, assuming that embedment is not an issue.

A potential implication of this hypothesis is that, when using CRSP, determining the largest rock that is likely to descend down a slope is not nearly as crucial for rockfall velocity analysis for smooth hard slopes with few slope breaks as for other slope types. Also, it may not be critical to ascertain the largest rock likely to fall down any slope, as long a rock size is chosen that will reach the “terminal” velocity for the slope in question (and the input coefficients used), as described above. However, since mass is a component in calculating kinetic energy, knowledge of the largest rock likely to descend down a slope is essential if an estimate of maximum rockfall kinetic energy is desired.

Table 2 also illustrates several observations. It appears likely that the dramatic decrease in the values of suggested normal and tangential coefficients from the smooth hard surfaces of the Swiss data to the rest of the slope types, which are somewhat softer and more irregular, may be due to differences in rock-slope interaction between the smooth hard slope type and the other slope types. For instance, it seems probable that falling rocks that embed into their underlying slope, such as occurs for most slope types, will possess less rotational energy than falling rocks that do not embed, as may transpire on hard slopes. Also, a shearing of slope materials seems likely to occur during a falling rock’s impact with a soft slope, resulting in a lesser amount of rotational energy gained from an impact on a soft slope compared to a relatively harder slope. In addition, it is clear that more of a falling rock’s energy is conserved, resulting in higher energies and longer bounces, during impact with a relatively hard slope than a relatively soft one. If each of the above statements is correct, then rocks falling on hard slopes have higher velocities and kinetic energies and longer bounces than rocks falling on softer slopes. Consequently, due to their lower velocities and shorter bounces, the rocks falling on the softer slopes would probably impact the slope more often, compounding the effects of embedment and shearing. Therefore, the gradual increase in suggested normal and tangential coefficient values presented in Table 2 from soft soil slopes across the table’s columns toward smooth hard slopes is possibly accounted for by decreasing degrees of rockfall embedment and shearing of slope materials and increasing conservation of energy as slope hardness increases. Particularly, it seems likely that slope material shearing possesses a greater influence on the tangential coefficient than the normal coefficient and that conservation of energy affects the normal coefficient more than the tangential coefficient. However, it is unclear as to which coefficient degree of embedment influences more. Finally, it should be noted that the hypotheses stated above have not been tested, but are logical conjecture. Table 3 summarizes these suppositions.

The new sets of suggested tangential coefficients of frictional resistance (R_t) and normal coefficients of restitution (R_n) for various slope types are summarized in Tables 4 and 5, respectively. It should be noted that the suggested ranges of coefficients presented in these tables have imprecise boundaries and values falling outside of these ranges may be appropriate for some slopes, even if a slope type is consistent with one of those indicated in the tables.

Table 3. Hypothetical Rock Slope Interactions as Basis for Observed Effects on Coefficients.

Slope type	Conservation of energy	Shearing of slope materials	Embedment into slope	Combined effect on R_t and R_n
Hard	High → high energy & long bounce	Low → high rotational energy	Low → high rotational energy	Increases
Soft	Low → low energy & short bounce	High → low rotational energy	High → low rotational energy	Decreases

Programming Results

The Colorado Rockfall Simulation Program, Version 4.0 possesses several advantages over previous versions. When the program was originally developed, many of the features available on today's computers had not yet been introduced. CRSP Version 4.0 incorporates the output produced from Version 3.0a with greatly increased "user-friendliness". This is accomplished primarily through CRSP's re-programming as a Windows application and its new mouse-driven environment. In addition, facilities such as the ability to acquire detailed output data for up to three analysis points (as opposed to one with previous versions) during a single CRSP run have been added to the program. Chapter 8 presents a detailed users' guide to CRSP 4.0 that describes all of the program's features.

Table 4. Suggested Tangential Coefficient Input Values.

Description of Slope	Tangential Coefficient (R_t)	Remarks
Smooth hard surfaces and paving	0.90 – 1.0	-R_t is not very sensitive compared to R_n, but may be important for hard or significantly vegetated slopes -Use lower R_t as the density of vegetation on the slope increases.
Most bedrock and boulder fields	0.75 – 0.95	
Talus and firm soil slopes	0.65 - 0.95	
Soft soil slopes*	0.50 - 0.80	

*Soft soil slope coefficients were extrapolated from other slope types due to lack of data.

Table 5. Suggested Normal Coefficient Input Values.

Description of Slope	Normal Coefficient (R_n)	Remarks
Smooth hard surfaces and paving	0.60 – 1.0	-For short slopes try lower values in applicable range. -If max. velocity/KE* are design criteria, use lower values in range; if avg. velocity/KE* are design criteria, use higher values in range.
Most bedrock and boulder fields	0.15 – 0.30	
Talus and firm soil slopes	0.12 – 0.20	
Soft soil slopes**	0.10 - 0.20	

*KE = kinetic energy
**Soft soil slope coefficients were extrapolated from other slope types due to lack of data.

CHAPTER 6—CONCLUSIONS

The Visual Basic re-programming has made CRSP a Windows application and considerably more "user-friendly" than prior versions. Because of the reprogramming, iterative calculations can be performed efficiently, the program can be navigated easily, and CRSP's printed output is of a much higher quality.

The re-calibration of the input coefficients produced suggested values that correspond to both a wide variety of slope conditions and changes that have been implemented into the CRSP code since the program was last calibrated. Conversely, the prior CRSP calibration effort utilized only one type of slope material, bedrock with boulders that fell somewhere in the middle of the soft-to-hard range of slope types. Due to this limited amount of data, the suggested coefficients from the prior calibration tended to overestimate rockfall velocities, kinetic energies, and bounce heights for soft slopes and underestimate these parameters for hard slopes. The wider range of slope types, including firm soil and talus to hard slopes, used for the current calibration yielded suggested coefficients that tend to estimate rockfall parameters more accurately for a wide variety of slope types. The results of using more slope types for the current calibration than for the original calibration are sets of suggested coefficients that comprise much wider ranges (0.50-1.0 for the tangential coefficient and 0.10-1.0 for the normal coefficient) than the coefficients suggested from the prior calibration, (0.78-0.92 for the tangential coefficient and 0.28-0.42 for the normal coefficient). Hence, the new set of suggested CRSP input coefficients should be much more appropriate than that produced by the original calibration. Therefore, the user can produce considerably more accurate and valuable CRSP output than with previous versions.

If a user wishes to use as design criteria CRSP predicted maximum velocity and kinetic energy, values within the lower ends of the suggested coefficient ranges should be used. The converse is true if CRSP predicted average velocity and kinetic energy are to be used for design.

Also, since the normal coefficient is significantly more sensitive than the tangential coefficient, more attention should be paid to the normal coefficient than the tangential coefficient in the course of selecting input coefficients for CRSP modeling and during site-specific calibration procedures.

Several other observations came to light during the completion of this project. The influence of rock size on rockfall velocity is recognized to decrease as rock diameter increases and is also observed to be minimal on smooth hard slopes with few slope breaks. Thus, it is proposed that on slopes where rock embedment occurs, the velocity of relatively large rocks is less affected by embedment than the velocity of relatively small ones and rockfall velocity is unaffected by embedment on smooth hard slopes, where embedment does not occur. It follows that, if these hypotheses are correct, determining the largest rock likely to fall down a slope for modeling velocity with CRSP is not as important for smooth hard slopes as for other slope types. However, knowledge of the largest rock probable to fall down a given slope is essential for modeling kinetic energy.

Also, the suggested coefficients generated from the current calibration increase with increasing slope hardness. The causes of this observance are likely to include decreasing rockfall embedment and shearing of slope materials and increasing rockfall conservation of energy upon impact with increasing slope hardness.

CHAPTER 7—RECOMMENDATIONS

While the current calibration is a significant improvement on the previous calibration effort, calibration of CRSP to an even wider variety of slopes and rockfall phenomena and investigation into the accuracy of aspects of the CRSP algorithm are desirable.

The current calibration effort covered smooth hard slopes, most bedrock and boulder fields, and firm soil slopes with talus. However, CRSP has never been calibrated to soft soil slopes and the suggested tangential and normal coefficients presented for soft soil slopes in Chapter 5 are merely extrapolations from suggested coefficients for other slope types. In addition, although calibration data for a slope with some talus was used, CRSP has never been calibrated to coarse talus surficial materials. Soft soil slopes and coarse talus slopes are two major slope types for which calibration is needed and other missing slope types may exist.

The current calibration effort is also limited to rockfall velocity and kinetic energy data from rockfall experiments. Other rockfall phenomena are modeled by CRSP, but since they have not been calibrated, the accuracy of their modeling is certainly in question. Bounce height is a major aspect of rockfall modeled by CRSP to which no calibration has been conducted. Bounce height statistics are generated by CRSP, but due to the lack of bounce height calibration, their reliability is probably lower than the reliability of statistics calculated for kinetic energy and bounce height. Rockfall run-out can also be modeled by CRSP, although no numerical data is produced. No concentration on run-out has been made during the development of the CRSP algorithm or subsequent calibration efforts. Thus, any attempt to gain run-out information from CRSP should be made cautiously and future attention to run-out modeling by CRSP is in order.

Finally, it is unclear whether CRSP models rockfall angular velocity correctly. A study into this matter and a reassessment of the suitability of the CRSP algorithm would be beneficial to the accuracy of the program.

CHAPTER 8—USE OF THE COLORADO ROCKFALL SIMULATION PROGRAM

Introduction

The Colorado Rockfall Simulation Program (CRSP) was developed for modeling rockfall and providing statistical analysis of probable rockfall behavior at any given site. This analysis can be used as a tool to study the behavior of rockfall, determine the need for rockfall mitigation, and aid in the design of rockfall mitigation. CRSP is based on field observations and data collected from studies of videotapes of rockfall. In order to model rockfall behavior, CRSP utilizes numerical input values assigned to slope and rock properties. The model applies equations of gravitational acceleration and conservation of energy to describe the motion of the rock. Empirically derived functions relating to velocity, friction, and slope material properties are used to model the dynamic interaction of the rock and slope. The statistical variation observed among rockfall events is modeled by randomly varying the angle at which a rock impacts the slope within limits set by rock size and slope characteristics. The program provides a site-specific analysis of rockfall with output of velocity, bounce height, and kinetic energy statistics at various locations on the slope.

This chapter is intended to provide the user of CRSP with the background and methods needed to effectively use CRSP to help analyze rockfall hazards and plan mitigation. Sufficient theory is presented in Chapter 2 to give the user the necessary understanding of the theoretical basis of rockfall modeling. A systematic guide on using the program is presented below. Two example problems are presented in Appendices C and D. Comparisons between CRSP output and rockfall test results provide the user with an idea of what confidence may be expected from simulation results.

Description of the Colorado Rockfall Simulation Program, Version 4.0

CRSP yields estimates of probable rockfall velocities, bounce heights and kinetic energies for natural, or cut slopes. Like any computer model, the accuracy of the results produced by CRSP is determined by the accuracy of the input data, the applicability of the program to the field situation, and the accuracy of the model. While every effort has been made to make the model as accurate as possible, the program user must determine the quality of the output produced by CRSP.

CRSP Version 4.0 is a computer rockfall model programmed in Visual Basic, based on prior versions written in BASIC code. CRSP 4.0 will run on Windows 95 and Windows NT operating systems and is available only for PC-compatible computers.

CRSP may be used in many situations encountered during construction in steep terrain. With a little practice, engineering geologists and geotechnical engineers with field data collection experience should be able to effectively use the program and the methodology outlined in this report. The experience gained from using CRSP in many locations throughout the United States indicates that the program is useful in designing rock cuts and ditches. Various combinations of cut slope and ditch configurations can be tested until a configuration is found that is both aesthetically acceptable and safe with respect to rockfall. The "Site-Specific Calibration" section later in this chapter describes how to ensure that users obtain the greatest accuracy of output.

CRSP requires the following input data:

- A slope profile, input as a series of straight-line segments, referred to as cells, designated by the Cartesian (x, y) coordinates of the endpoints of each line.
- An estimation of the roughness of the slope surface (relative to rock radius) within each cell.
- Coefficients (R_t and R_n) that determine the rock energy loss upon slope impact.
- The size, shape, and starting location of the rocks comprising the rockfall events.

CRSP uses this input data in a stochastic model to produce statistics on probable rockfall velocity, kinetic energy, and bounce height based on a series of rock rolls under identical conditions. The following data is output by CRSP:

- The slope profile showing cell locations and the position of each simulated rock every tenth of a second as it travels downslope.
- The maximum, average, minimum, and standard deviation of rock velocities at each of one to three selected points (analysis points) on the slope.
- The maximum, average, and standard deviation of rock velocities at the end of each cell.
- The maximum, average, geometric mean, and standard deviation of rock bounce heights at each analysis point.
- The maximum and average bounce heights at the end of each cell.
- The maximum, average, and standard deviation of kinetic energies at each analysis point.
- Cumulative probability analyses of velocity, kinetic energy, and bounce height at each analysis point.
- Graphs of the distribution of rock velocities and bounce heights at each analysis point.

- Graphs of the maximum velocities and bounce heights along the slope.
- The number of stopped rocks in each ten-foot or ten-meter slope interval.

Field Data Collection for CRSP Input

Since rockfall hazard investigations are often conducted in response to a problem, finding the area is usually simple. If the investigation is being conducted for or near a roadway or railroad, good places to start identifying rockfall hazards are accident records and talking to maintenance personnel. This may provide a good idea of where and how often dangerous rockfall events occur. Location of rockfall hazard areas may also be accomplished by looking for evidence of recent rockfall events. While a single rock falling from a cliff may not leave an obvious scar, many rockfall events involve many rocks and leave an identifiable path. These paths are often best spotted from across a valley where a clear view of the slope is available. Examination of recent air photographs may accomplish the same objective. A comprehensive investigation should examine the slopes for potential source zones such as highly fractured or weathered rock masses or zones of accumulation such as talus slopes, bolder fields, etc.

Input data for CRSP consist of rock size, surface roughness of the slope, coefficients representing the materials in the slope, and coordinates for the cells defining the slope profile. Selection of input parameters begins with identification of the rockfall path from the source area to the area that may require protection. If more than one potential rockfall path is present, then multiple slope profiles may be required. The profile of this path must be input into CRSP as a series of straight-line segments called cells. This profile may be obtained from surveying the slope or detailed large-scale topographic maps. Division of the profile into cells and refining the profile is best done in the field, where changes in slope and slope material can be observed.

Data collection starts below the rockfall area with a detailed slope profile. If the slope is being surveyed, then the input data may be collected at the same time as the slope profile. The best data is obtained by climbing directly up the rockfall path, if this can be done safely. If the rockfall path is not accessible, then the data will have to be collected from a distance. As the investigation proceeds up the slope, the slope profile is divided into cells and each cell is assigned a range of probable inputs. The data form in Appendix B may be helpful.

Values for surface roughness, tangential coefficient, and normal coefficient must be selected for each cell. Also, cell boundaries and rock sizes must be chosen.

To ensure the greatest accuracy of CRSP, the program should be calibrated to each individual site. The “Site-Specific Calibration” section later in this chapter describes the approach.

Rock Size Determination

The size of the rocks involved in rockfall events depends on the size of the blocks in the source area and on the durability of the rocks. While it is conceivable that a rock breaks during descent or a smaller rock could produce a worst case, the worst case is usually for the largest rock that travels the length of the rockfall path. The largest rocks found at the base of the rockfall path that can be identified as having fallen from the source area make a good choice for rock size determination. If no rocks are available at the base of the path, then a rock size can be determined from the source area by measuring joint spacings. The rock size or sizes selected will be used later to aid in the determination of surface roughness.

Additionally the rock type or types should be noted. This will aid in the choice of appropriate rock density when running input files using CRSP. The "Running CRSP" section later in this chapter offers more information on rock density selection.

Cell Boundary Selection

Cell boundaries are used to define the slope profile and areas of uniform slope and characteristics. Cells are input into CRSP as the (x, y) coordinates of their endpoints. Cells may have any slope, but the beginning x-coordinate must equal the ending x-coordinate of the preceding cell.

Cell boundaries are selected where changes in slope occur and/or where the slope material changes. The number of cells to use depends on the length and complexity of the slope. Too few cells will decrease the accuracy of the simulation, but too many cells make the investigation needlessly difficult. Closely spaced cells may be inappropriate, because smaller variations in the slope are modeled by the surface roughness. Also, cell configurations that require excessive precision may result in erroneous outputs because the variables in the program are single precision. The influence of changes in slope becomes smaller with distance; therefore, more detail is put into the slope profile near the area where mitigation is being considered.

Surface Roughness

Surface roughness is a function of the size of the rock and the irregularity of the surface as described in the section on "CRSP Algorithm" in Chapter 2 (Figure 2). Surface roughness is an estimation of how much the slope angle may vary within the radius of the rock.

The beginning rockfall investigator may want to take some measurements of surface roughness. This may be done by stretching a measuring tape down the slope (within each cell) and measuring the distance to the slope perpendicular to the tape. Within each slope distance of one-rock radius, the greatest measurement that occurs with some frequency is the surface roughness. With a little practice, an estimation of the surface roughness may substitute for these time consuming measurements.

Because the program selects an impact angle variation up to the value defined by the surface roughness, the largest probable surface roughness should be used. Remember, this is not always the value for the largest bump on the slope, or an average variation in the slope, rather it is the value of the largest variation that occurs with some frequency. A range of probable surface roughness values should be selected for each cell, and if more than one rock size is being considered, separate surface roughness values are collected for each rock size. On very smooth surfaces, such as pavement, surface roughness is a function of the irregularity of the rock. In such cases appropriate surface roughnesses will typically be between 25 and 50 percent of the rock radius. One case for which surface roughness is extremely important is talus slopes. In all cases, a range of probable surface roughness values should be collected for use in a sensitivity analysis.

Tangential Coefficient

The tangential coefficient of frictional resistance determines how much the component of the rock's velocity parallel to the slope is slowed during impact. Vegetation and, to a lesser extent, slope material influence the tangential coefficient. A range of probable values should be selected for each cell, for use in a sensitivity analysis of the slope. Suggested ranges of tangential coefficient (R_t) values for various slope materials are presented in Table 4 (Chapter 5).

As discussed earlier, the tangential coefficient is significantly less sensitive than the normal coefficient, but the tangential coefficient may become more important for vegetated slopes.

Tangential coefficient values for slopes with vegetation more than a few feet tall are difficult to assess. The coefficient for an individual rock may be low; however, the first rocks down the hill clear a path for the next rocks.

Normal Coefficient

The normal coefficient of restitution is a measure of the change in the velocity normal to the slope after impact, compared to the normal velocity before the impact. The normal coefficient is determined by the rigidity of the slope surface.

Table 5 (Chapter 5) shows the ranges of suggested normal coefficient values for different materials. During the program calibration, it was observed that the normal coefficient appears to be somewhat dependent on slope length, with a longer slope corresponding to a greater value of R_n. Also, as discussed earlier, the normal coefficient is particularly sensitive compared to the tangential coefficient.

One way to judge the firmness of the slope is that footprints will be left on soft soil slopes, while little or no impression will be left on firmer soil slopes. Keep in mind that a soft soil may become frozen and hard in the winter.

Site-Specific Calibration

In order to achieve the highest degree of accuracy from CRSP, the program should be calibrated to each distinct study site. This can be accomplished by first estimating probable ranges of surface roughness, tangential coefficients, and normal coefficients for the slope, as described above. The ranges can then be input into CRSP (as detailed in the "Creating An Input Data File" and "Running CRSP" sections later in this chapter), along with the rest of the collected data, and the output compared to field observations. For example, if rocks are recognized to frequently stop at particular locations on the slope, CRSP should be in accord. Similarly, if rocks, which have fallen from the slope, are observed twenty-five feet from the slope base, CRSP should not show that all rocks of that size stop on the slope. The user can adjust surface roughness, tangential coefficient, and normal coefficient combinations to model what they see in the field. Since surface roughness can be directly measured or estimated in the field and the tangential coefficient is generally not very sensitive, the calibration should concentrate primarily on the normal coefficient. However, as discussed earlier, the tangential coefficient may be sensitive for significantly vegetated slopes.

Historical Rockfall Events

Awareness of rockfall hazards has increased substantially in recent years. This can be attributed to the increase in development in the mountainous regions here in the United States and abroad. The recent development of rockfall hazard rating systems has also increased awareness and more effort is being made in the identification of the hazards.

In Colorado, most reported rockfall events are investigated and an assessment of the conditions that led to the failure is determined. The path of the rock is followed to evaluate the behavior of the rockfall event. The locations of each impact are mapped and the damage to vegetation is recorded. From this information, the event can be recreated and an estimation of the trajectory, bounce heights and bounce lengths can be made.

Physical data of the site is quantified by surveying the path of the event and the location of the source area. The dimensions of the rock(s) is measured. This information can then be used in CRSP and adjusted according to the actual rockfall event.

Case History: Gypsum Rockfall-Event, Colorado

In November of 1990, a rockfall occurred 10 miles east of Glenwood Canyon near the town of Gypsum. Several large boulders, averaging four to six feet in diameter, detached near the crest of the hillside. Many of these boulders reached Interstate 70 at the bottom of the slope and some of the material was deposited along the slope.

Deposits of boulders in the median and along the slope indicated that this was a continual rockfall area. Close investigation of the source area revealed that the majority of unstable material had not yet detached. Two large boulders, each approximately eight feet in diameter, had wedged near the base of a funnel shaped source area. Behind the wedge was an additional 20 to 30 yards of unstable material.

A CRSP model was developed and calibrated based on the recent event, which was used to predict future rockfall behavior. The input data file was compiled based on the suggested values given in Tables 4 and 5. A sensitivity analysis was conducted based on adjustments to the normal and tangential coefficients. As expected, adjusting the normal coefficient of friction provided a reasonable model. Following several simulations, the adjusted values were used to accurately model the observed rollout and depositional zones.

The model indicated that a berm and ditch near the base of the slope should retain any fallen material. The required dimensions of the structure would be a 35-foot wide ditch in front of a 15-foot high impact wall, with the impact surface constructed to near vertical. The wall height and vertical configuration was necessary to insure that the large boulders would not climb the wall face due to the high rotational velocity. A composite wall utilizing a tire-faced geosynthetic-reinforced soil and concrete L-panels was constructed to a height of 18 feet. Behind the wall was a 25-foot wide berm. The excessive width was required for the high impact energies predicted by the model.

The composite wall and ditch configuration was tested by blasting the large boulders loose from the funnel shaped chute to release the material trapped by the boulders. All of the material removed by the blast was retained by the impact wall, including the two eight foot diameter boulders

In July of 1991, a natural failure occurred from the same source, and all of the rockfall material was successfully contained by the berm.

From *Rockfall Hazard Mitigation methods,* publication no. GHWA SA-93-085

Full Scale Field Testing

Large projects, such as corridor improvements, may justify full scale testing of actual rockfall behavior. The analysis of actual rock rolling is often done in conjunction with the removal of loose material as part of an overall rockfall mitigation program. Although time consuming and costly, it can be very useful in determining the appropriate range of values for the normal and tangential coefficients.

The program involves marking the slope with a series of reference lines at regular intervals that are perpendicular to the slope's plunge. Video cameras are installed to capture the time duration from each reference line and ultimately determine the velocity of the rocks. If high-speed cameras are used, the rotational velocity can also be captured.

Before the rocks are rolled, the individual rocks are measured on three axes to determine the dimensions of the rocks. The weight of the rock can be calculated using the estimated specific gravity of the rock or more accurately measured with a load cell if desired.

The video captures the initial velocity the moment the rock is pried or pushed from the source area. It also allows the bounce height, bounce length, translational velocity and rotational velocity to be determined as it travels down the slope. From this data the total kinetic energy can be calculated and the rockfall behavior can be verified. This information is then compared with the analysis performed by CRSP and the input parameters can be adjusted to fit the actual site conditions.

Once the model is calibrated to the site, mitigation measures can be designed using the appropriate values for kinetic energy and bounce height. However, CRSP, like any other model, does not address every situation or every condition of all rockfall events. The designer should still use sound judgement based on extensive experience in engineering geology and erosional processes to verify the data and it's validity.

Case History: Gaviota Pass Rockfall Project, California

This project involves investigation and construction plans for the California Department of Transportation's Gaviota Pass Rockfall Project in Santa Barbara County. A portion of California State Route 101 is located within mountainous terrain that is subject to rockfall. Numerous auto accidents caused by rockfall had been recorded in the area. At the request of maintenance staff, the California Department of Transportation Engineering Geologists performed rockfall studies. Included in the studies were detailed geologic rockfall investigations.

The investigations consisted of detailed field mapping to identify rockfall locations and to characterize rockfall sizes, frequency, and site accessibility for construction. The investigation also included rock-rolling tests at selected locations to determine rockfall velocities, trajectories, and kinetic energies. Rock rolling field data were also used for computer modeling of rockfall behavior at every potential rockfall location. Computer analysis enabled engineering geologists to model hundreds of rockfalls. The computer model used was the Colorado Rockfall Simulation Program (CRSP).

Nine sites were identified as having rockfall problems. Rockfall energies ranged from 15 foot-tons to 70 foot-tons. Typical rockfall sizes are between 1 to 3 feet in diameter. After careful analysis, several rockfall mitigation measures were selected that satisfied engineering geology and environmental concerns.

The designs were protection and control measures, and included flexible rockfall barriers, draped wire mesh, and anchored wire mesh. Scaling was performed prior to all work. Because of the steep and narrow terrain, about half of the 1400 feet (427 meters) of flexible barrier installed, had to be constructed on the slope. The other 700 feet (213.5 meters) was constructed near grade on benches 3 feet above the roadway. The flexible barriers used woven wire rope rock nets provided by Brugg Cable Products and L'Entreprise Industrielle.

From *Rockfall Hazard Mitigation Methods*, Publication No. FHWA SA-93-085

Installing CRSP

CRSP 4.0 includes an installation wizard. To install CRSP, simply place either Installation Disk 1 or the CD (depending on which distribution medium has been obtained) into the appropriate drive of the computer. Then use the Windows "Run" command to run: "setup.exe" from the appropriate CD or disk drive. If using Windows 95, the "Run" command is on the "Start" menu. Alternatively, setup.exe can be run through DOS by typing the drive followed by "setup.exe" at a DOS prompt (e.g., a:\setup.exe).

Once the setup program begins running, the user follows the on-screen instructions to complete the installation. During this process, the user can approve a default location to install CRSP or select an alternative location. Installed along with CRSP's executable ("*.exe") file are all of the files necessary to run the program. Also included are two existing data files, glenwood.dat and rifle.dat, that may be used as examples and to verify that CRSP is operating properly.

If using Windows 95, the installation wizard will automatically place CRSP in the **Start** menu. However, if the user desires to access CRSP through a shortcut icon on the computer's desktop, the user must manually create the shortcut by one of several methods. One simple way is to depress the right mouse button on the desktop and choose **New**. This will bring up another menu, from which **Shortcut** should be chosen. Next, on-screen instructions will be presented. At the **Command line**, the user needs to select the **crsp4.exe** file as the item to which the shortcut is desired. This selection can be achieved by choosing **Browse** and double-clicking on **crsp4.exe** at the location on the hard drive that the user accepted upon installation (the default directory is CRSP). Finally, the user is prompted to select a convenient name for the shortcut. This name will appear below the CRSP icon on the desktop. Other methods for creating shortcuts in Windows are available in the users' manuals for those programs.

Creating an Input Data File

An input data file can be created by using the file editor included within the CRSP program. This section will examine what should be included in the input file.

Input Data

CRSP will require the following information for an input file:

- A slope profile, input as a series of straight-line segments called cells, designated by the coordinates of the endpoints of each line.

- An estimation of the roughness of the slope surface within each cell. Surface Roughness will likely change with rock size (see the "CRSP Algorithm" section in Chapter 2).

- Coefficients of restitution and frictional resistance.

- The size, shape, and starting location of the rocks comprising the rockfall events.

It is helpful to organize this information in tabular form to simplify the data entry. To help with this, a table called "CRSP Data Form", included in Appendix B, can be photocopied, and used to tabulate field data.

When setting up the input for the data file, the following rules must be followed:

1. Establish a Cartesian coordinate system for the slope of interest that consists of only positive x- and positive y-values (i.e., a quadrant I grid). Also, define the largest y-coordinate of the slope to correspond to x = 0 (Figure 9).

2. Number the cells from left to right. The cells will be defined by their endpoint coordinates.

3. CRSP requires that at least one point of interest (analysis point) be entered for which the program will provide a detailed statistical analysis. The user may choose to include one, two, or three analysis points. Usually, an analysis point is a position where mitigation is being considered. Only the x-coordinate of an analysis point will need to be entered into the data file (CRSP will calculate the corresponding y-coordinate).

4. CRSP will simulate rockfall from various source locations. The source zone is defined by upper and lower elevations only, which must be entered into the data file as upper and lower y-coordinates.

5. CRSP will simulate rockfall barriers within the profile; however the upslope face of the barrier may not be vertical or the program will show an error. The upslope face may be modeled at an angle less than vertical, say 0.25 to 1.0 vertical.

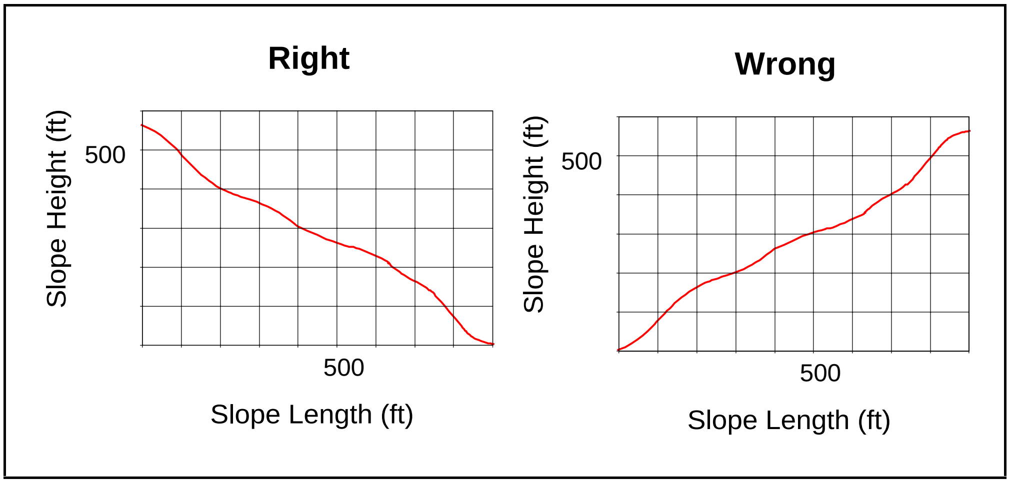


Figure 9. Examples of slope orientation for CRSP on the Cartesian grid (Pfeiffer et al., 1995).

Documentation Conventions

Henceforth, this report will use different typefaces to help the user understand the operation of the program. The following conventions are adopted:

Bold	Bold typeface will be used to represent text that appears on the screen or anything the user must type.
Italic	Italic typeface will be used to denote a key on the keyboard that is pressed (e.g., *Tab* means press the tab key).

Writing the Input File

CRSP includes an easy-to-use input file editor for the production of input data files. These files are given the extension "*.dat" by CRSP 4.0. To use the input file editor choose **New Input File** from CRSP's **File** menu.

Upon choosing the **New Input File** command, the **Input File Specifications** window (Figure 10) appears. This screen contains 8 boxes for user input. To enter data, the user can toggle between input boxes using *Tab*, *Enter*, or by selecting a box with the left mouse button. The user enters the following data into the given input boxes on the **Input File Specifications** window (boxes for optional information may be left blank):

- **Units of Measure**, either **U.S.** or **Metric** are entered through a pull-down list box. U.S. units are comprised of: feet as the distance unit, feet per second as the velocity unit, foot-pounds as the energy unit, pounds as the weight unit, and pounds per cubic

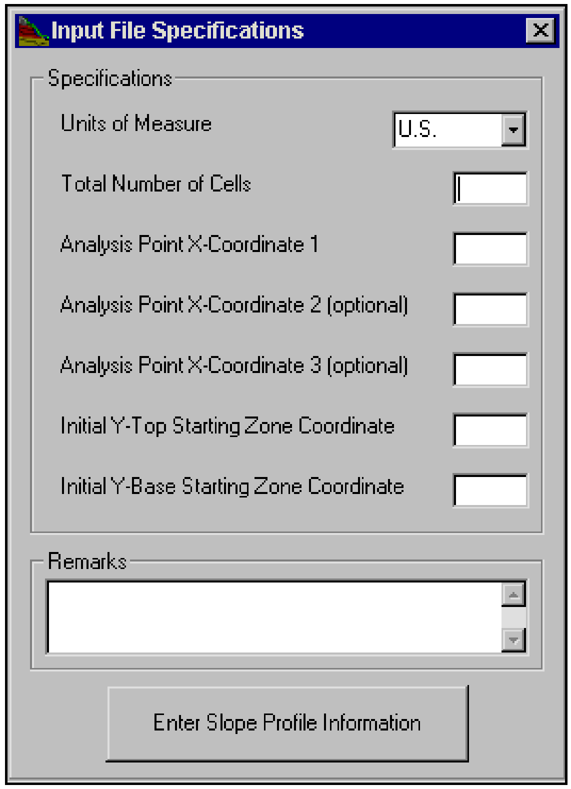


Figure 10. CRSP Input File Specification window.

feet as the density unit. Metric units refer to: meters as the distance unit, meters per second as the velocity unit, Joules as the energy unit, kilograms as the mass unit, and kilograms per cubic meter as the density unit.

- **Total Number of Cells** in the input file. This value must be a positive integer.

- **Analysis Point X-Coordinate 1** is the positive value corresponding to the horizontal location of analysis point 1.

- **Analysis Point X-Coordinate 2** is the positive value corresponding to the horizontal location of analysis point 2. This entry is optional (in case only one analysis point is desired). Analysis point 2 cannot be used without analysis point 1.

- **Analysis Point X-Coordinate 3** is the positive value corresponding to the horizontal location of analysis point 3. This entry is optional (in case only one or two analysis points are desired). Analysis point 3 cannot be used without analysis point 2.

- **Initial Y-Top Starting Zone Coordinate** is the positive value representing the upper elevation of the rockfall source zone. This value must be greater than or equal to the Initial Y-Base Starting Zone Coordinate (see below).

- **Initial Y-Base Starting Zone Coordinate** is the positive value representing the lower elevation of the rockfall source zone. This value must be greater than or equal to the Begin Y value (see below) for the final cell in the input file.

- **Remarks** are any comments or descriptions the user wishes to include with the file. This information is optional.

Once the user is finished entering data in the **Input File Specifications** window, the **Enter Slope Profile Information** button should be selected. This action will present the **Input File Editor** window (Figure 11).

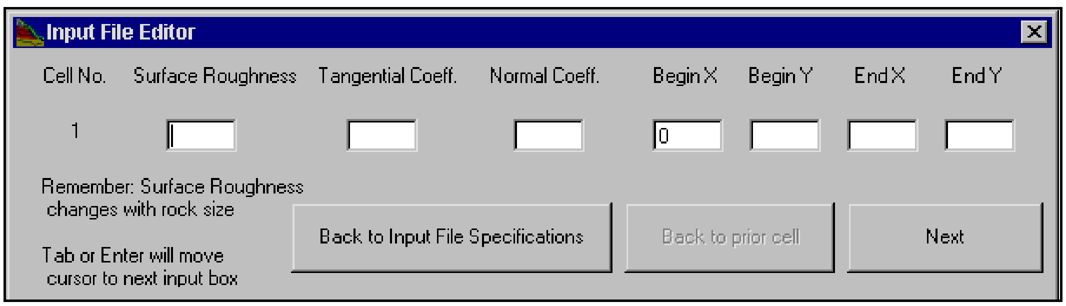


Figure 11. CRSP Input File Editor window.

The **Input File Editor** window is where the user enters the data for each cell of the slope profile. The input boxes for cell number 1 appear first and the cell number is automatically entered for each cell as the leftmost entry on the screen. The user then enters the information listed below for cell number 1 and selects the **Next** button when finished with that cell. This will present the input boxes for cell number 2 and a similar procedure is followed for each subsequent cell. The user also has the option to go back and change data from previous cells, by selecting the **Back to prior cell** button, or to change the **Units of Measure**, **Total Number of Cells**, etc., by selecting the **Back to Input File Specifications** button. The information required for each cell is as follows:

- **Surface Roughness** must be a positive value.

- **Tangential Coefficient** must be a positive value between 0 and 1. See Table 4 (Chapter 5) for suggested values.

- **Normal Coefficient** must be a positive value between 0 and 1. See Table 5 (Chapter 5) for suggested values.

- **Begin X** is a cell's starting x-coordinate, must be a positive value, and must be equivalent to the **End X** value from the preceding cell. The **Begin X** value is entered automatically by CRSP and cannot be changed except for cell number 1. Zero is entered automatically for cell number 1, but this can be changed to any convenient positive starting value. CRSP will adjust the **Begin X** value automatically should the user return to the previous cell and change the **End X** value.

- **Begin Y** is a cell's starting y-coordinate and must be a positive value. This value is also entered automatically by CRSP, but, unlike **Begin X**, can be changed in case the user desires to have a vertical cliff face.

- **End X** is a cell's ending x-coordinate and must be a positive value greater than the **Begin X** value for the same cell.

- **End Y** is a cell's ending y-coordinate and must be a positive value.

Once the user reaches the data input area for the last cell, the **Next** button changes into the **Finish** button. After data for the last cell is entered and the user selects **Finish**, the **Save File As…** box (Figure 12) is presented for the user to choose a **File name** for the input file and the folder location for its storage. Once the user enters a filename and selects **OK**, the file is saved to the specified place with a "*.dat" file extension. Should the user choose to exit the input file editor before reaching this final step, the input file will not be saved.

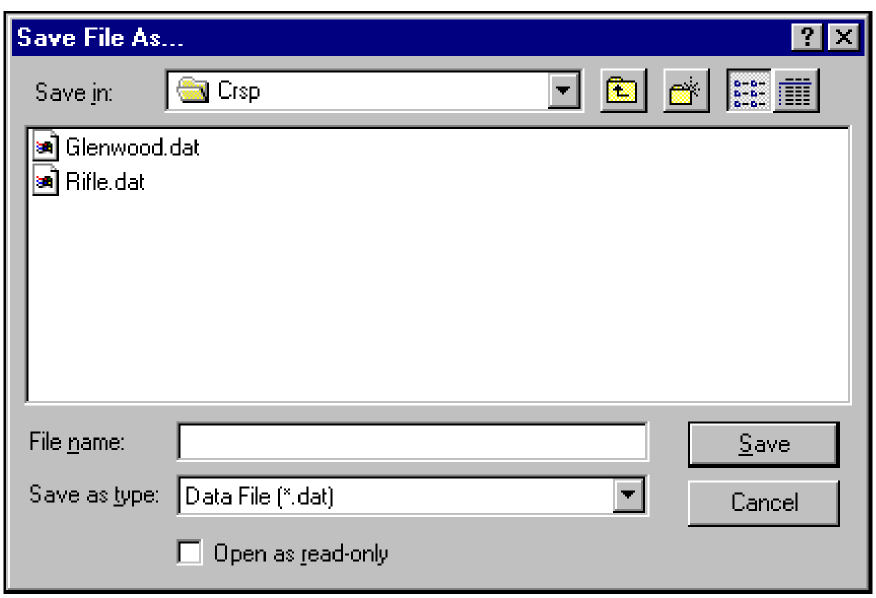


Figure 12. CRSP Save File As . . . box.

The input file format is shown below:

Line 1	→	"Units",C_n,X_{an1},X_{an2},X_{an3},Y_2,Y_1,C
Lines 2 through $C_n + 1$	→	S, R_t, R_n, X_b, Y_b, X_e, Y_e

where:

"Units"	=	system of units (U.S. or metric)
C_n	=	total number of cells used for simulation
X_{an1}	=	x-coordinate of analysis point 1
X_{an2}	=	x-coordinate of analysis point 2 (optional)
X_{an3}	=	x-coordinate of analysis point 3 (optional)
Y_1	=	y-coordinate of the top of the source rock zone
Y_2	=	y-coordinate of the bottom of the source rock zone
C	=	remarks, comment, or descriptive statement (optional)
S	=	surface roughness
R_t	=	tangential coefficient of frictional resistance
R_n	=	normal coefficient of restitution
X_b	=	x-coordinate of the beginning of the cell
Y_b	=	y-coordinate of the beginning of the cell
X_e	=	x-coordinate of the end of the cell
Y_e	=	y-coordinate of the end of the cell

Although, creating an input file within CRSP 4.0 is simple, the user could create an input file using any ASCII text editor. To do so, simply follow the format presented above exactly as shown, with no spaces after the commas. Data for cell number 1 appears as the second line of the file and subsequent cells follow (each on a separate line). If less than three analysis points are desired, enter a zero (**0**) for X_{an2} and/or X_{an3}. If the user chooses not to enter any remarks, two quotation marks (**""**) should be entered at the end of the first line of the file, for C (as shown above).

Note that while CRSP 4.0 will accept input files created by prior CRSP versions (although they have a slightly different format), the prior versions of CRSP will not accept files created using Version 4.0. This is largely a product of the addition of an option to use one to three analysis points, although other minor changes to the input file format were implemented.

The file, glenwood.dat, as produced by CRSP Version 4.0, is reproduced below as an example:

```
"U.S.",15,885,0,0,800,810,"Glenwood Canyon Site"
1.5,.85,.35,0,794,224,620
1.8,.85,.35,224,620,248,610
2.5,.85,.35,248,600,306,540
1,.81,.32,306,530,385,480
1,.81,.32,385,480,500,390
1.2,.81,.32,500,390,557,360
.70,.8,.31,557,360,848,157
.60,.8,.31,848,157,925,110
1,.82,.31,925,110,933,110
.5,.8,.32,933,95,968,80
.1,.9,.4,968,78,1002,78
1,.8,.32,1002,60,1069,25
.2,.82,.32,1069,25,1075,27
.1,.9,.4,1075,27,1104,27
1,.82,.32,1104,27,1153,4
```

Running CRSP

Before CRSP can be run, an input data file must be made. See the "Creating an Input Data File" section in this chapter for instructions on how to make an input file. This section will give systematic instructions on how to run CRSP.

Upon starting CRSP, a title screen (Figure 13) will appear for a few seconds, followed by an acknowledgment screen (Figure 14); this is followed by a disclaimer screen (Figure 15). The user need not wait for these introductory windows to disappear before using the program; the program is accessible through CRSP's menu bar immediately upon entrance.

After entering CRSP, an input file can be run by selecting the **Open** command from the **File** menu. Invoking the Open command will bring-up the **Open Existing File** box (Figure 16), from which the user should choose the **File of type** ("Data Files (*.dat)", "Bitmaps (*.bmp)", "CRSP files (*.csp)", or "All Files (*.*)"), **File name** for the file to be opened, and its location. To run an input file, **Data Files (*.dat)** must be chosen as the **File of type** (unless using an input file created by a prior CRSP version, which may have no extension). Files with the extensions of "*.csp" (CRSP output files) and "*.bmp" (bitmap slope profile files) can also be opened by CRSP. See the "Viewing an Output File" and "Viewing a Slope Profile" sections, respectively, later in this chapter for information on these types of files.

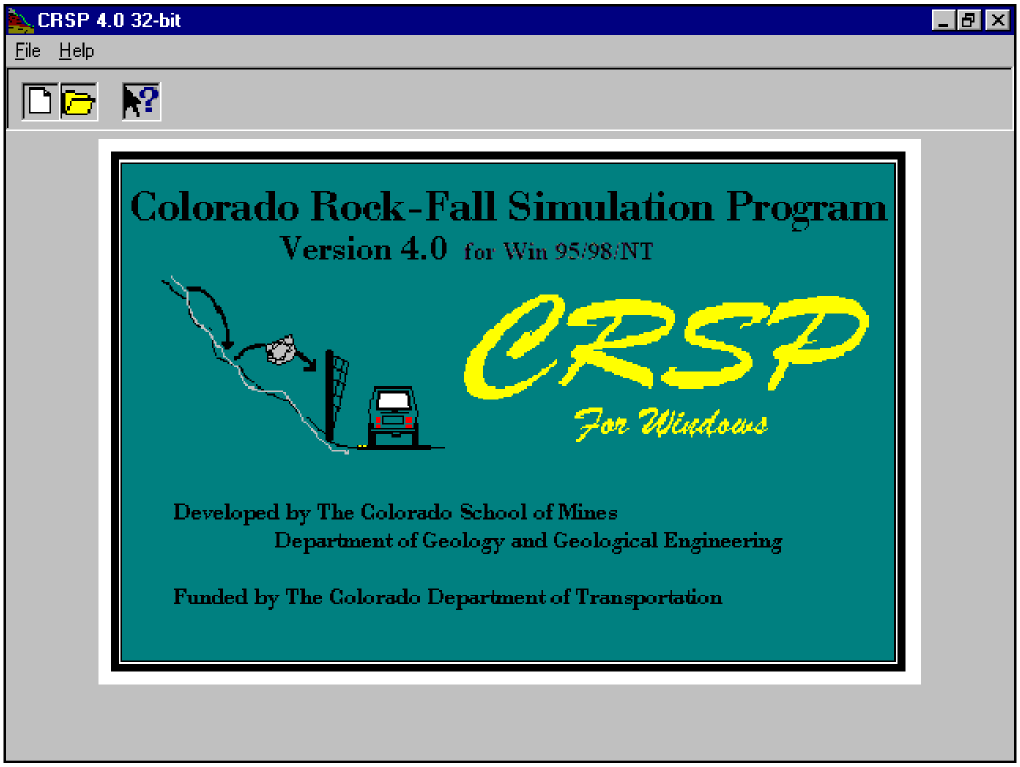


Figure 13. CRSP title screen.

Figure 14. CRSP acknowledgement screen.

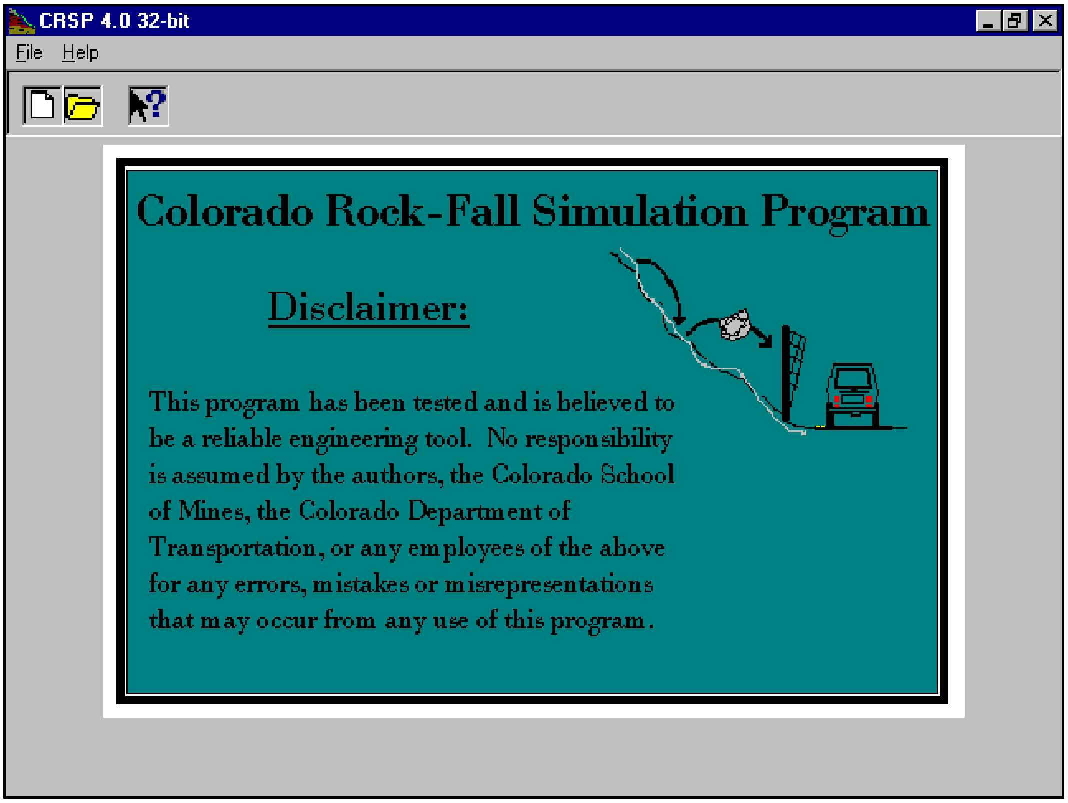


Figure 15. CRSP disclaimer screen.

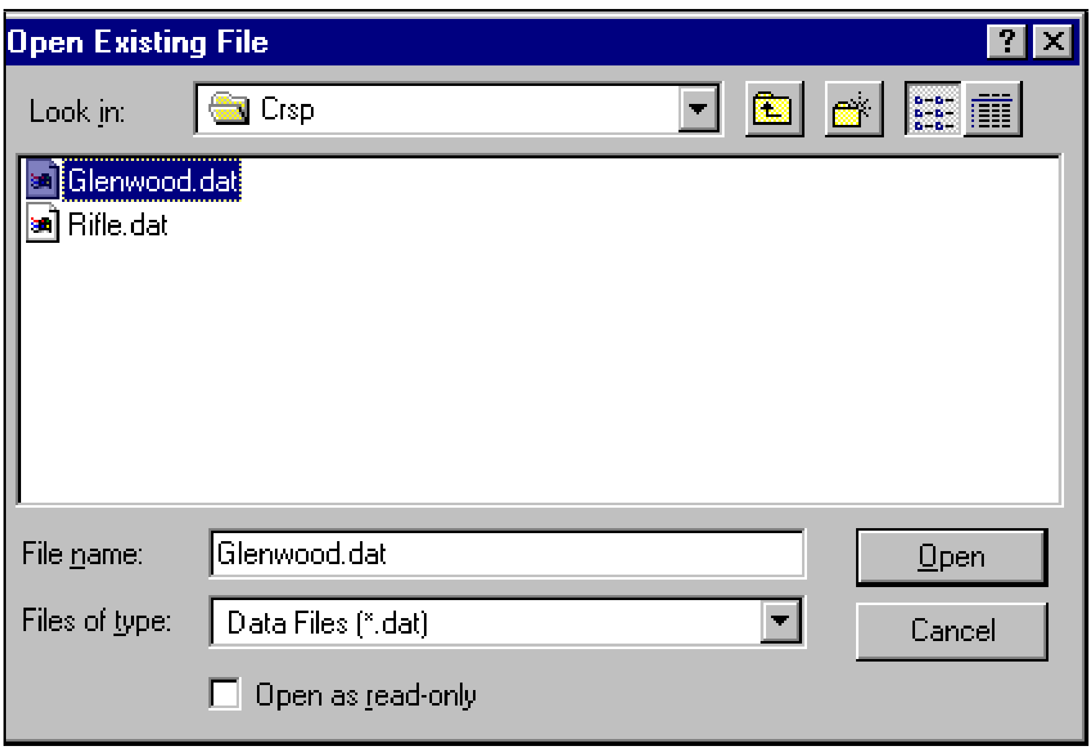


Figure 16. CRSP Open Existing File box.

Once an input data file has been selected from the **Open Existing File** box, the **CRSP Input File Preview – Part A** window (Figure 17) appears. This window is similar to the "Input File Specifications" window encountered when creating an input file. Displayed in the **CRSP Input File Preview – Part A** window is the following information from the input file:

- Units of Measure
- Total Number of Cells
- Analysis Point X-Coordinate 1
- Analysis Point X-Coordinate 2
- Analysis Point X-Coordinate 3
- Initial Y-Top Starting Zone Coordinate
- Initial Y-Base Starting Zone Coordinate
- Remarks

The user should check the displayed data to ensure that no changes are desired. If desired, changes can be made by selecting the appropriate input box, deleting the existing information, and replacing it with new data. CRSP does not allow the **Total Number of Cells** to be decreased, but adding cells is acceptable. The same rules from the "Writing

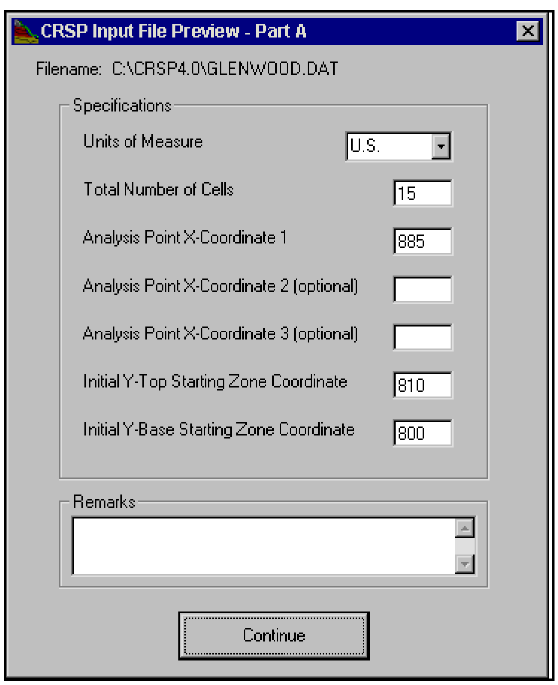
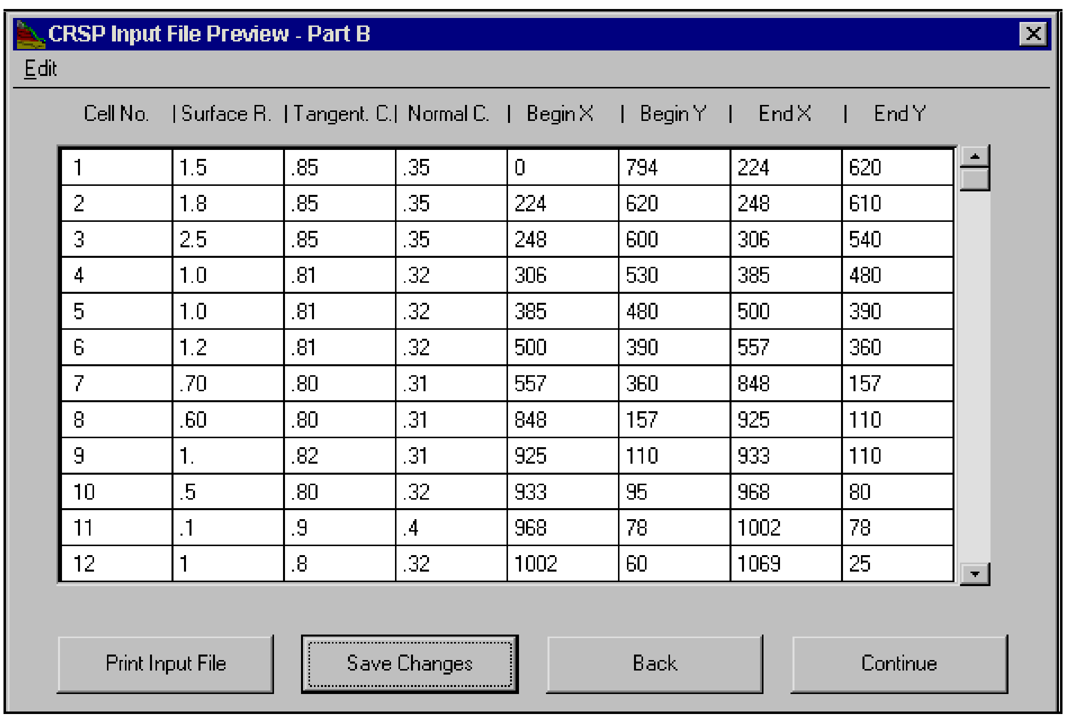


Figure 17. CRSP Input File Preview—Part A window.

the Input File" section (in this chapter) for the types of input that are acceptable for each datum are applicable. Remember that surface roughness changes when various rock sizes are modeled (see the "CRSP Algorithm" section in Chapter 2). When the user is satisfied with the information displayed, the **Continue** button should be selected.

Next, the **CRSP Input File Preview – Part B** window (Figure 18) will appear. A grid showing all data for each cell is presented. If more than 12 cells are included in the input file, a scrollbar is available to the right of the grid to allow the user to view the grid from top to bottom. The data (for each cell) presented in the grid is the same as that entered in the "Input File Editor" window used while creating the input file:

- **Surface Roughness**
- **Tangential Coefficient** (see Table 4 in Chapter 5 for suggested values)
- **Normal Coefficient** (see Table 5 in Chapter 5 for suggested values)
- **Begin X**
- **Begin Y**
- **End X**
- **End Y**



Cell No.	Surface R.	Tangent. C.	Normal C.	Begin X	Begin Y	End X	End Y
1	1.5	.85	.35	0	794	224	620
2	1.8	.85	.35	224	620	248	610
3	2.5	.85	.35	248	600	306	540
4	1.0	.81	.32	306	530	385	480
5	1.0	.81	.32	385	480	500	390
6	1.2	.81	.32	500	390	557	360
7	.70	.80	.31	557	360	848	157
8	.60	.80	.31	848	157	925	110
9	1.	.82	.31	925	110	933	110
10	.5	.80	.32	933	95	968	80
11	.1	.9	.4	968	78	1002	78
12	1	.8	.32	1002	60	1069	25

Figure 18. CRSP Input File Preview—Part B window.

Like the "Input File Preview – Part A" window, the user should check the data presented in the **Input File Preview – Part B** window to see if it is still acceptable. If changes are desired, any part of the grid (except for **Cell Number**) can be edited at this point. To move through the grid, select any part of it using the left mouse button and then use the *Tab*, *Enter*, or *Arrow* keys. Changes can be implemented by removing the existing data with the *Backspace* or *Delete* keys and replacing it with new data. Additionally, **Cut**, **Copy**, and **Paste** commands are available from the **Input File Preview – Part B** window's pull-down **Edit** menu. The same rules discussed in the "Writing the Input File" section for acceptable input values apply.

While viewing the **Input File Preview – Part B** window, four buttons are accessible: **Print Input File**, **Save Changes**, **Back**, and **Continue**. Choosing the **Print Input File** button will call the Print box (Figure 19) to produce a paper copy of the information presented in both Parts A and B of the Input File Preview. **Save Changes** allows the user to save the input file (using the old filename, and thereby overwriting the existing file, or a new one) to disk after any changes have been made. If an input file created using a prior version of CRSP is being run, selecting **Save Changes** will save the input file using the CRSP 4.0 format. **Back** returns the user to the **Input File Preview – Part A** window. Finally, the **Continue** button should be selected when the user is ready to proceed with the running of the input file.

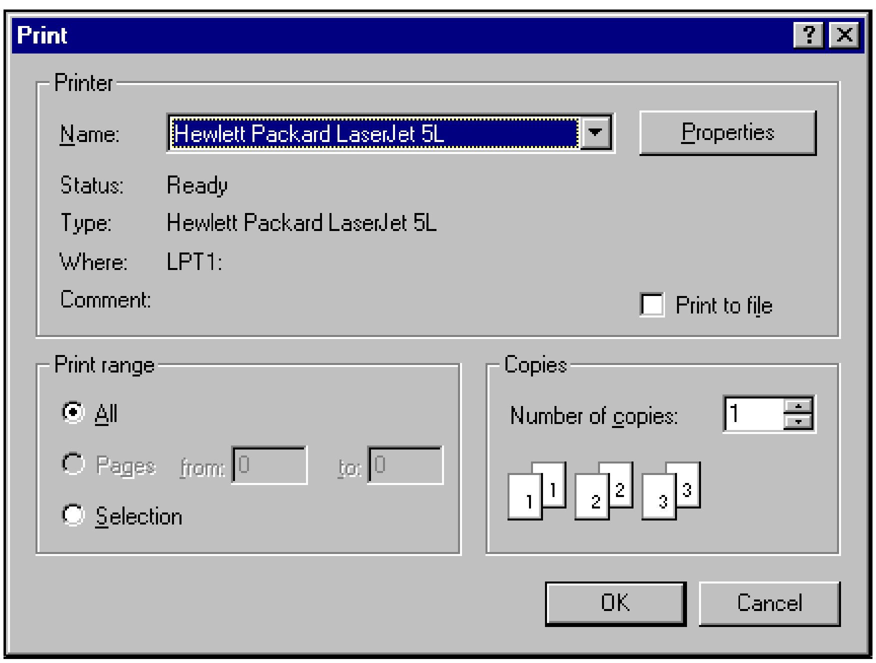


Figure 19. CRSP Print box.

Next, the **Rock Simulation Specifications** window (Figure 20) is shown. This screen allows the user to choose the parameters involved with the individual simulation (this information is not included in the input file). Default values are given for each piece of information, but the user is free to select other values. If the user wants to reinstate the default values, a **Revert to Default Values** button is available. Table 6 presents the information requested for this window and the corresponding default values.

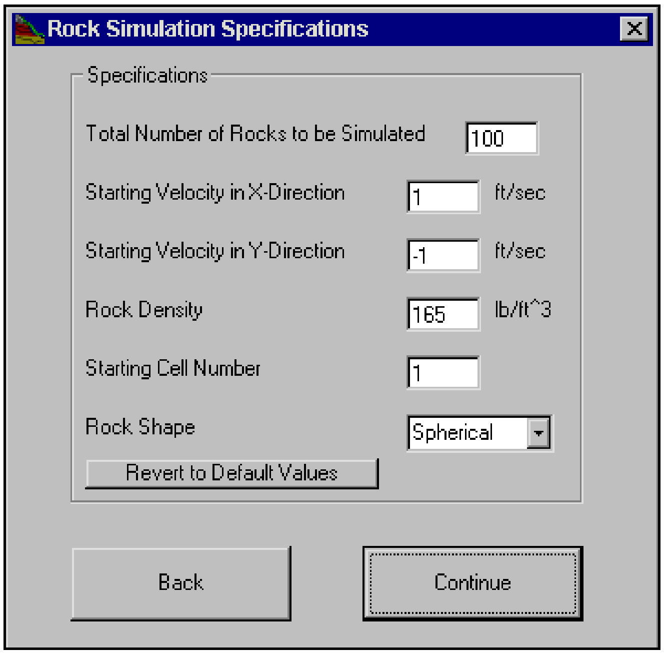


Figure 20. CRSP Rock Simulation Specification window.

Table 6. Rock Simulation Specifications and Default Values.

Rock Simulation Specification	U.S. Unit Default Value	Metric Unit Default Value
Total Number of Rocks to be Simulated	100	100
Starting Velocity in X-Direction	1 ft/sec	0.3 m/sec
Starting Velocity in Y-Direction	-1 ft/sec	-0.3 m/sec
Rock Density	165 lb/ft^3	2646 kg/m^3
Starting Cell Number	1	1
Rock Shape	Spherical	Spherical

Rock Density varies according to rock type. When U.S. units are used, CRSP actually employs unit weights (weight per unit volume) rather than a strictly defined density (mass per unit volume). For metric units, densities are used. Table 7 lists some typical unit weights and densities for different types of rocks.

Table 7. Typical Rock Unit Weights and Densities (After: Hoek and Bray, 1981, p. 23)

Rock Type	U.S. Units: Unit Weight (lb/ft^3)	Metric Units: Density (kg/m^3)
Hard igneous rocks – granite, basalt, porphyry	160 to 190	2550 to 3060
Metamorphic rocks – quartzite, gneiss, slate	160 to 180	2550 to 2850
Hard sedimentary rocks – limestone, dolomite, sandstone	150 to 180	2340 to 2850
Soft sedimentary rocks – sandstone, coal, chalk, shale	110 to 150	1730 to 2340

The **Starting Cell Number** refers to the first cell to be viewed during the simulation. It does not indicate the cell at which the rocks begin rolling. The rocks are rolled from the rockfall source zone (as indicated by its upper and lower y-values in the input file) regardless of the **Starting Cell Number** chosen. The user is allowed to choose **Starting Cell Number**s other than 1 to enable viewing of areas of interest (on the slope profile during the simulation) in greater detail than if the whole slope was chosen. The ending cell number can be chosen in the next window.

Three **Rock Shape**s are available from a pull-down list for the simulation: **Spherical**, **Cylindrical**, and **Discoidal**. Spherical rocks are usually chosen because they generally represent the worse case. This is true since they comprise the most mass for a given radius. However, the other shapes are available for situations where cylindrical or discoidal rocks are observed in the field as being appropriate, or for sensitivity analyses of the rock shape on the output.

When the user is finished with the **Rock Simulation Specifications** window, the **Continue** button should be pressed. A **Back** button is also available to allow the user to return to the Input File Preview screens to make changes.

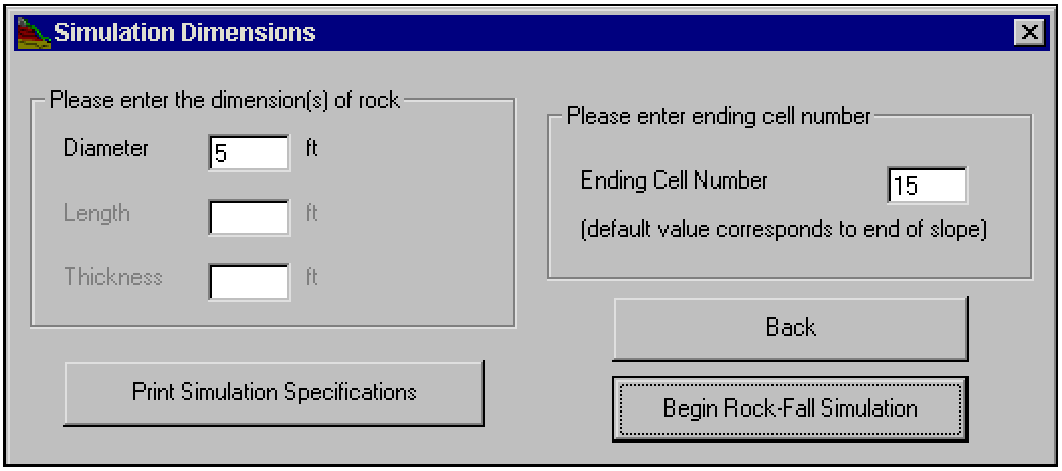


Figure 21. CRSP Simulation Dimensions window.

Pressing **Continue** brings-up the **Simulation Dimensions** window (Figure 21). At this screen, the user enters the dimensions for the rock to be simulated. If the user has chosen a spherical rock shape (at the **Rock Simulation Specifications** window), only a **Diameter** can be entered. If a cylindrical shape is chosen, **Diameter** and **Length** must be entered. Finally, if a discoidal rock is selected, **Diameter** and **Thickness** must be input. At this point, the user also enters the **Ending Cell Number** to be viewed during the simulation. Again, the starting and ending cell numbers represent the area of the slope profile to be viewed while CRSP runs, but do not affect the point from which rocks are rolled. Rockfall always begins at the source zone (as selected for the input file) for the simulation. The last cell number is entered as the default for **Ending Cell Number**. This default can be reset (after it has been changed) by selecting the **Revert to Default Values** button in the **Rock Simulation Specifications** window.

A **Back** button is available to allow the user to return to previous windows and make changes. In addition, the information from the **Rock Simulation Specifications** and **Simulation Dimensions** screens can be printed to a paper copy by selecting the **Print Simulation Specifications** button.

Once the rock dimension and ending cell number information has been entered, CRSP is ready to run the input file. Select the **Begin Rockfall Simulation** button to view the slope profile and start the simulation.

A screen showing the slope profile (Figure 22) will appear next. The profile is plotted according to x- and y-axes, which show the scale. If metric units have been chosen, the plot scale is 20 meters per division. If U.S. units are used, the scale is 20 feet per division. Labeled tick marks illustrating the scale are attached to the x- and y-axes. Above the plot of the slope profile, the x-coordinate locations of analysis points 1, 2, and 3 are shown. As the simulation progresses, the trajectory of each simulated rock is illustrated on the slope profile. This is accomplished by the plotting of a dot, indicating rock position, every tenth of a second. The result is that the user can view the trajectories of all simulated rocks together. This presentation allows the user to see where high bounce heights occur and, thus, where problematic areas might exist on the slope or where low bounce heights occur and, thus, where mitigation by use of barriers may be feasible.

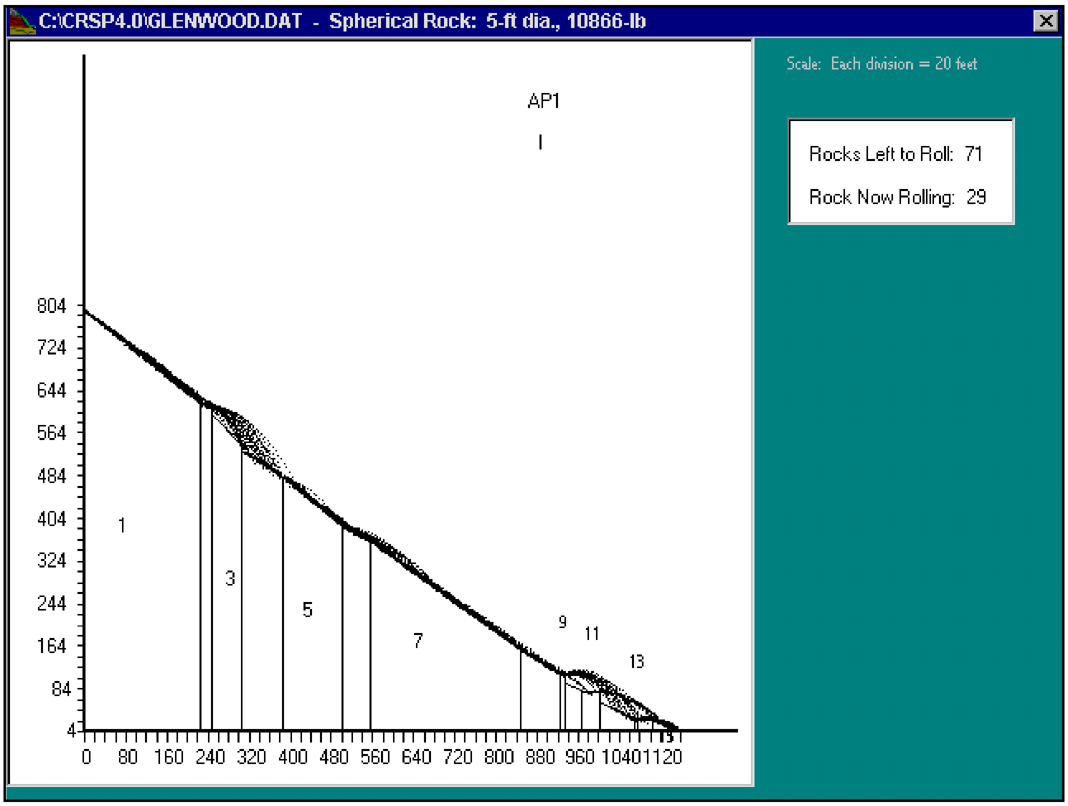


Figure 22. CRSP slope profile window (with rockfall simulation in-progress).

Additionally, the rock shape, dimensions, and calculated mass (if using metric units) or weight (if using U.S. units) are displayed at the top of the screen. The number of **Rocks Left to Roll** and the **Rock** (number) **Now Rolling** are shown to the right of the slope profile. This information is updated after each simulated rock is rolled.

If at any time the user wishes to terminate the simulation, the *Esc* key will end the rockfall run. CRSP checks after every five rocks rolled to see whether the *Esc* key has been pressed and, if so, allows the user to return to the main window.

After the simulation has completed and the user is finished viewing the screen, three options are available: **View Results**, **Print Slope Profile Image**, or **Save Slope Profile Image** (Figure 23). **View Results** advances the user to the presentation of the output from the simulation (see the "CRSP Output Data" section later in this chapter). The **Print Slope Profile Image** button produces a paper copy of the slope profile without the rock trajectories (which are still viewed on the screen). The **Save Slope Profile Image** creates a bitmap ("*.bmp") file of the slope profile with rock trajectories. This file can be opened later using CRSP (for viewing only) or can be opened using a graphics program, such as Microsoft Paint®, where the image can be edited and printed.

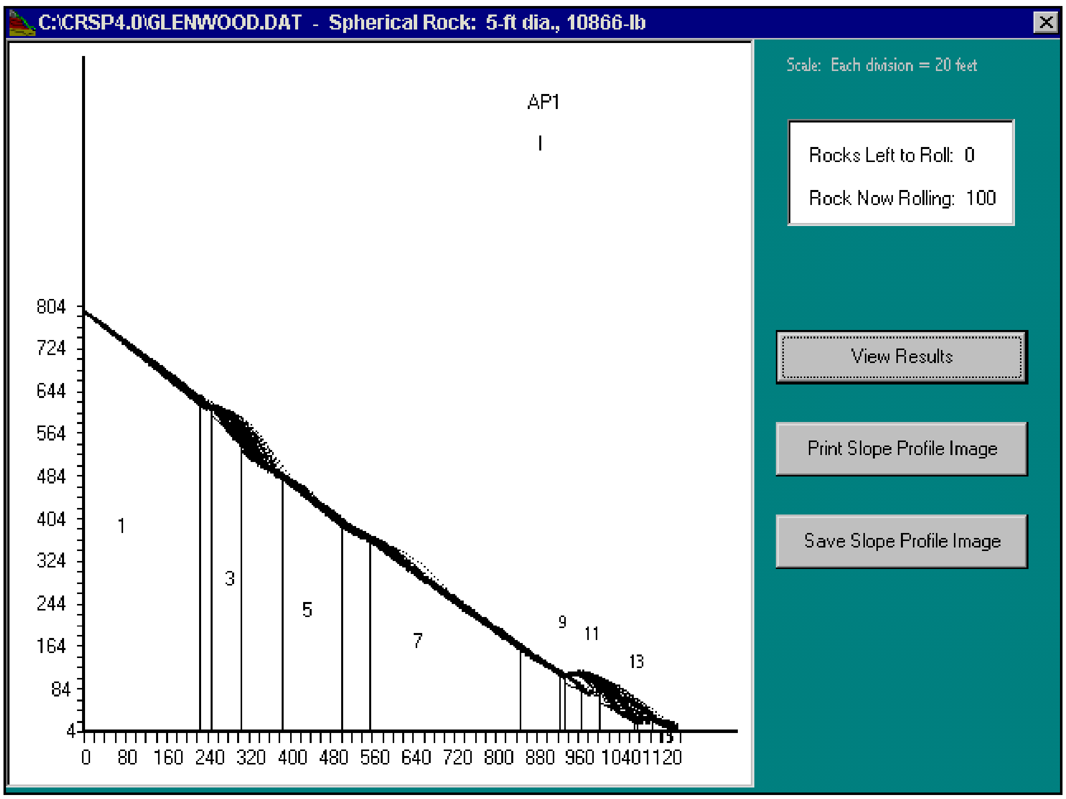


Figure 23. CRSP slope profile window (after rockfall simulation has completed).

Errors

CRSP generates error messages when it receives input that it cannot accept. Table 8 lists the errors and explains how to correct them. Information about an error message can be given by CRSP's help system at any time, including when the error message is present on the screen (by pressing the *F1* key on the keyboard). See the "CRSP Help System" section later in this chapter for more information.

Table 8. CRSP errors.

Error Message (listed alphabetically)	Correction
Analysis Point 3 cannot be used without Analysis Point 2.	If only 2 analysis points are desired, set **Analysis Point X-Coordinate**s **1** and **2** to the desired values and leave **Analysis Point X-Coordinate 3** blank.
Analysis Point X-Coordinate 1 must be less than Analysis Point X-Coordinate 2.	Set **Analysis Point X-Coordinate 1** as the lower of the two analysis-point-values desired.
Analysis Point X-Coordinate 1, 2, or 3 is not within the range of X values given for the slope.	Ensure that all analysis points are greater than the **Begin X** value for Cell Number 1 and less than or equal to the **End X** value for the last cell.
Analysis Point X-Coordinate 2 must be less than Analysis Point X-Coordinate 3.	Set **Analysis Point X-Coordinate 2** as the lower of the two values desired for analysis points 2 and 3.
Begin X and End X (from previous cell) values do not match.	Set the **End X** from the previous cell to match the **Begin X** from the current cell.
Cannot Proceed	An error occurred while saving a file. Check input and try again.
CRSP does not allow cell numbers to be changed.	Instead of changing a cell number, either create a new input file or rearrange cell coordinates to correspond to desired changes.
CRSP does not allow the number of cells to be decreased at this stage.	Do not attempt to decrease the number of cells in the input file at the **Input File Preview – Part A** screen (it may be increased if desired). To accomplish a reduction in number of cells, create a new input file.
CRSP has performed an illegal function and will close this file.	This error only occurs if the user has entered illogical data in the input file or simulation specifications that CRSP cannot catch. Check input for errors.
Disk Full	Another disk or drive must be used or some files must be deleted on the full disk.
Disk Not Ready	Ensure floppy disk is completely inserted into drive.
File Already Open	A file must be closed before it can be reopened.

Table 8. CRSP errors.

Error Message (listed alphabetically)	Correction
File Not Found	Ensure the file location information (e.g., drive or folder within a drive) is set correctly.
Initial Y-Top Starting Zone Coordinate must be greater than or equal to Initial Y-Base Starting Zone Coordinate.	Set **Initial Y-Top Starting Zone Coordinate** as the greater of the two starting zone values desired.
Invalid bitmap	Ensure you only save slope profile images as bitmaps ("*.bmp") and that an image was not incompletely saved due to a full disk.
Please enter a positive integer for Total Number of Cells.	Ensure that the input for **Total Number of Cells** is an integer greater than zero.
Please enter a positive integer for Total Number of Rocks to be Simulated.	Ensure that the input for **Total Number of Rocks to be Simulated** is an integer greater than zero.
Please enter a positive number for Analysis Point X-Coordinate 1, 2, or 3.	Ensure that the input for **Analysis Point X-Coordinate 1**, **2**, or **3** is a value greater than zero. **Analysis Point X-Coordinates 2** and **3** are optional and may be left blank.
Please enter a positive number for Diameter.	Ensure that the input for sphere, cylinder, or disk **Diameter** is a value greater than zero.
Please enter a positive number for Initial Y-Top or Y-Base Starting Zone Coordinate.	Ensure that the input for **Initial Y-Top** or **Y-Base Starting Zone Coordinate** is a value greater than zero.
Please enter a positive number for Length.	Ensure that the input for cylinder **Length** is a value greater than zero.
Please enter a positive number for Rock Density.	Ensure that the input for **Rock Density** is a value greater than zero.
Please enter a positive number for Starting Velocity in X-Direction.	In order to start a rock moving down the slope, **Starting Velocity in X-Direction** must be greater than zero.
Please enter a positive number for Thickness.	Ensure that the input for disk **Thickness** is a value greater than zero.
Please enter either 'U.S.' or 'Metric' as the Units of Measure.	Ensure that only **Metric**, **metric**, **U.S.**, or **u.s.** is entered in **Units of Measure** input box.

(Continued)

Table 8. CRSP errors.

Error Message (listed alphabetically)	Correction
Please enter 'Spherical', 'Cylindrical', or 'Discoidal' as the Rock Shape.	One of these three shapes must be chosen. CRSP does not offer the modeling of other **Rock Shape**s.
Please make sure a positive integer is entered as the Starting or Ending Cell Number.	Ensure that an integer greater than or equal to 1 is entered as the **Starting Cell Number** and an integer less than or equal to the last cell number is entered as the **Ending Cell Number**.
Please make sure a positive number is entered in each input box.	Ensure that data is entered in each non-optional input box and that the values are greater than zero.
Please make sure a response is entered in each input box.	Ensure that data is entered into all non-optional input boxes. **Remark**s and **Analysis Point X-Coordinates 2** and **3** are optional.
Please make sure all Begin X values match the End X values from the previous cell.	Set the **End X** from the previous cell to match the **Begin X** from the current cell.
Please make sure each End X value is greater than or equal to the Begin X value from the same cell.	Ensure that x-values become larger with distance from the y-axis.
Please make sure numbers are entered for the Starting X and Y Velocities.	Ensure that positive or negative values are entered for **Starting X Velocity** and **Starting Y Velocity.**
Please make sure the Begin X value matches the End X value from the previous cell.	Ensure that x-values become larger with distance from the y-axis.
Please make sure the Tangential Coefficient or the Normal Coefficient is between 0 and 1.	Ensure that all **Tangential Coefficients** and **Normal Coefficients** are positive numbers between zero and one, inclusive.
The rockfall source zone cannot be below the beginning of the last cell.	Ensure the **Initial Y-Base Starting Zone Coordinate** is a value greater than or equal to the **Begin Y** value for the last cell in the input file.
There is an error in your file.	File must be created again due to unknown error. It may have incompletely saved due to a full disk.
This file is not compatible with CRSP.	Ensure that only "*.dat", "*.csp", and "*.bmp" files are opened and that "*.dat" files follow CRSP input file format (format from prior CRSP versions is acceptable).

CRSP Output Data

The following data is output by CRSP:

- The slope profile (Figure22) showing cell locations and the position of each simulated rock every tenth of a second as it travels downslope. The slope profile is discussed in more detail in the "Running CRSP" section located earlier in this chapter.
- The maximum, average, minimum, and standard deviation of rock velocities at each of one to three selected points (analysis points) on the slope.
- The maximum, average, and standard deviation of rock velocities at the end of each cell.
- The maximum, average, geometric mean, and standard deviation of rock bounce heights at each analysis point.
- The maximum and average bounce heights at the end of each cell.
- The maximum, average, and standard deviation of kinetic energies at each analysis point.
- Cumulative probability analyses of velocity, kinetic energy, and bounce height at each analysis point.
- Graphs of the distribution of rock velocities and bounce heights at each analysis point.
- Graphs of the maximum velocities and bounce heights along the slope.
- The number of stopped rocks in each ten-foot or ten-meter slope interval.

After the **View Results** button on the slope profile screen is selected, the first screen to be shown is the **Analysis Point 1 Data** window (Figure 24). The top of this window presents the **Remarks** input earlier by the user, the x- and y-coordinates of the analysis point, and the **Total Rocks Passing Analysis Point**. As long as at least one simulated rock passed the analysis point, the velocity, bounce height, and kinetic energy information pertaining to the analysis point is given. If no rocks passed the analysis point, no statistical data is given. The user can make a paper copy of the **Analysis Point 1 Data** by selecting the **Print** button. The user can also return to the slope profile screen by pressing the **Back** button or continue viewing the CRSP output by selecting **Next**.

When the **Next** button is pressed, the user is asked: "Do you wish to view the statistical analyses for analysis points?" An affirmative response indicates that a cumulative probability analysis of velocity, kinetic energy, and bounce height will be presented for each analysis point (in the **Analysis Point Statistical Analysis** windows). A negative response means that the user will not view the **Analysis Point Statistical Analysis** screens. **Analysis Point Statistical Analysis** screens are not displayed for analysis points that had no rocks passing.

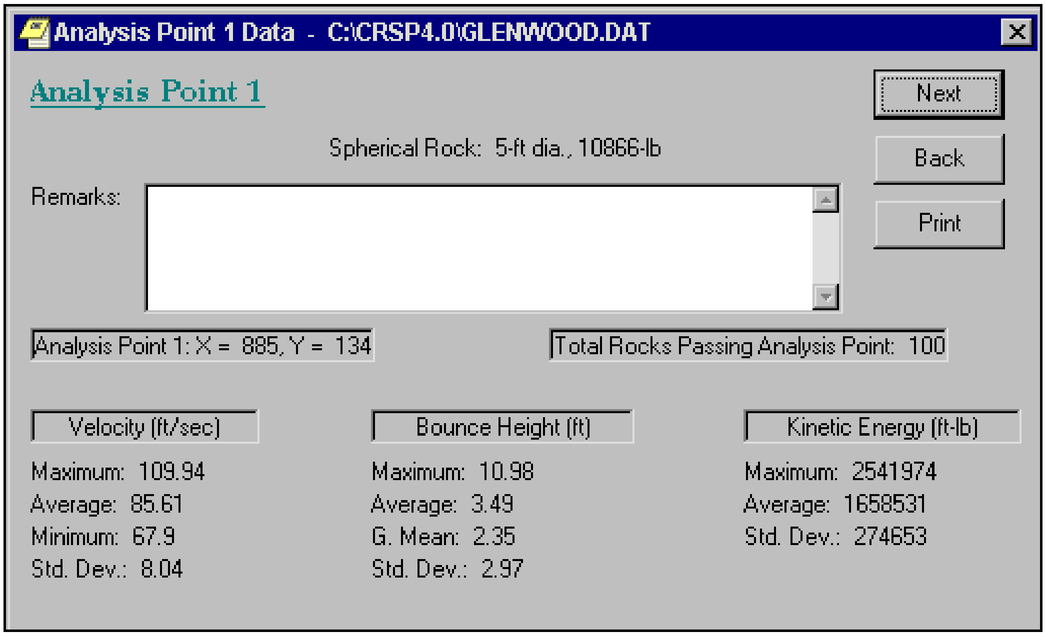


Figure 24. CRSP Analysis Point Data window.

If the user has chosen to view the cumulative probability analyses, the next screen to be displayed is the **Analysis Point 1 Statistical Analysis** (Figure 25). This window again presents the analysis point x- and y-coordinates and the **Total Rocks Passing Analysis Point**. The screen also shows the cumulative probabilities (i.e., the probability that a parameter will not exceed the given value) for **Velocity**, (kinetic) **Energy**, and **Bounce Height** at **50, 75, 90, 95,** and **98 percent** levels of confidence. Velocity and kinetic energy are analyzed assuming a normal distribution while bounce height is examined assuming a log distribution (due to the extreme variation in its values). The cumulative probability analysis may be useful for design of rockfall mitigation, as a level of confidence may be chosen corresponding to values of velocity, kinetic energy, and bounce height that are likely not to be surpassed with the given level of confidence. However, many CRSP users choose not to use the cumulative probability analyses and instead work with the information provided in the **Analysis Point Data** and subsequent windows. The **Analysis Point 1 Statistical Analysis** window also presents the **Print**, **Back**, and **Next** buttons, which cause similar actions as the corresponding buttons on the **Analysis Point 1 Data** screen.

When the **Next** button is selected, if the user has utilized a second analysis point, the **Analysis 2 Point Data** window is presented, followed by the **Analysis Point 2 Statistical Analysis** (provided the user has opted to view the statistical analyses). If a third analysis point has been selected, the **Analysis 3 Point Data** screen is then presented followed by the **Analysis Point 3 Statistical Analysis** window. These windows are similar to the corresponding windows for Analysis Point 1 presented in Figures 24 and 25.

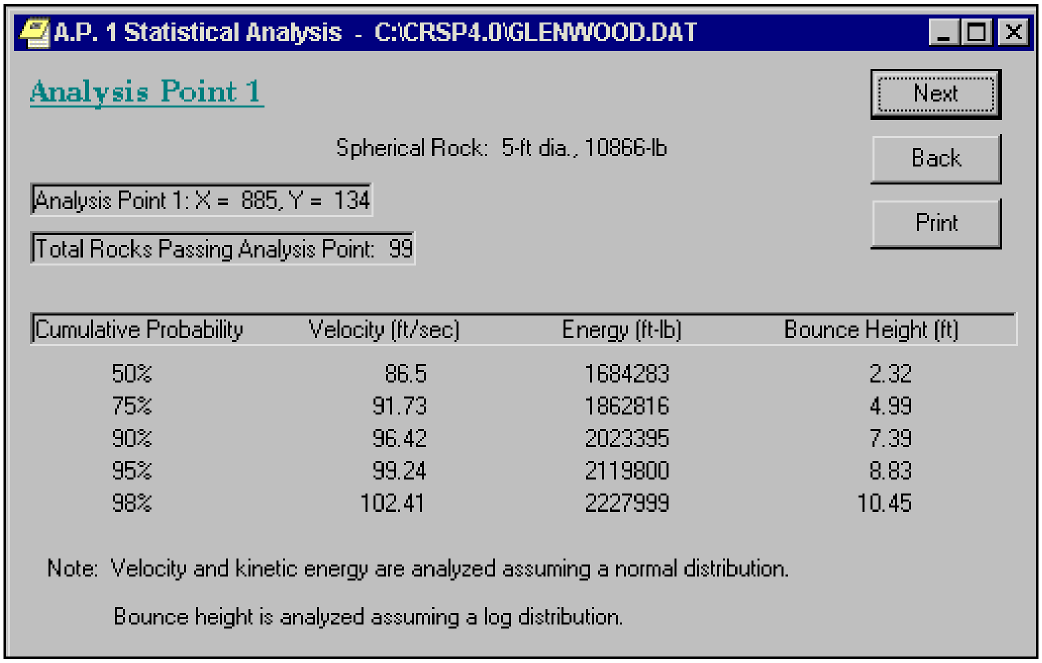


Figure 25. CRSP Analysis Point Statistical Analysis window.

After the **Analysis Point Data** and **Statistical Analysis** windows are displayed for all applicable analysis points, an **Analysis Point Bounce Height Distribution** histogram (Figure 26) is shown for each analysis point (the histogram is not shown for analysis points which had no rocks passing). Each histogram plots bounce height (at the analysis point) as the abscissa and frequency (of occurrence) as the ordinate. The four buttons below the histogram allow the user to **Print Graph, Copy Graph**, go **Back**, or view the **Next** graph. The **Copy Graph** button places a copy of the graph onto the Windows clipboard so it can be transferred to other applications (graphics programs, word processors, etc.). The graphs can only be copied one at a time; the user will probably need to have the other program running at the same time as CRSP. The CRSP graph can be placed into other programs by using that application's Paste command.

Following the bounce height distribution plots is a series of **Analysis Point Velocity Distribution** histograms (one for each analysis point that had rocks passing; Figure 27). This chart is similar to the bounce height histogram and plots velocity as the abscissa and frequency as the ordinate. Again, the **Print Graph, Copy Graph**, **Back**, and **Next** buttons are available for user selection.

After the histograms are presented, the **Bounce Height Graph** (Figure 28) is displayed. This figure is a plot of horizontal distance along the slope (abscissa) versus maximum bounce height (ordinate). This graph is not related to any analysis points and thus is shown regardless of where rocks may stop on the slope. Once again, the user may choose from the **Print Graph, Copy Graph**, **Back**, and **Next** buttons.

The final chart produced by CRSP is the **Velocity Graph** (Figure 29), which plots horizontal distance along slope as the abscissa and maximum velocity as the ordinate. This graph is also not related to any analysis points and is always shown. Once more, the **Print Graph, Copy Graph**, **Back**, and **Next** buttons are available to the user.

After the user selects the **Next** button, CRSP presents a table of **Data Collected at End of Each Cell** (Figure 30). The table lists the maximum, average, and standard deviation velocities and the maximum and average bounce heights at the end of each cell of the slope profile. The buttons below the table allow the user to **Print Cell Data**, go **Back**, and view the **Next** table.

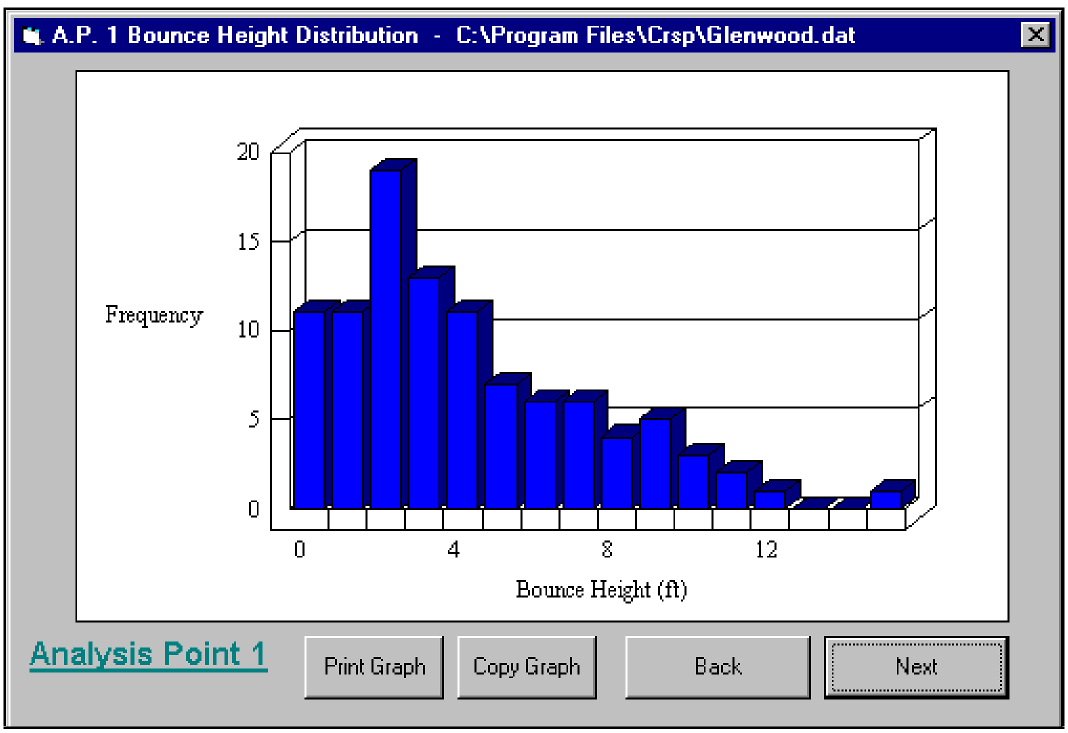


Figure 26. CRSP Analysis Point Bounce Height Distribution window.

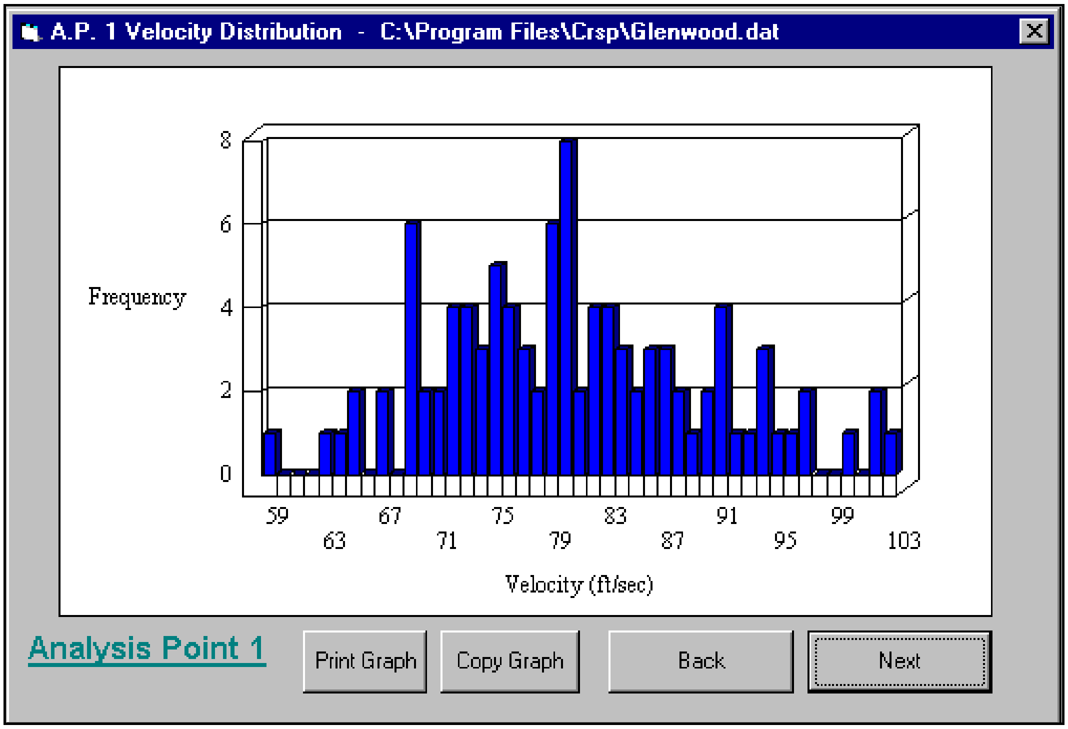


Figure 27. CRSP Analysis Point Velocity Distribution window.

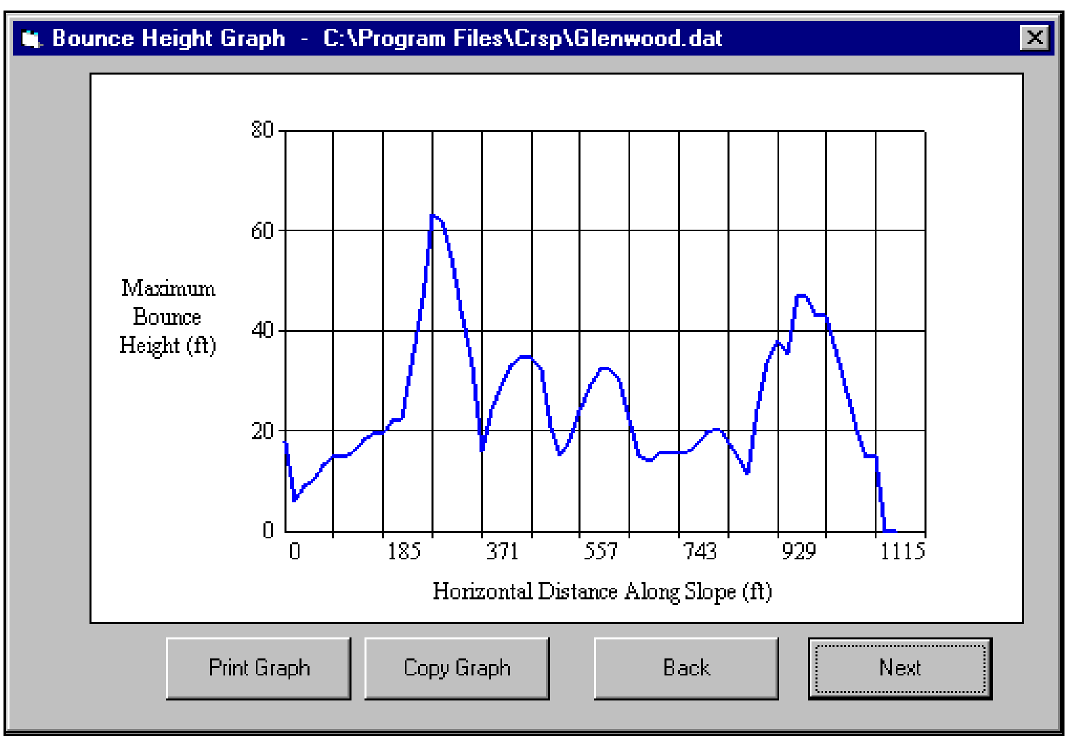


Figure 28. CRSP Bounce Height Graph window.

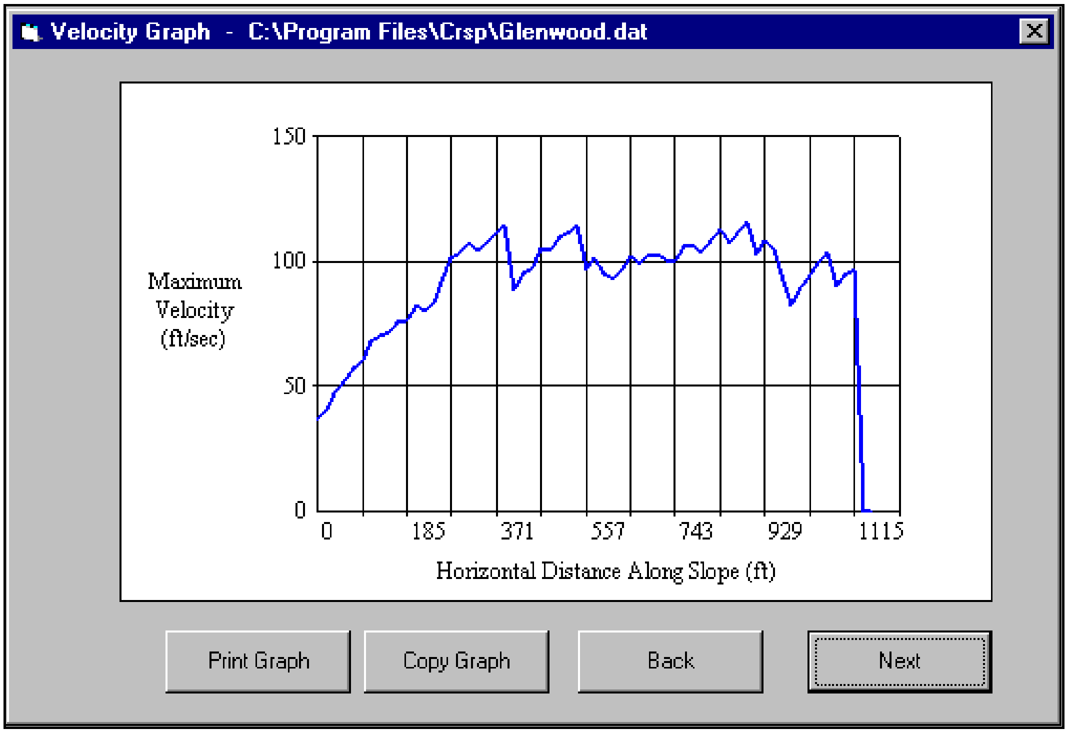
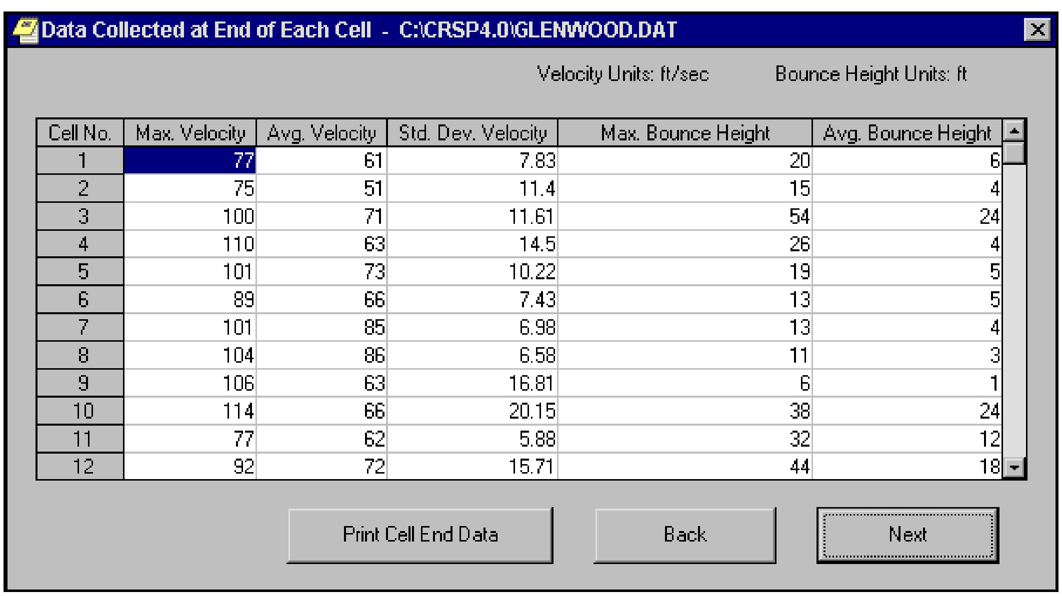


Figure 29. CRSP Velocity Graph window.



Cell No.	Max. Velocity	Avg. Velocity	Std. Dev. Velocity	Max. Bounce Height	Avg. Bounce Height
1	77	61	7.83	20	6
2	75	51	11.4	15	4
3	100	71	11.61	54	24
4	110	63	14.5	26	4
5	101	73	10.22	19	5
6	89	66	7.43	13	5
7	101	85	6.98	13	4
8	104	86	6.58	11	3
9	106	63	16.81	6	1
10	114	66	20.15	38	24
11	77	62	5.88	32	12
12	92	72	15.71	44	18

Figure 30. CRSP Data Collected at End of Each Cell window.

The final CRSP output is a table of the number of **Rocks Stopped** (Figure 31) within each 10-foot or 10-meter (depending on whether the user has chosen U.S. or metric units) interval of slope. At this window, the user again has the options to **Print Rocks Stopped Data**, go **Back**, or view the **Next** screen (available through buttons).

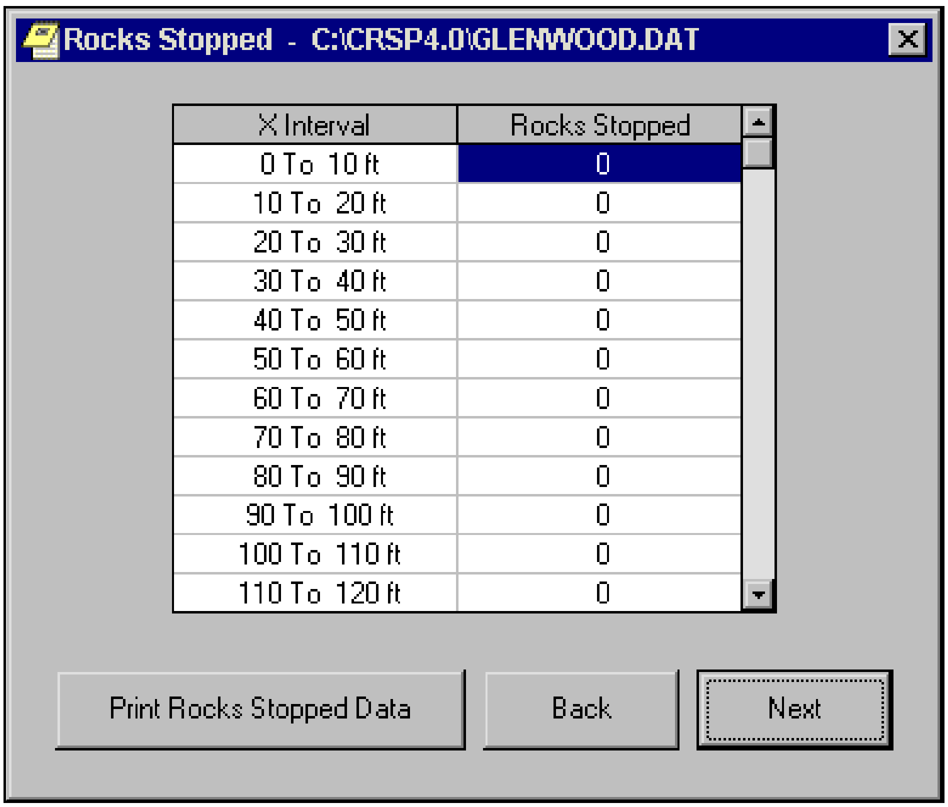


Figure 31. CRSP Rocks Stopped window.

The last window displayed for CRSP output is called **Final Options** (Figure 32). This screen displays six buttons from which one or more options may be chosen:

- **Back** returns the user to the **Rocks Stopped** table.
- **View Results Again** allows the user to return to the **Analysis Point 1 Data** window and then go through the output again.

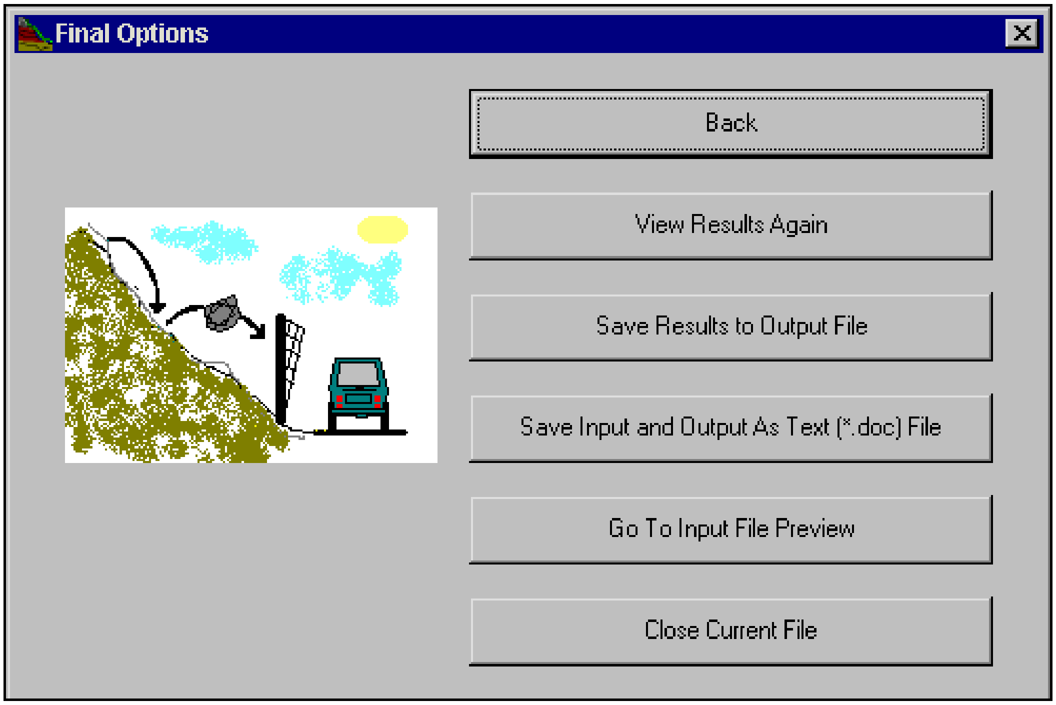


Figure 32. CRSP Final Options Window.

- **Save Results to Output File** creates a "*.csp" file which allows the user to view the output from the current run at any time. See the "Viewing an Output File" section later in this chapter for more information.
- **Save Input and Output As Text (*.doc) File** allows the user to make a file which cannot be opened by CRSP, but can be used with a word program, such as Microsoft Word®. When the user opens the file in a word processing program, all CRSP input and output is available in a form that allows for easy inclusion in documents. Due to the varying column sizes with different files, columns in the file may be poorly aligned. This can be corrected by adding or deleting spaces and tabs. Such an inconvenience may be worthwhile if a text form of CRSP input and output is needed.

- **Go To Input File Preview** returns the user to the **Input File Preview – Part A** window from which a file can be run again. The input used from the current run will still be displayed in the input boxes so that not all information (such as rock shape and size) must be re-input. All new information to run the open file can be input at this stage, if desired. Default values for the **Rock Simulation Specifications** and **Simulation Dimensions** windows can be reset by choosing the **Revert to Default Values** button at the **Rock Simulation Specifications** screen.

- **Close Current File** clears CRSP of all data involved with the current file and presents a blank window with only the CRSP toolbar and menu bar available (similar to when CRSP is first entered). When a file is closed, if CRSP senses that the user may have altered it during the input file preview, the user will be asked: "File appears to have changed. Do you wish to save?" If **Yes** is selected, the **Save File As…** box appears and the user can save the input file using the same name as used previously, overwriting the existing file, or select a new name. If **No** is selected, the file remains unchanged. At this time, the user can choose from any of the options in the **File** or **Help** menus (some are also accessible through the toolbar buttons), including to **Exit** CRSP. Exiting the program can be accomplished by selecting **Exit** from the **File** menu.

Viewing an Output File

Output files can be viewed only within CRSP and are accessed by choosing "CRSP Files (*.csp)" as the **File type** from the **Open Existing File** box presented when the user activates the **Open** command from the **File** menu.

Once a CRSP output file is open, the **Analysis Point 1 Data** window is displayed and contains all the same information as when the output file was originally viewed. All output (including tables and graphs) follows in the same order as usual. See the "CRSP Output Data" section earlier in this chapter for more information.

Viewing a Slope Profile

A slope profile which has been saved (as a bitmap (*.bmp) file) during a CRSP run can be viewed either within CRSP or through a graphics program that handles bitmap files, such as Microsoft Paint®.

To view a saved slope profile through CRSP, select "Bitmaps (*.bmp)" as the **File type** from the **Open Existing File** box presented when the **Open** command from the **File** menu is activated. The slope profile window (Figure 22) will then be displayed. However, the user cannot print the slope profile at this point. Printing a slope profile must be performed during a CRSP run or through a graphics program. To close the slope profile window and bitmap file, click the "**x**" button on the upper right of the screen.

CRSP Help System

The CRSP help system is a tool to obtain on-screen program use information while using CRSP. The contents of the help system are generally a scaled-down version of the material found in this chapter. However, items of interest might be easier found by using the on-screen version.

The system can be accessed through the **Help** menu, the **Help** button on CRSP's toolbar, or by pressing the *F1* key on the keyboard. When the **Help** menu is used, two options are present: **CRSP Help Topics** and **Search For Help On…**. **CRSP Help Topics** lists the major topic headings covered by the help system and allows the user to choose one for more information. **Search For Help On…** provides the user with a search engine to aid in finding a help topic of interest. All topics are listed in alphabetical order below for selection. When the help system is accessed through the toolbar button or by pressing *F1*, either the help topics window (Figure 33) will be displayed or, if CRSP can determine what help is needed (such as when an error has occurred), a particular help topic will be presented.

The CRSP help system also contains its own help option to obtain detailed information on its use. To engage "help on help" enter the CRSP help system, as described above, and select **Help**.

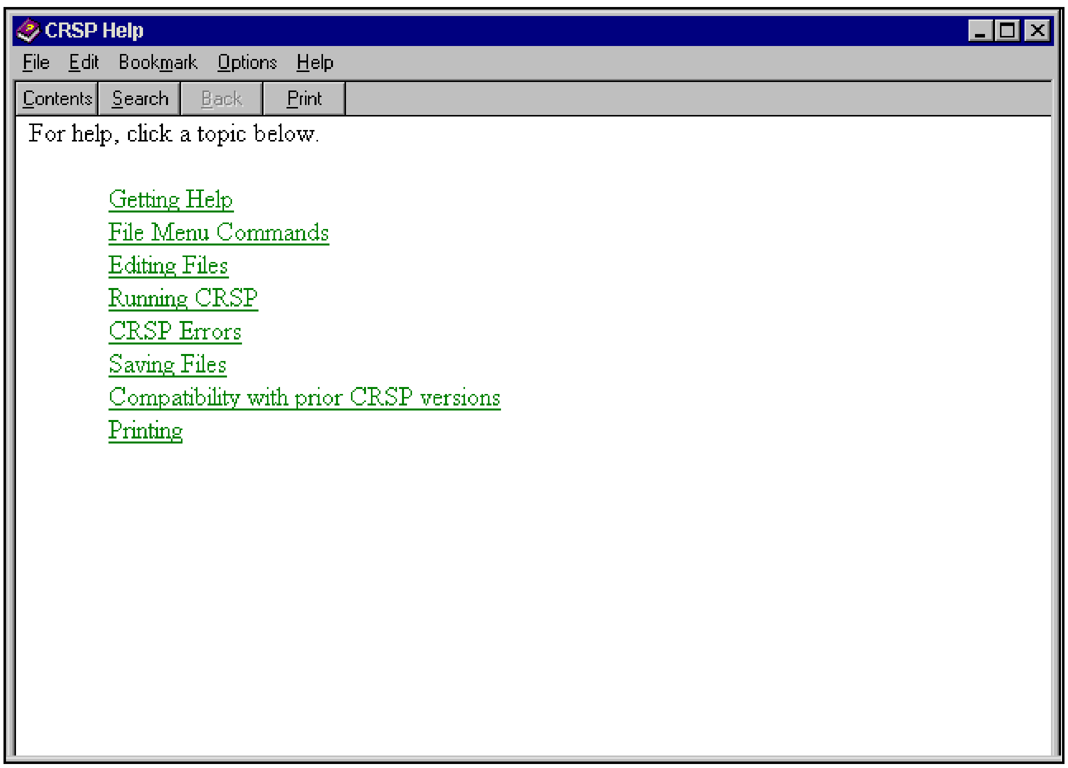


Figure 33. CRSP Help Topics Window.

REFERENCES

Duffy, J.D., 1992, Field Tests of Flexible Rockfall Barriers: Brugg Cable Products, 79 p.

Duffy, J.D., 1996, Field Tests and Evaluation of Hi-Tech Low Energy Chain Link Rockfall Fence: California Department of Transportation, San Luis Obispo, CA, 39 p.

Duffy, J.D., and Hoon, W., 1996, Field Tests and Evaluation of Hi-Tech 50 and 70 Foot-ton Rockfall Fences: California Department of Transportation, San Luis Obispo, CA, 42 p.

Evans, C.L., 1989, The Design of Catch Bench Geometry in Surface Mines to Control Rockfall, Thesis, University of Arizona, 170 p.

Habib, P., 1976, Note sur le rebondissement des blocs rocheux, in Meeting on Rockfall Dynamics and Protective Works: Insituto Sperimentale Modolli E Structture, Bergamo, Italy, pp. 123-125.

Hoek, E., and Bray, J.W., 1981, Rock Slope Engineering: E & FN SPON, London, 358 p.

Larsen, J.O., 1993, Rockfall Simulation Models and Their Practical Application, Thesis, University of Colorado at Boulder, 38 p.

McCauley, M.L.; Byron, W.W.; and Naramore, S.A., 1985, Rockfall Mitigation: California Department of Transportation, Sacramento, CA, 147 p.

Nichol, M.R., and Watters, R.J., 1983, Comparison and effectiveness of rock fall mitigation techniques applied by states in the USA and Canada, *in* Proceedings 20th Annual Engineering Geology and Soils Engineering Symposium, Boise, ID, pp. 123-142.

Pearce, M.T., 1994, A Field Verification of The Total Kinetic Energy Predicted by The Colorado Rockfall Simulation Program, Unpublished paper: Department of Civil Engineering, University of California-Berkeley, 20 p.

Pfeiffer, T.J., 1989, Rockfall Hazard Analysis Using Computer Simulation of Rockfalls, Thesis, Colorado School of Mines, 103 p.

Pfeiffer, T.J.; Higgins, J.D.; Andrew, R.D.; Schultz, R.J.; and Beck, R.B., 1995, Colorado Rockfall Simulation Program Version 3.0a User's Manual: Colorado Department of Transportation, Denver, CO, 60 p.

Pfeiffer, T.J.; Higgins, J.D.; Schultz, R.; and Andrew, R.D., 1991, Colorado Rockfall Simulation Program Users Manual for Version 2.1: Colorado Department of Transportation, Denver, CO, 127 p.

Pierson, L.A.; Davis, S.A.; and Pfeiffer, T.J., 1994, The Nature of Rockfall as the Basis for a New Fallout Area Design Criteria for 0.25:1 Slopes: Oregon Department of Transportation, Salem, OR, 31 p.

Piteau and Associates Limited, 1980, Slope stability analysis for rock fall problems: the computer rock fall model for simulating rock fall distributions, part D, *in* Rock Slope Engineering, Federal Highway Administration Reference Manual FHWA-TS-79-208: Department of Transportation, Washington, DC, pp. 62-68.

Ritchie, A.M., 1963, The evaluation of rock fall and its control: Highway Research Record, National Academy of Sciences – National Research Council, Washington, DC, Number 17, pp. 13-28.

Smith, D.D., and Duffy, J.D., 1990, Field Tests and Evaluation of Rockfall Restraining Nets: California Department of Transportation, Sacramento, CA, 138 p.

Wu, S.S., 1984, Rockfall evaluation by computer simulation: Transportation Research Record, Transportation Research Board, Washington, DC, Number 1031, pp. 1-5.

Appendix A—CRSP CALIBRATION GRAPHS

The following graphs represent the results of the Colorado Rockfall Simulation Program re-calibration and are discussed in Chapter 5. For each of the four data sets used in the calibration (Caltrans Brugg/Industrial Enterprise, Hi-Tech, Swiss, and Rifle tests), graphs were produced to show the effects of selected tangential and normal coefficients on kinetic energy and velocity (due to limited field data, only velocity information is presented for the Rifle tests), keeping all other variables constant for each data set. A more complete description of the graphs is presented in Chapter 4.

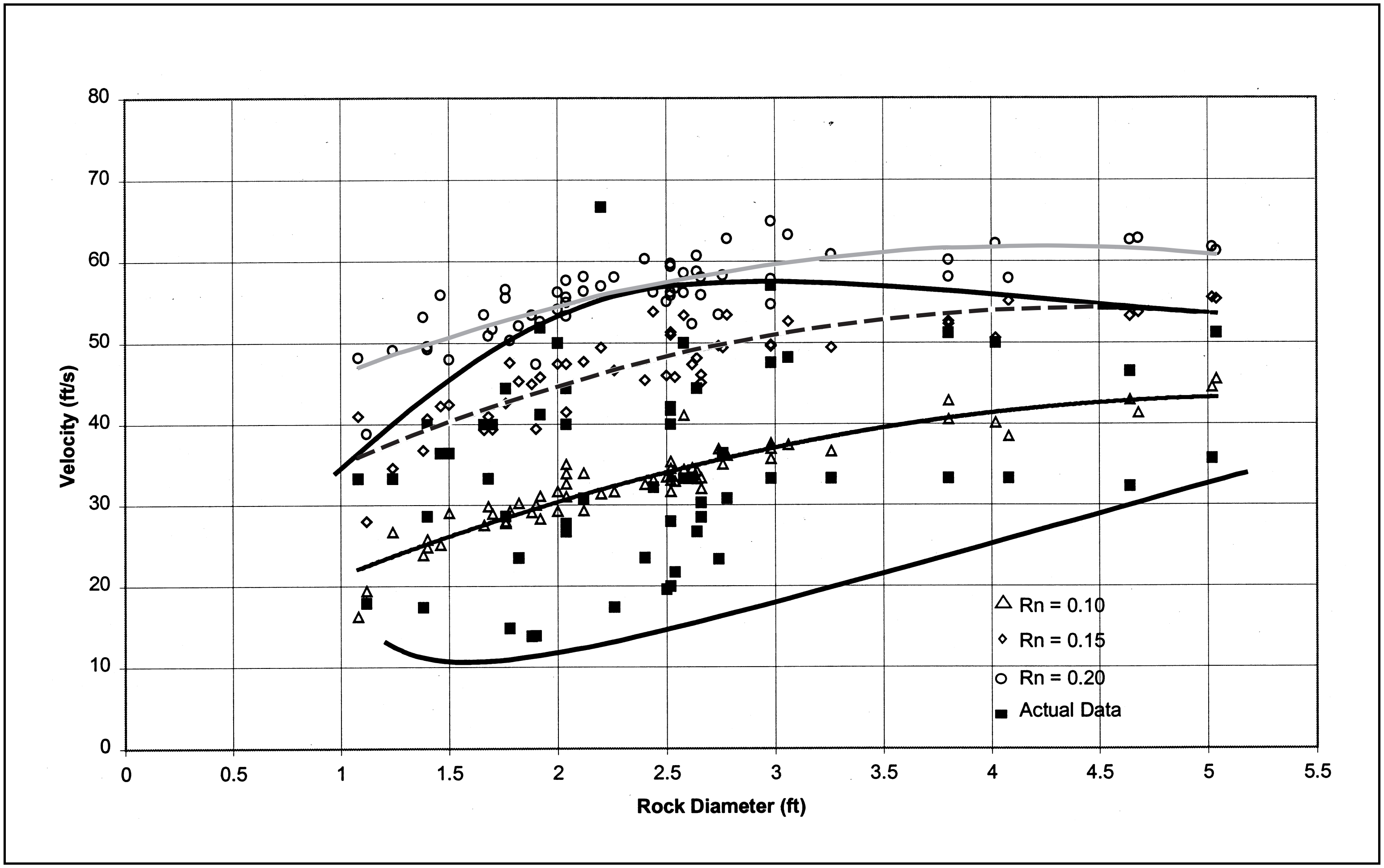


Figure A-1. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted maximum velocity at R_t of 0.95 and various values of R_n for Caltrans Brugg/Industrial Enterprise tests. Surface roughness equals 0.5 feet.

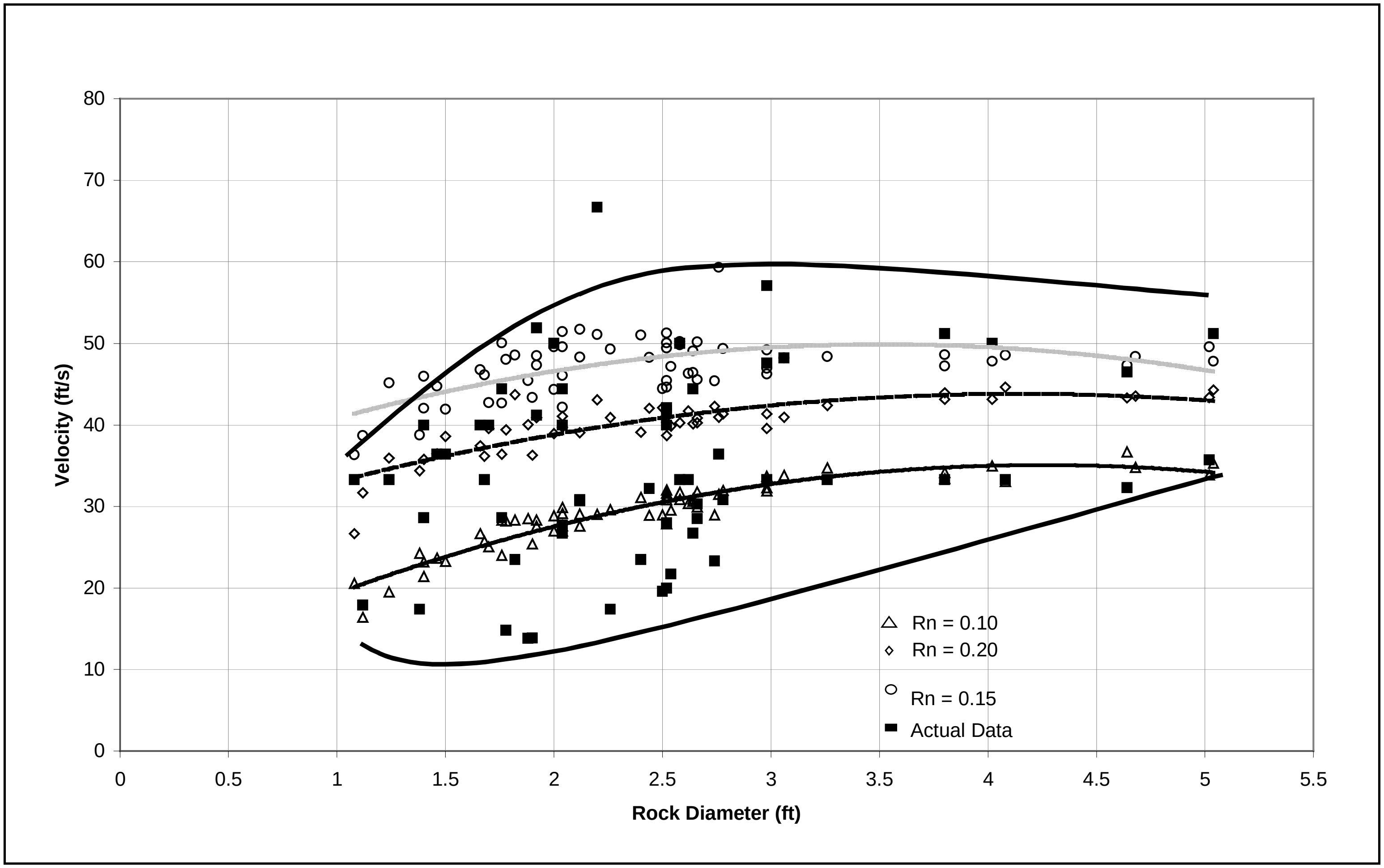


Figure A-2. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted maximum velocity at R_t of 0.65 and various values of R_n for Caltrans Brugg/Industrial Enterprise tests. Surface roughness equals 0.5 feet.

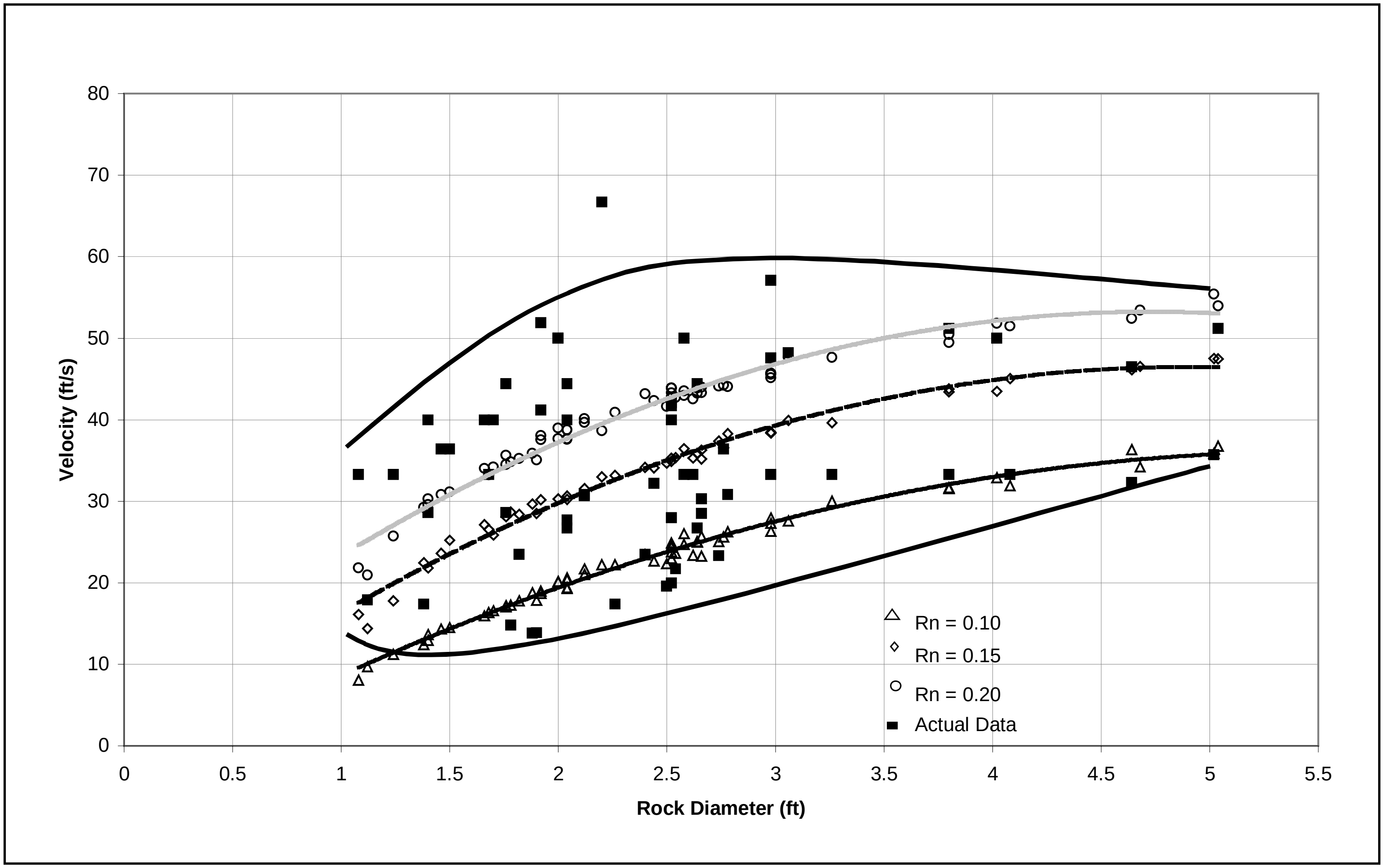


Figure A-3. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted average velocity at R_t of 0.95 and various values of R_n for Caltrans Brugg/Industrial Enterprise tests. Surface roughness equals 0.5 feet.

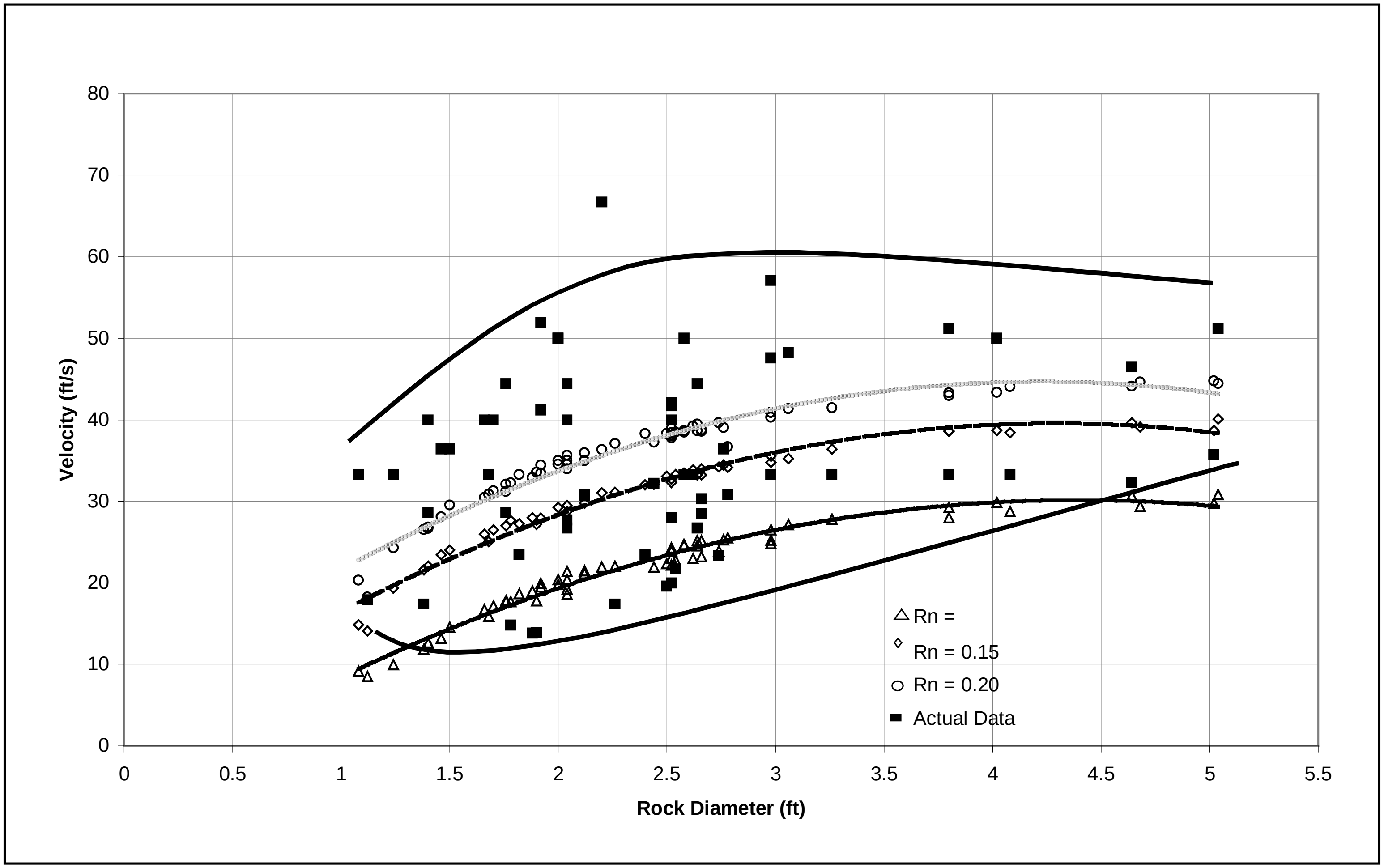


Figure A-4. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted average velocity at R_t of 0.65 and various values of R_n for Caltrans Brugg/Industrial Enterprise tests. Surface roughness equals 0.5 feet.

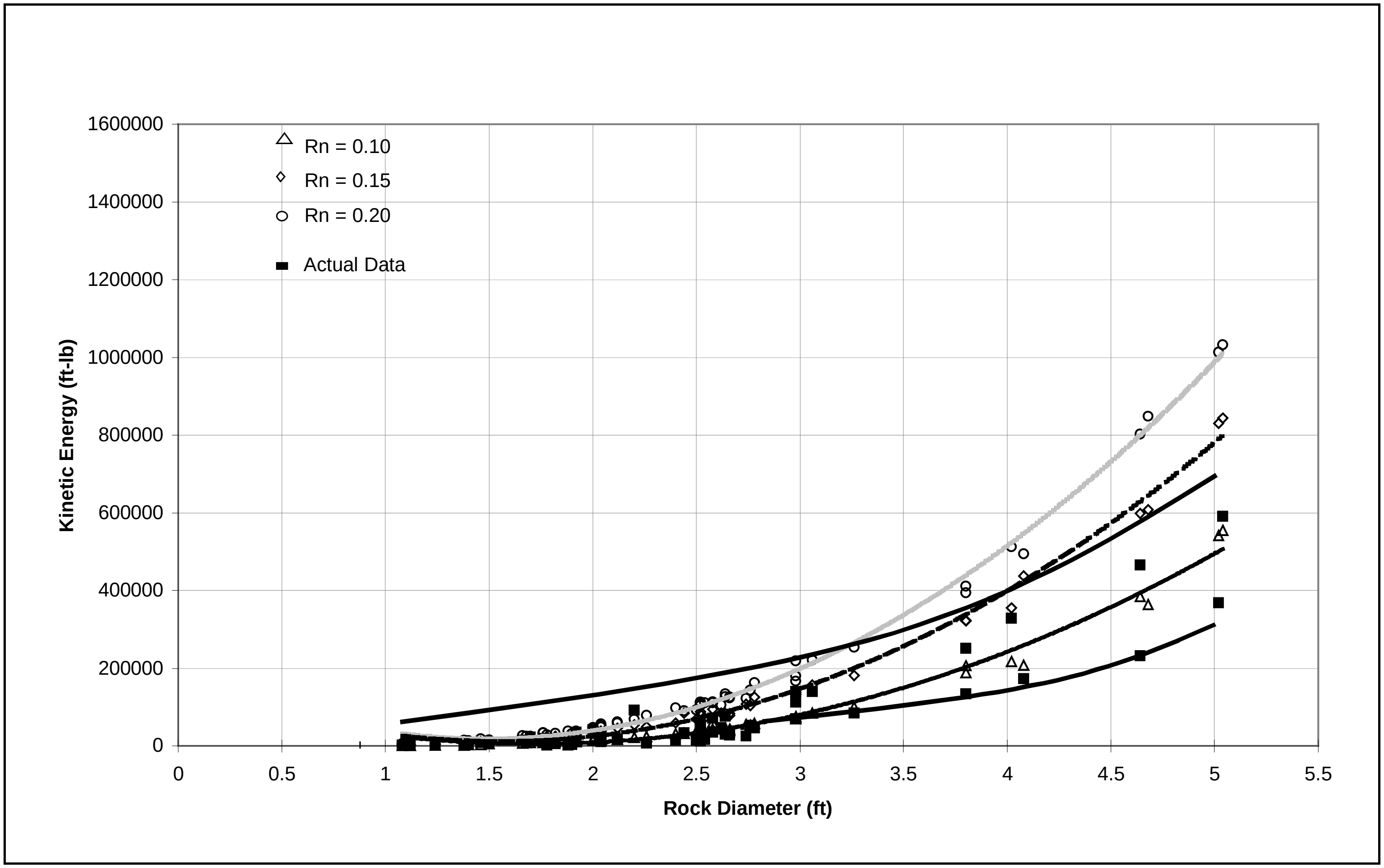


Figure A-5. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted maximum kinetic energy at R_t of 0.95 and various values of R_n for Caltrans Brugg/Industrial Enterprise tests. Surface roughness equals 0.5 feet.

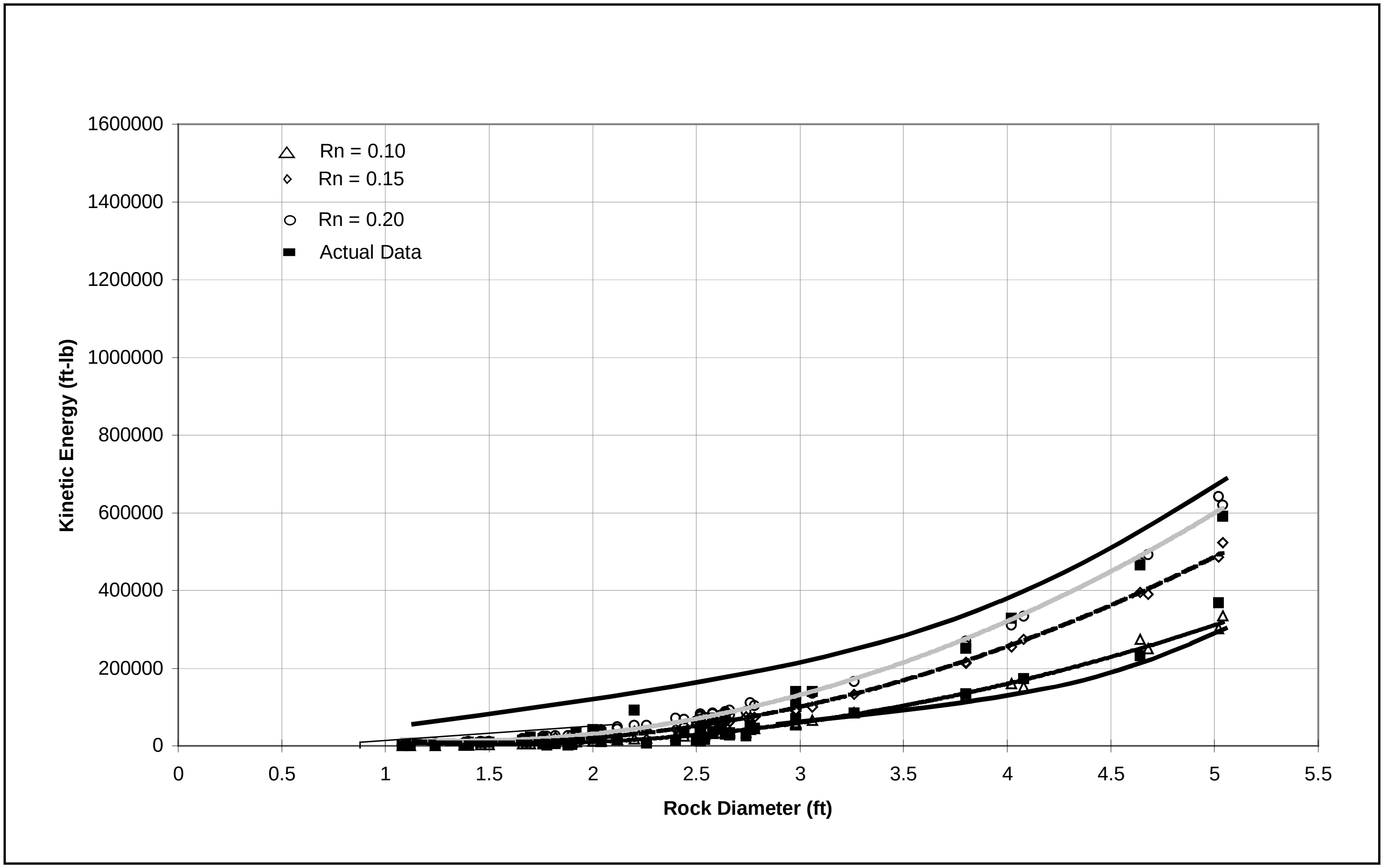


Figure A-6. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted maximum kinetic energy at R_t of 0.65 and various values of R_n for Caltrans Brugg/Industrial Enterprise tests. Surface roughness equals 0.5 feet.

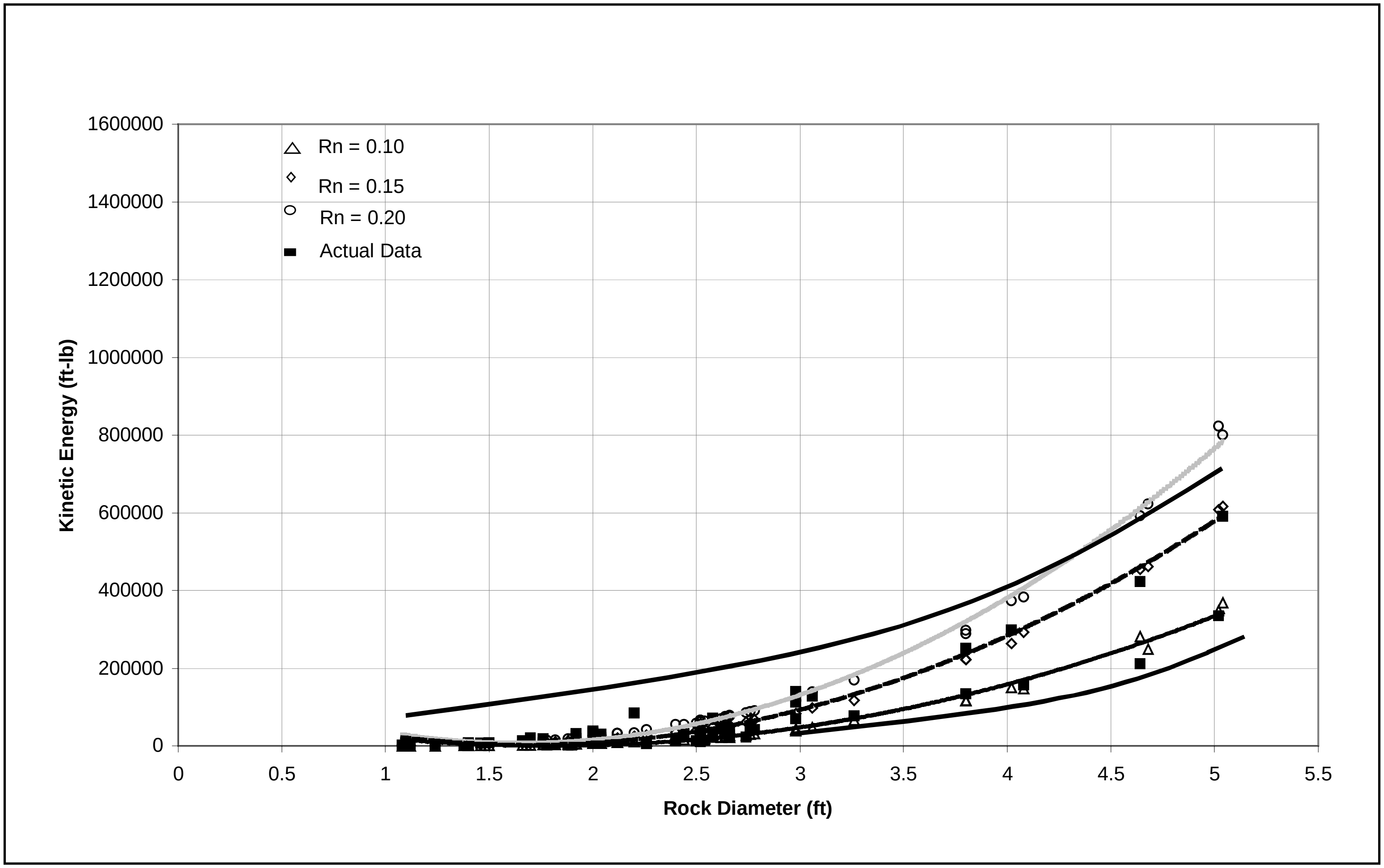


Figure A-7. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted average kinetic energy at R_t of 0.95 and various values of R_n for Caltrans Brugg/Industrial Enterprise tests. Surface roughness equals 0.5 feet.

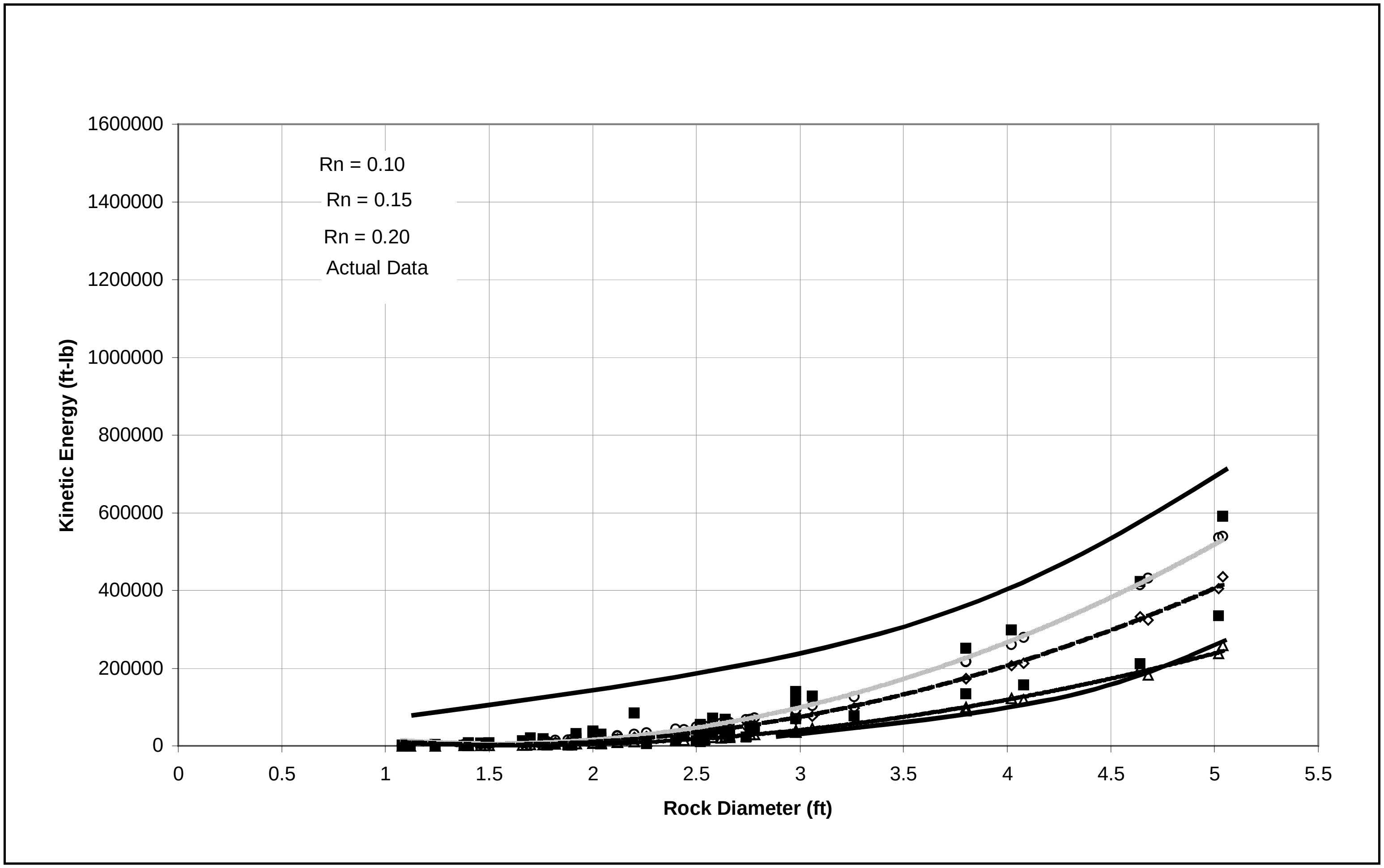


Figure A-8. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted average kinetic energy at R_t of 0.65 and various values of R_n for Caltrans Brugg/Industrial Enterprise tests. Surface roughness equals 0.5 feet.

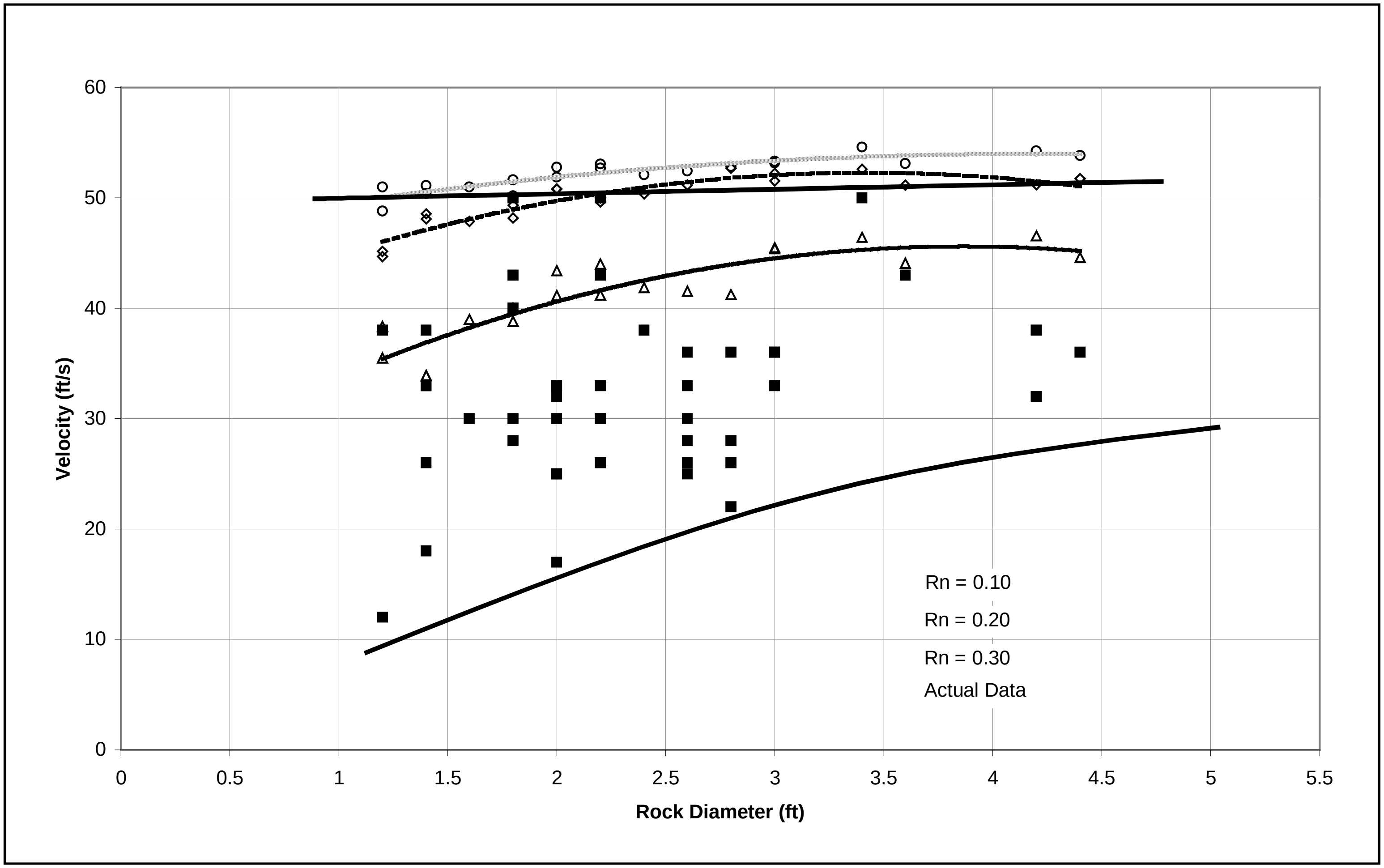


Figure A-9. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted maximum velocity at R_t of 0.95 and various values of R_n for Hi-Tech tests. Surface roughness equals 0.5 feet.65

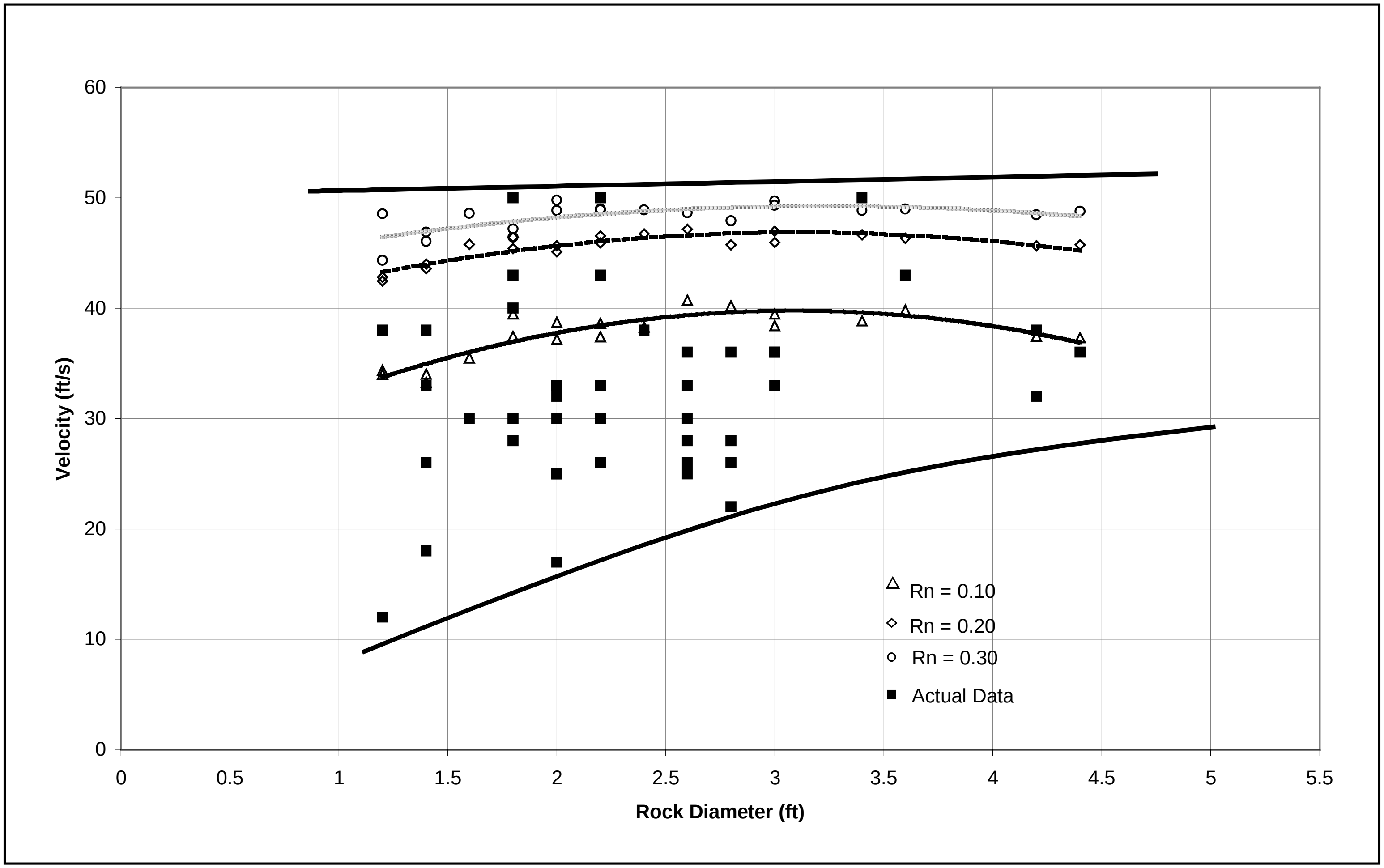


Figure A-10. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted maximum velocity at R_t of 0.65 and various values of R_n for Hi-Tech tests. Surface roughness equals 0.5 feet.

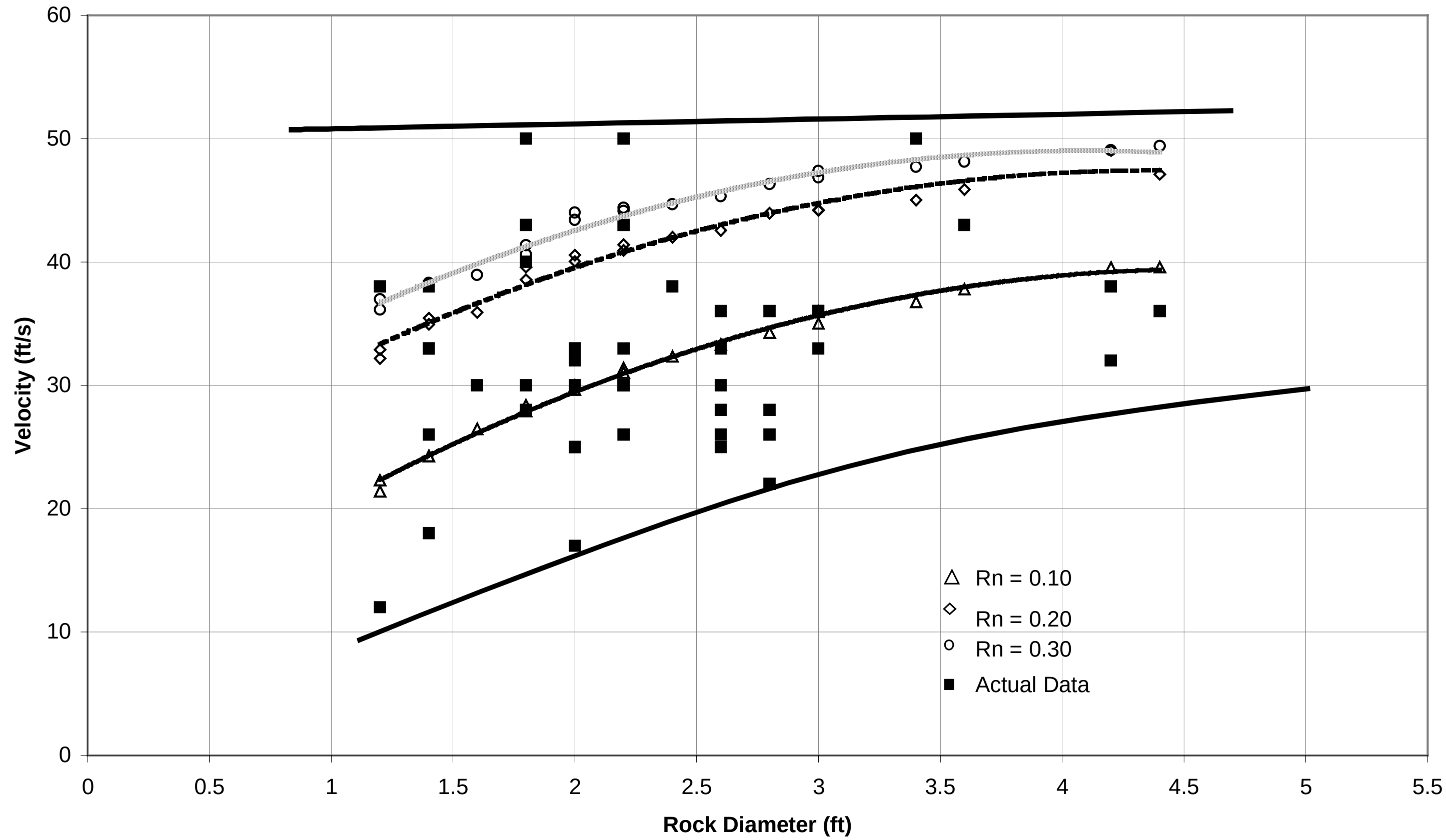


Figure A-11. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted average velocity at R_t of 0.95 and various values of R_n for Hi-Tech tests. Surface roughness equals 0.5 feet.

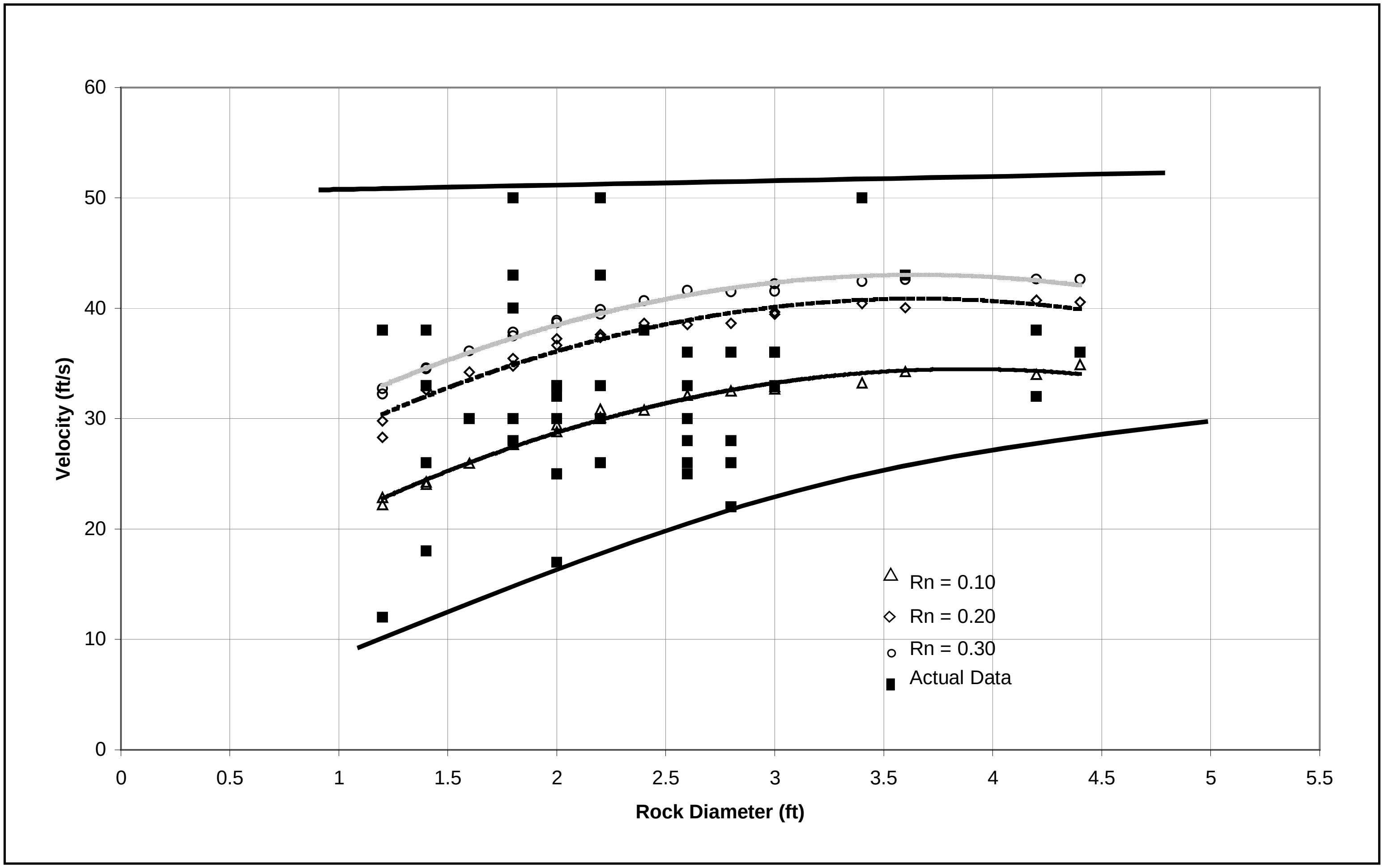


Figure A-12. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted average velocity at R_t of 0.65 and various values of R_n for Hi-Tech tests. Surface roughness equals 0.5 feet.

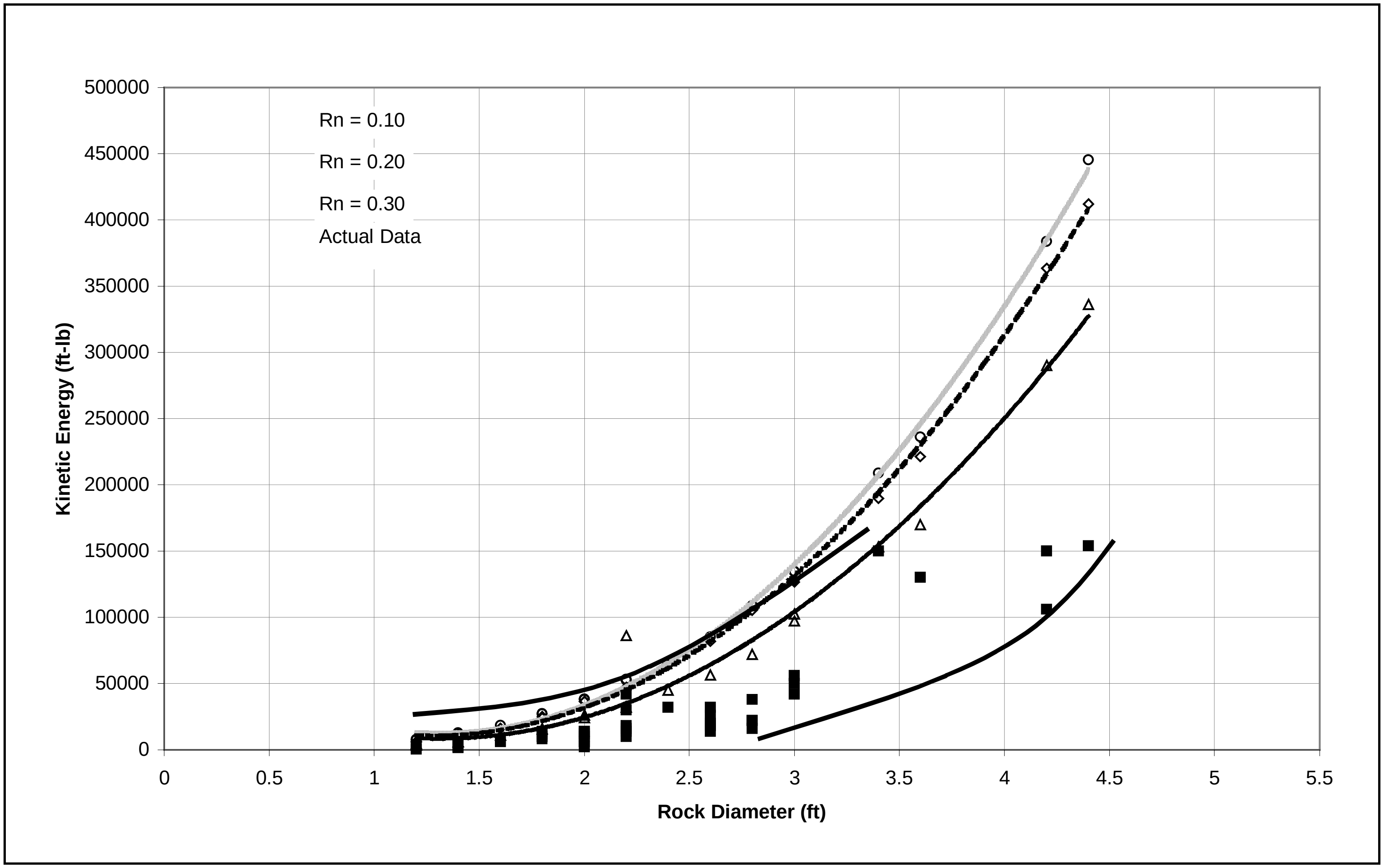


Figure A-13. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted maximum kinetic energy at R_t of 0.95 and various values of R_n for Hi-Tech tests. Surface roughness equals 0.5 feet.

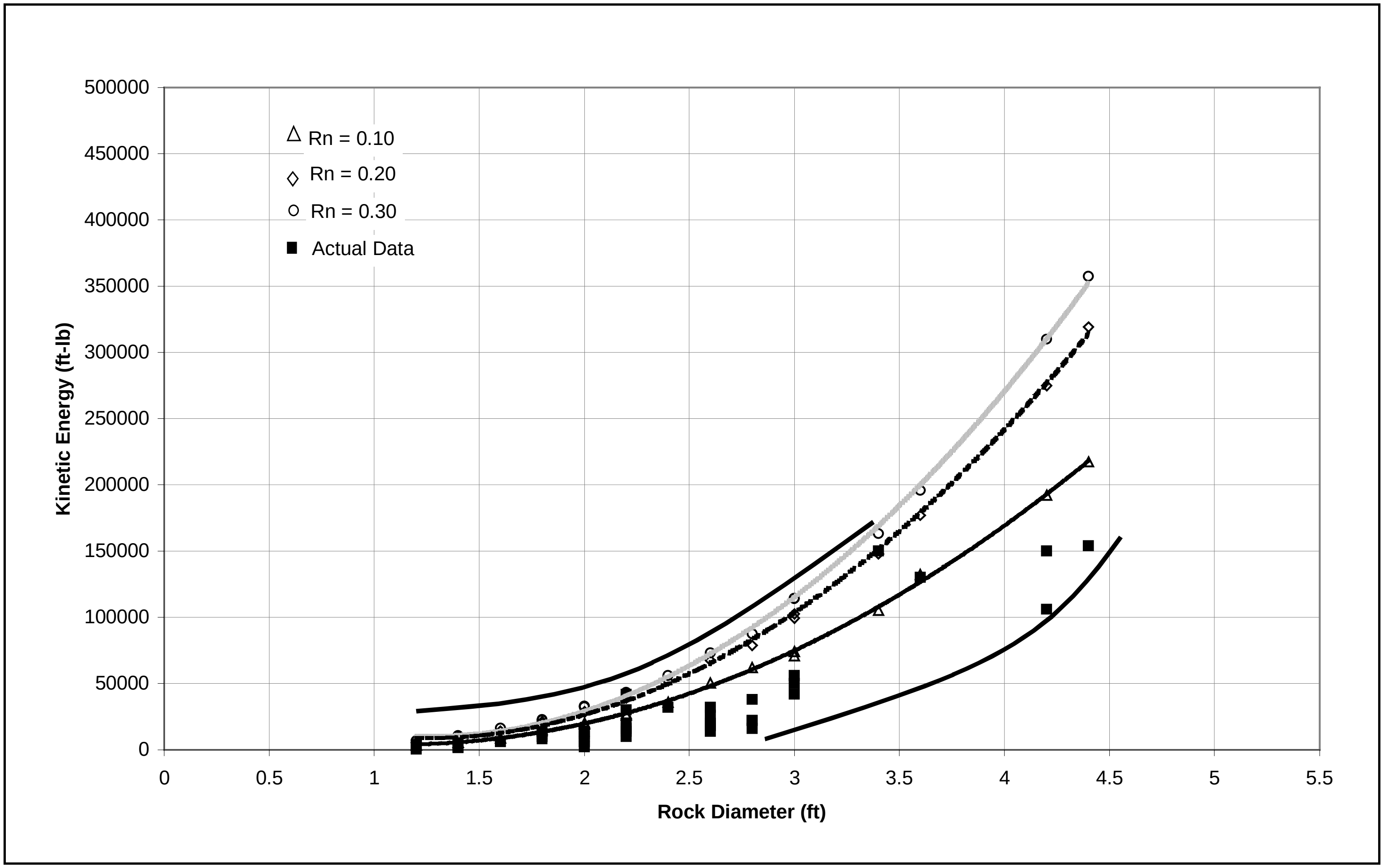


Figure A-14. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted maximum kinetic energy at R_t of 0.65 and various values of R_n for Hi-Tech tests. Surface roughness equals 0.5 feet.

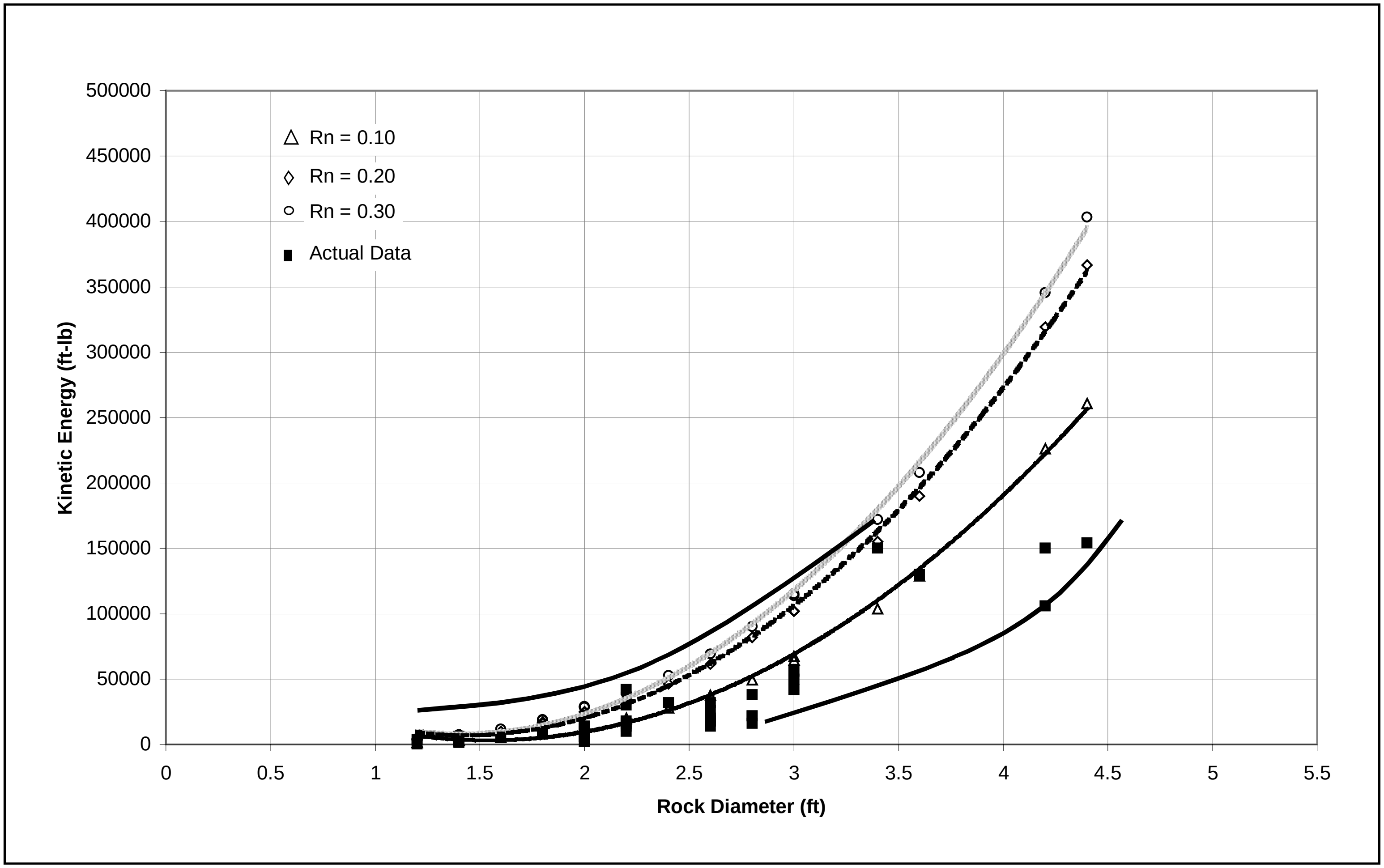


Figure A-15. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted average kinetic energy at R_t of 0.95 and various values of R_n for Hi-Tech tests. Surface roughness equals 0.5 feet.

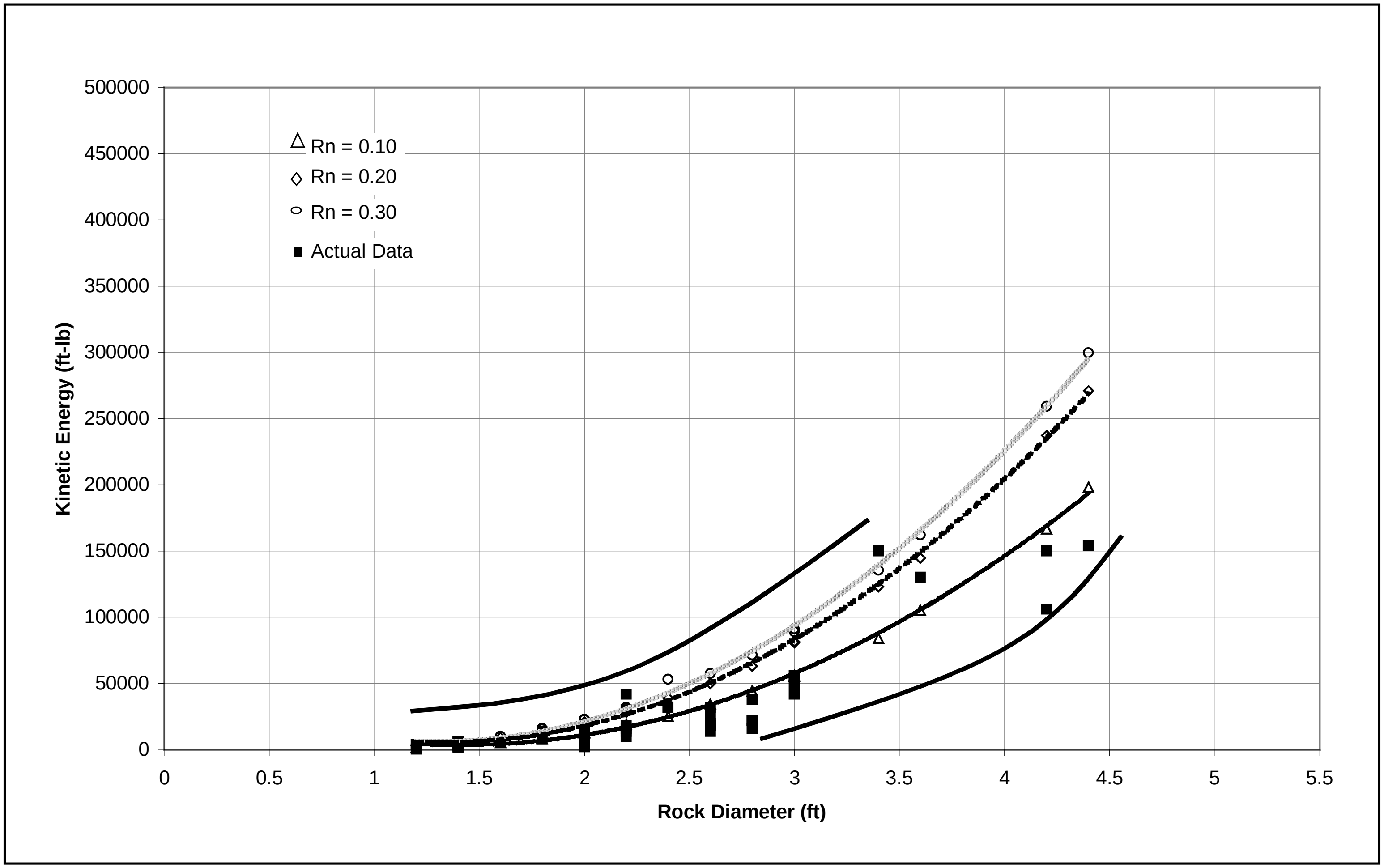


Figure A-16. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted average kinetic energy at R_t of 0.65 and various values of R_n for Hi-Tech tests. Surface roughness equals 0.5 feet.

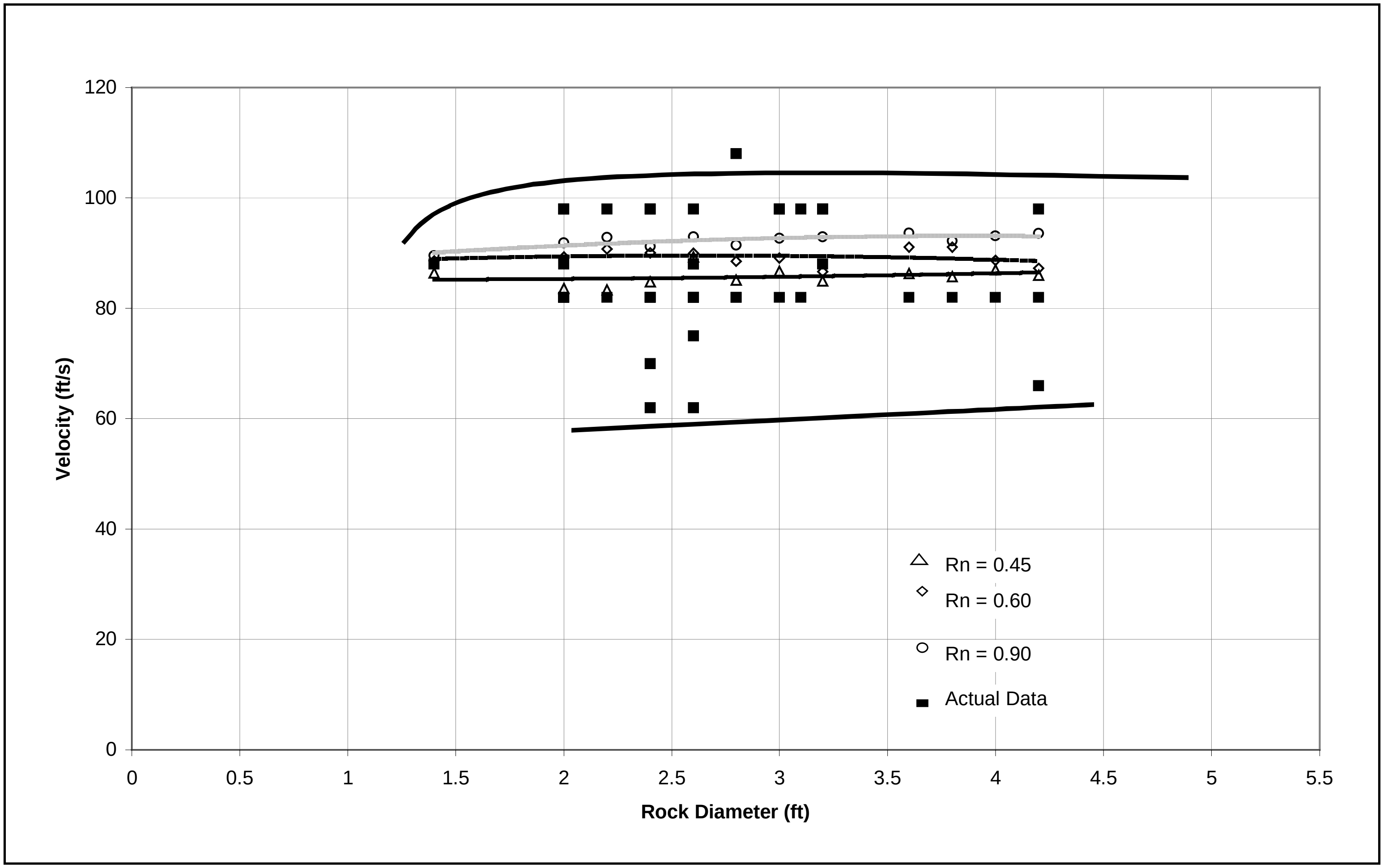


Figure A-17. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted maximum velocity at R_t of 0.95 and various values of R_n for Swiss test. Surface roughness equals 0.5 feet.

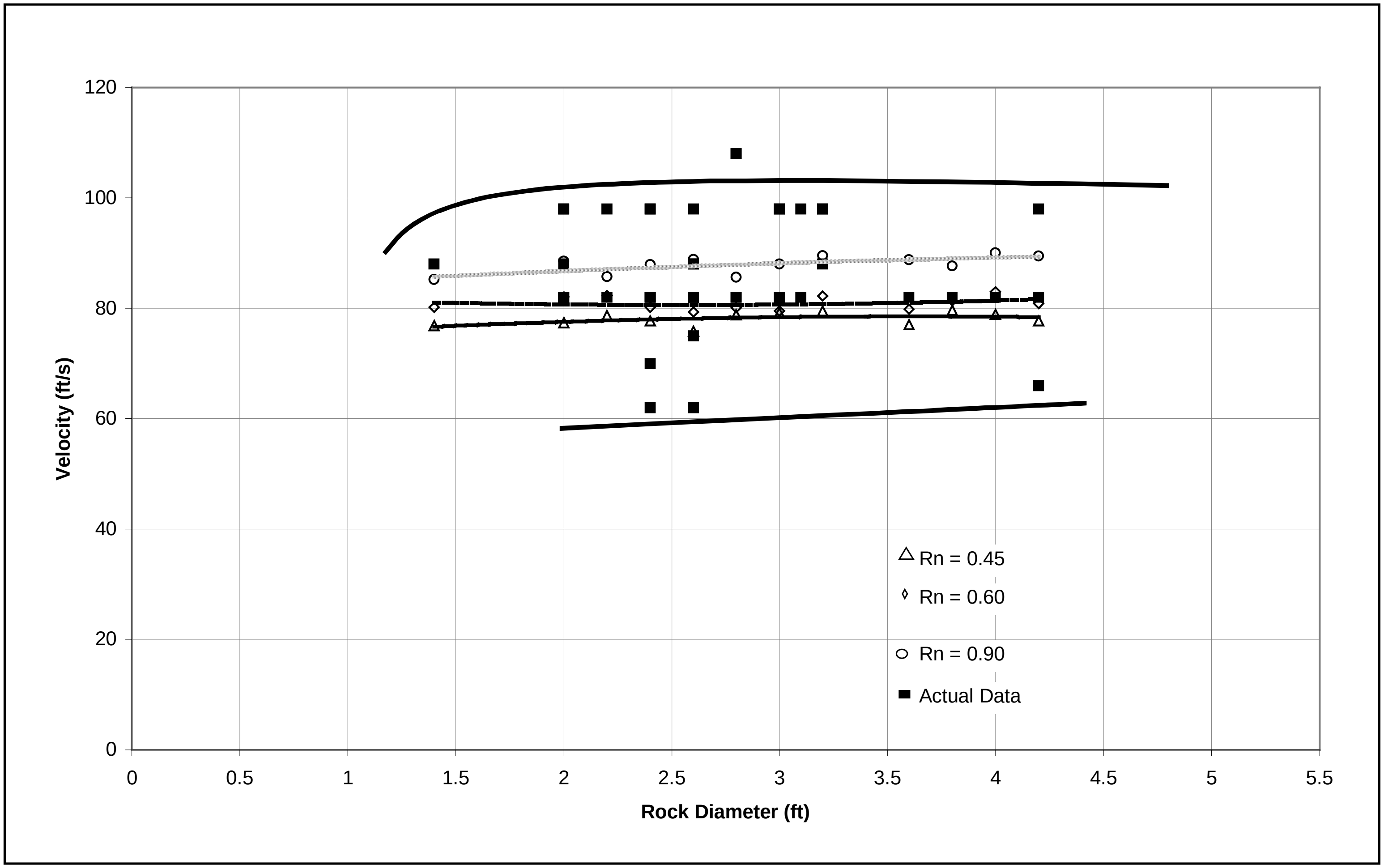


Figure A-18. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted maximum velocity at R_t of 0.65 and various values of R_n for Swiss test. Surface roughness equals 0.5 feet.

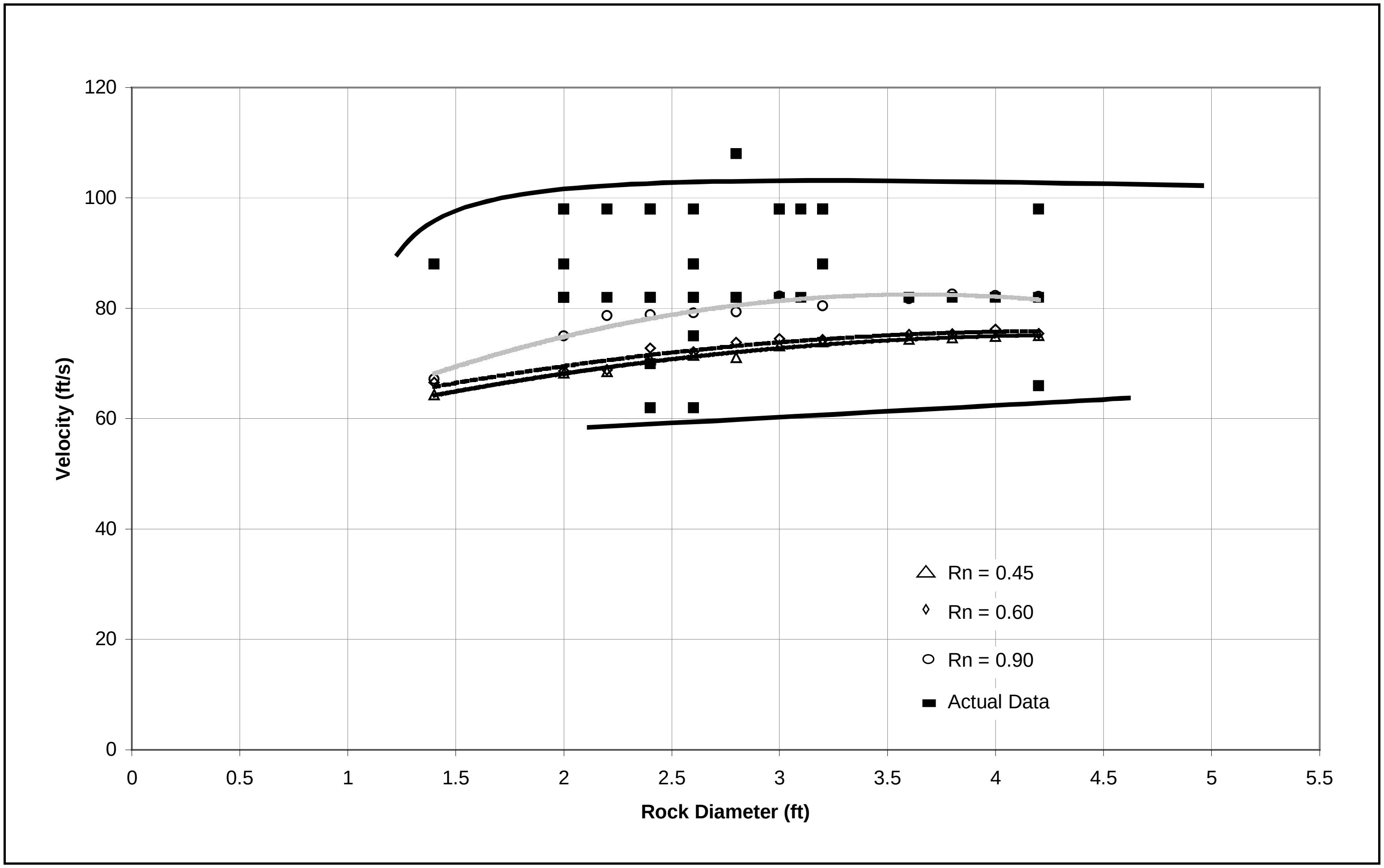


Figure A-19. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted average velocity at R_t of 0.95 and various values of R_n for Swiss test. Surface roughness equals 0.5 feet.

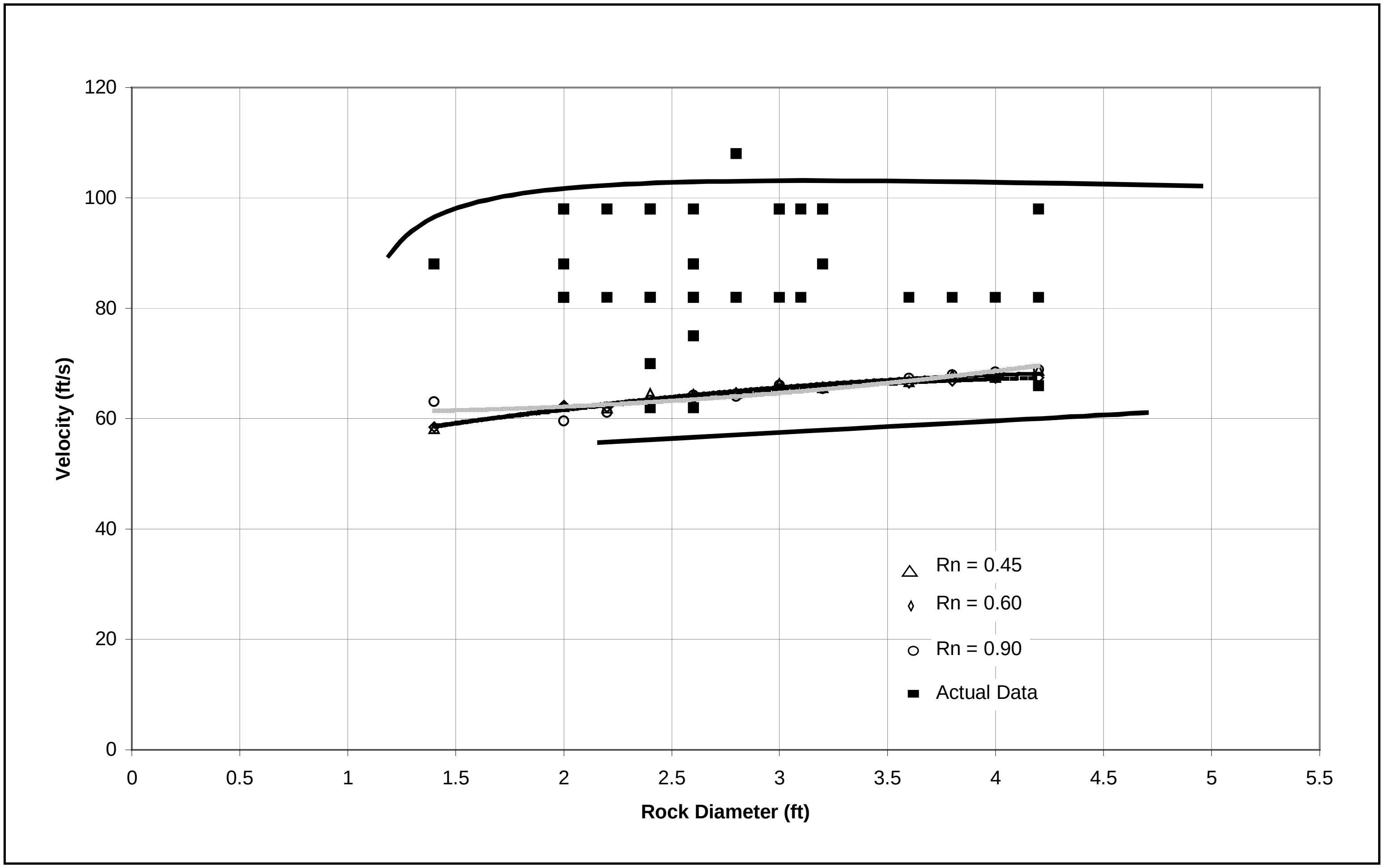


Figure A-20. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted average velocity at R_t of 0.65 and various values of R_n for Swiss test. Surface roughness equals 0.5 feet.

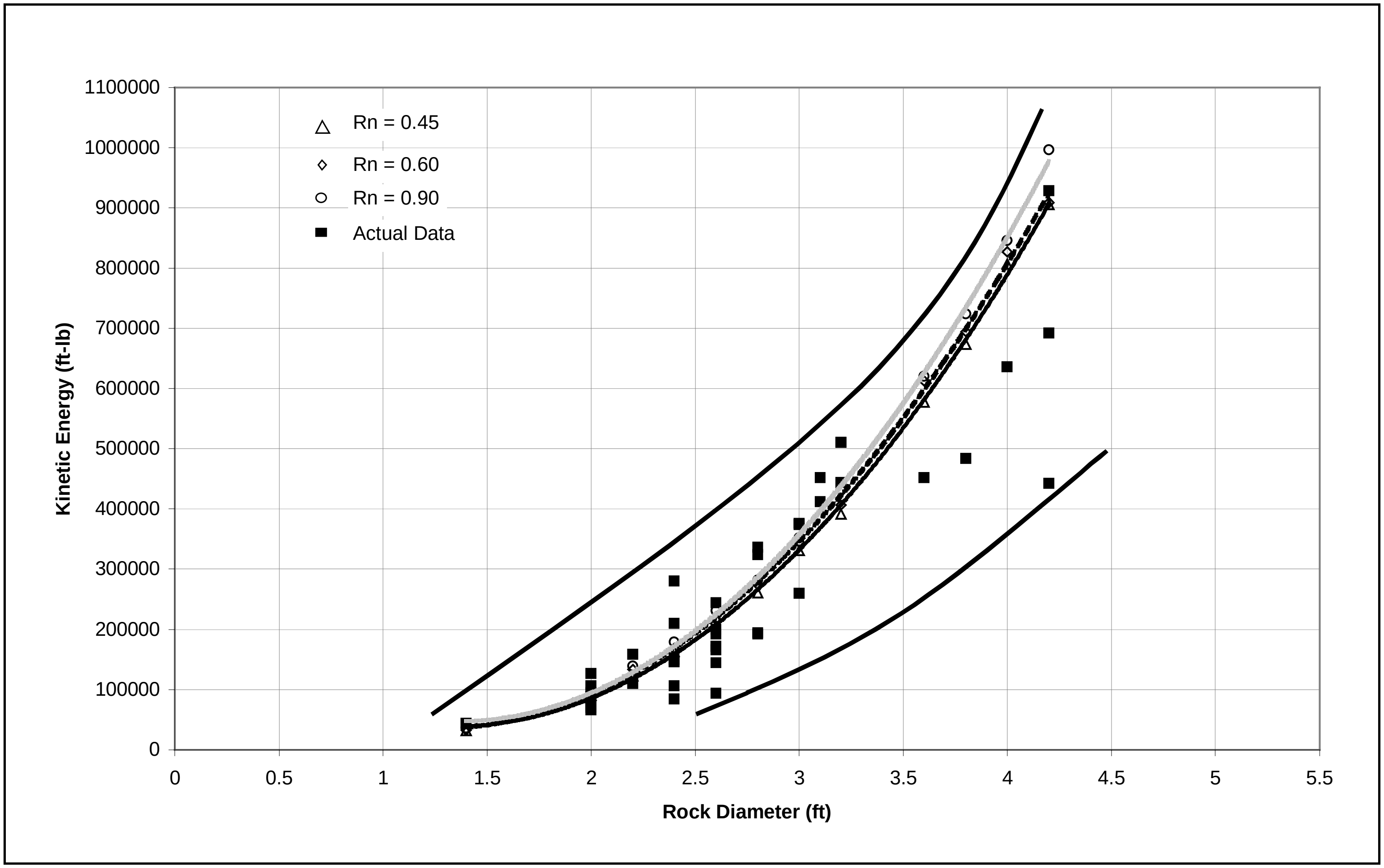


Figure A-21. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted maximum kinetic energy at R_t of 0.95 and various values of R_n for Swiss test. Surface roughness equals 0.5 feet.

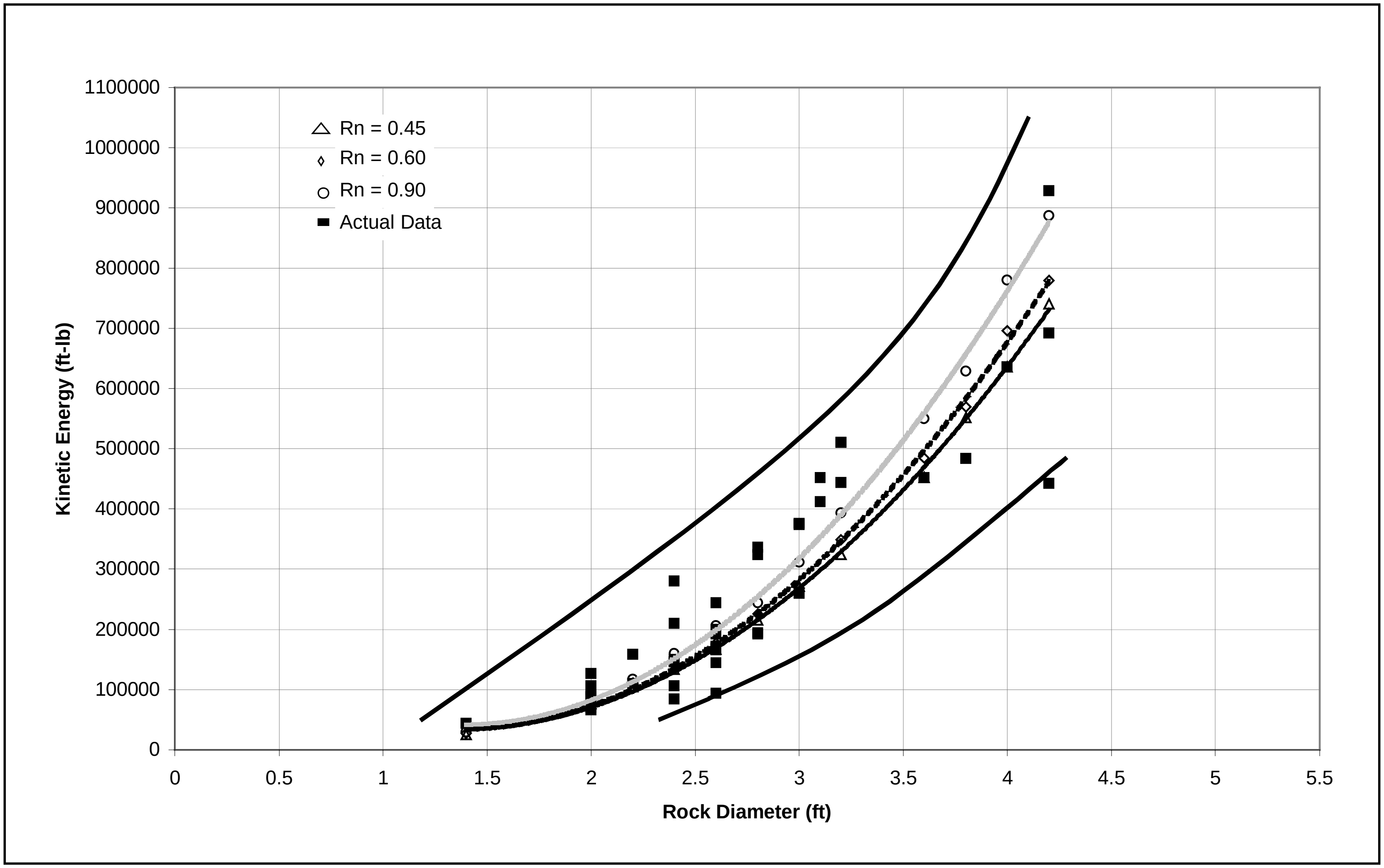


Figure A-22. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted maximum kinetic energy at R_t of 0.65 and various values of R_n for Swiss test. Surface roughness equals 0.5 feet.

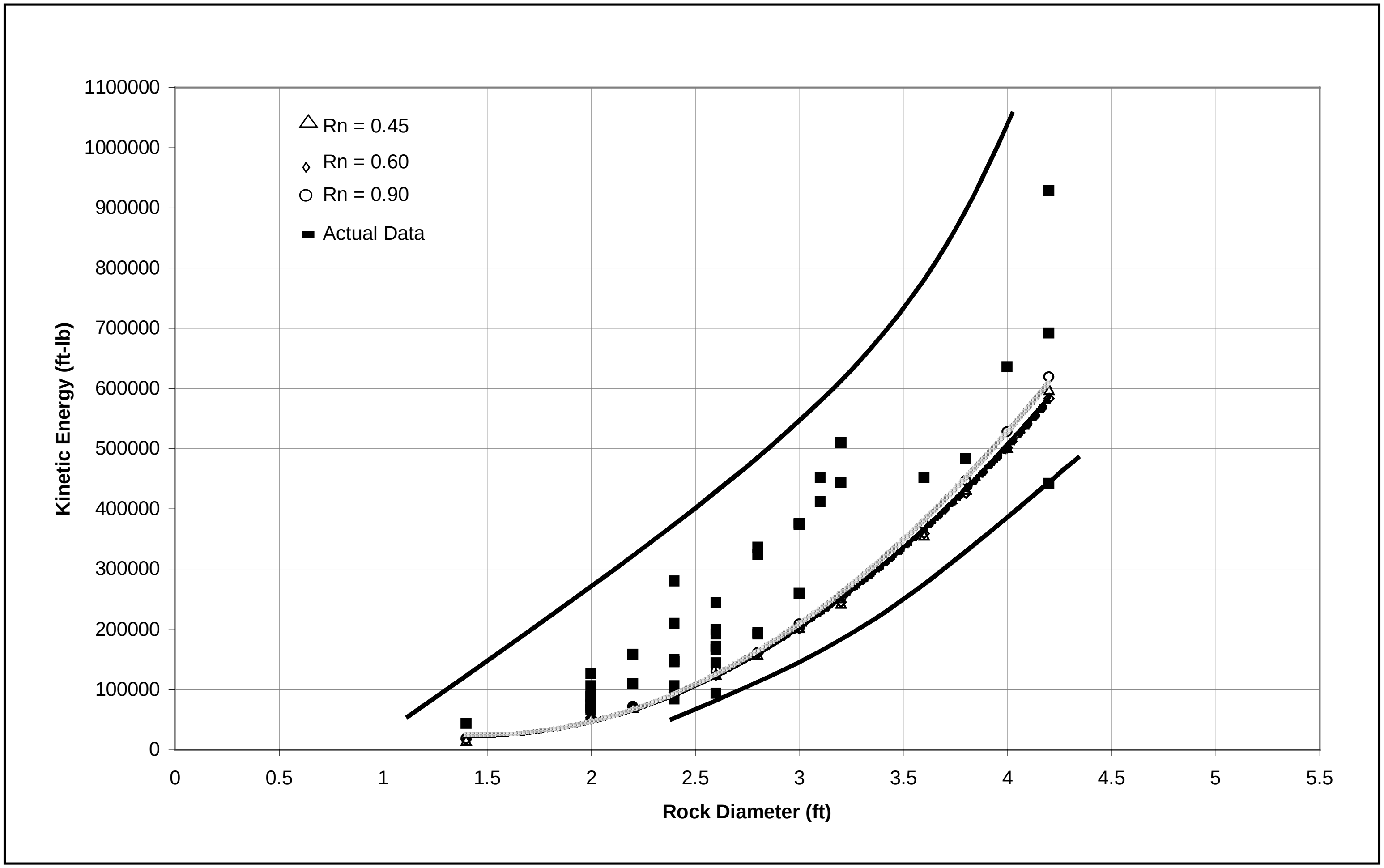


Figure A-23. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted average kinetic energy at R_t of 0.95 and various values of R_n for Swiss test. Surface roughness equals 0.5 feet.

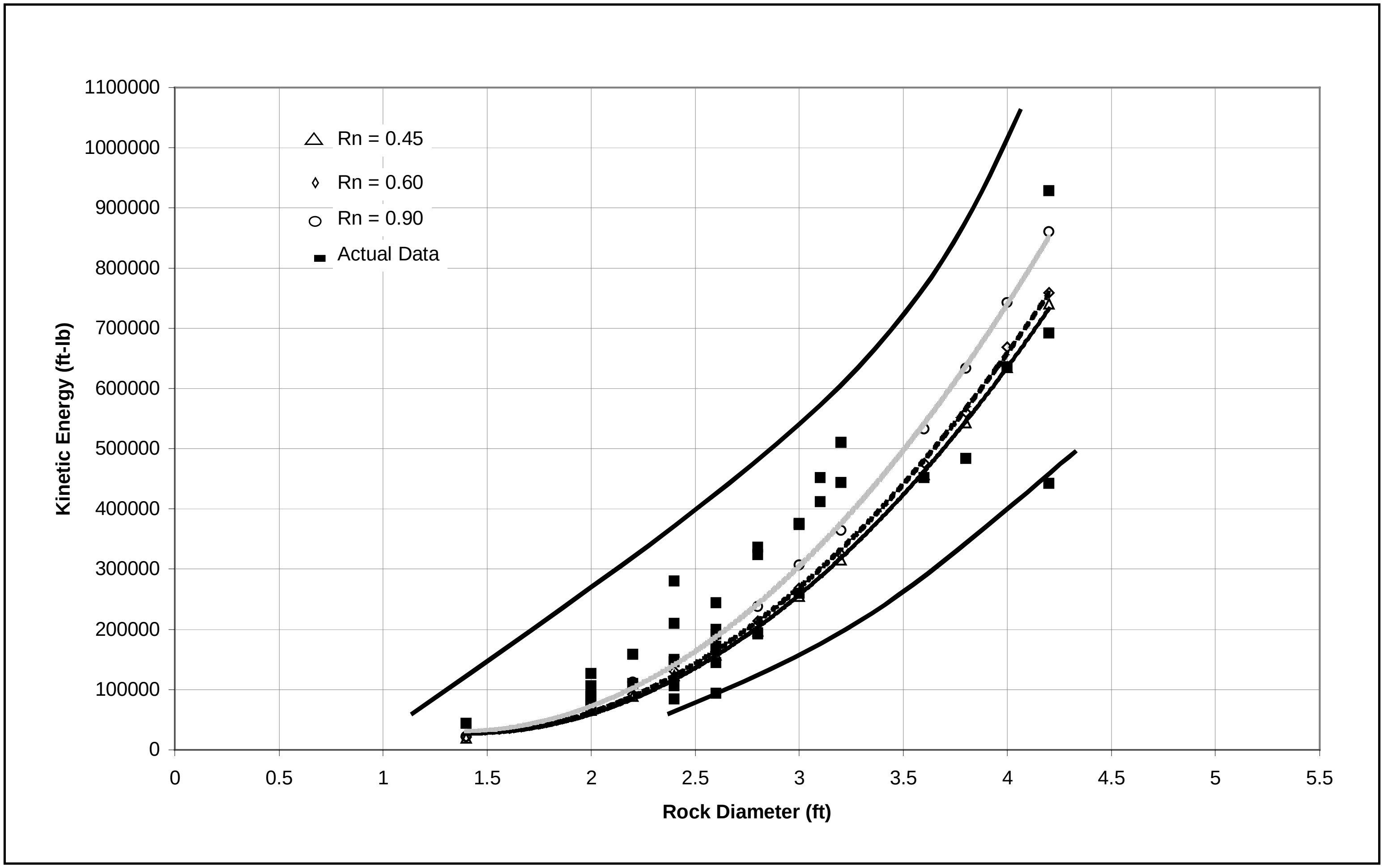


Figure A-24. Envelope of actual kinetic energy and trends (second order polynomial) of CRSP predicted average kinetic energy at R_t of 0.65 and various values of R_n for Swiss test. Surface roughness equals 0.5 feet.

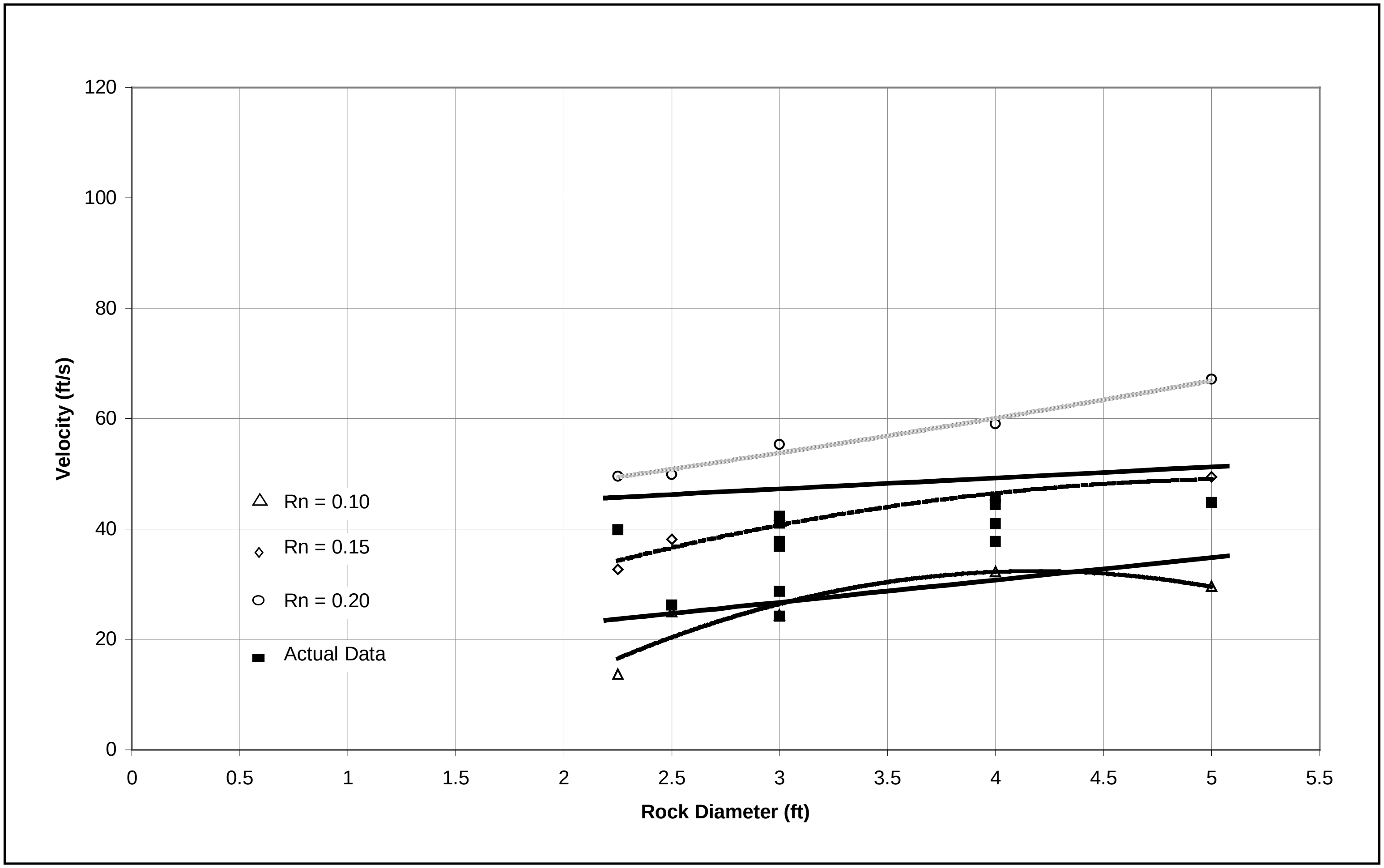


Figure A-25. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted maximum velocity at R_t of 0.95 and various values of R_n for Rifle test. Surface roughness equals 0.5 feet.

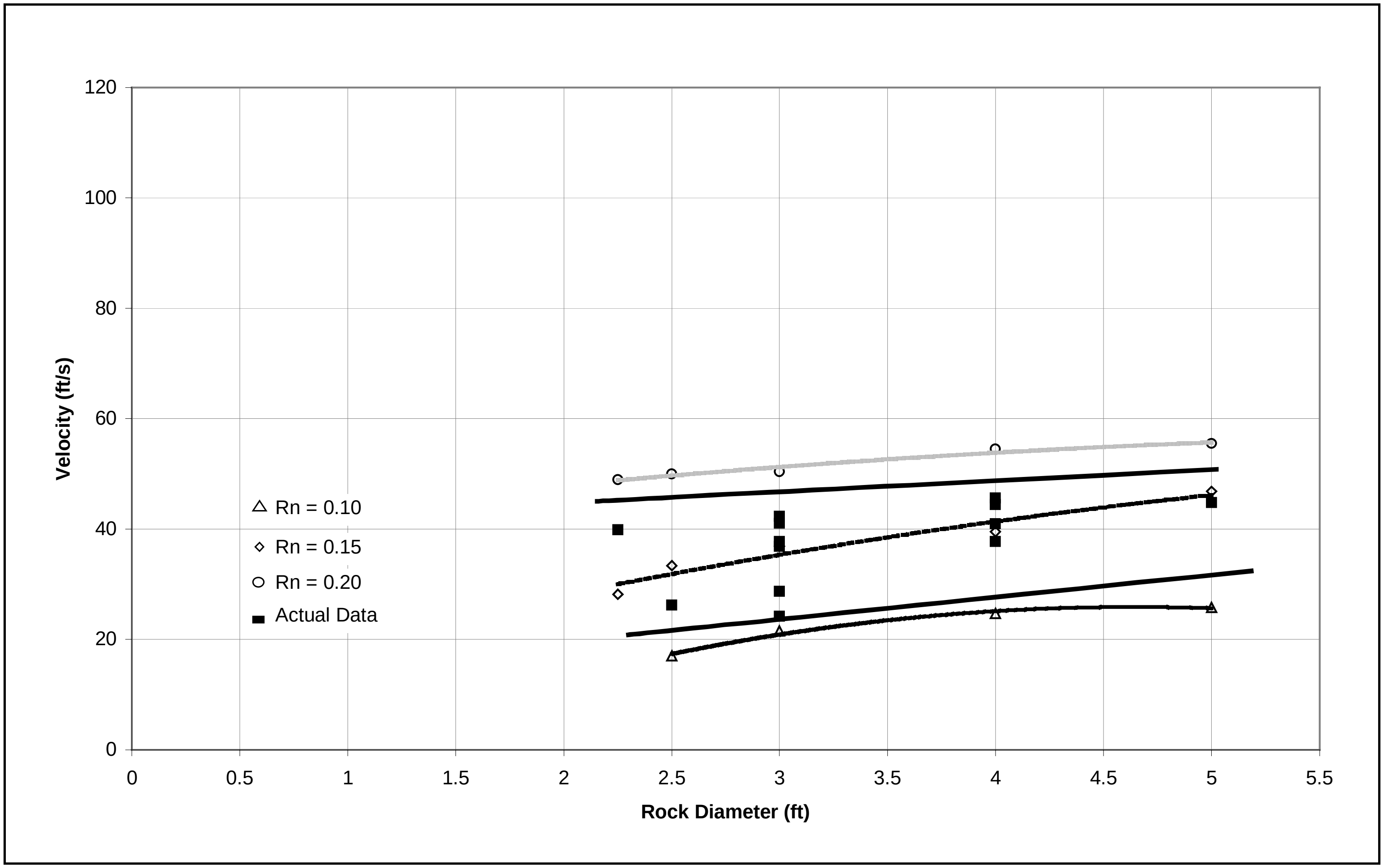


Figure A-26. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted maximum velocity at R_t of 0.65 and various values of R_n for Rifle test. Surface roughness equals 0.5 feet.

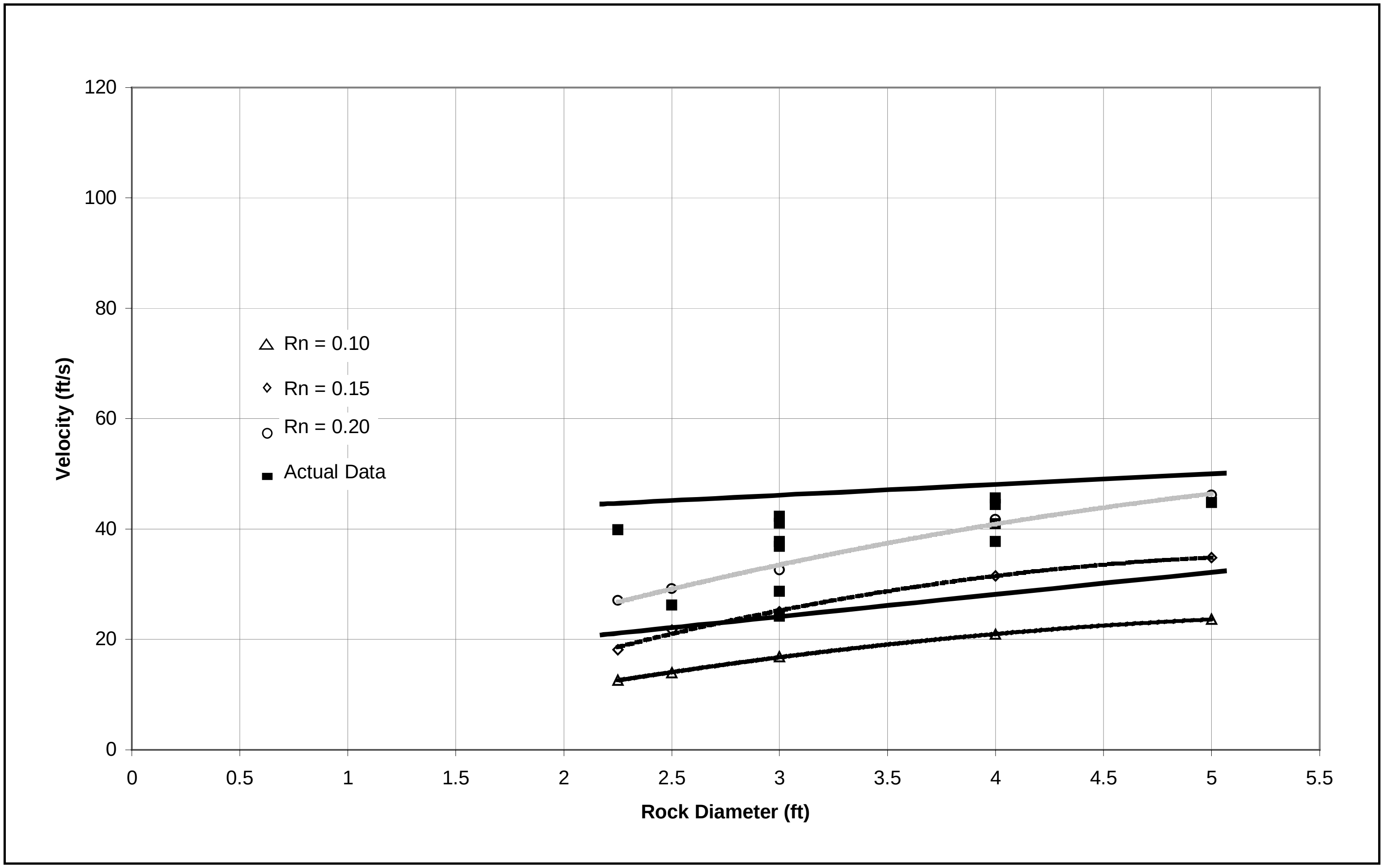


Figure A-27. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted average velocity at R_t of 0.95 and various values of R_n for Rifle test. Surface roughness equals 0.5 feet.

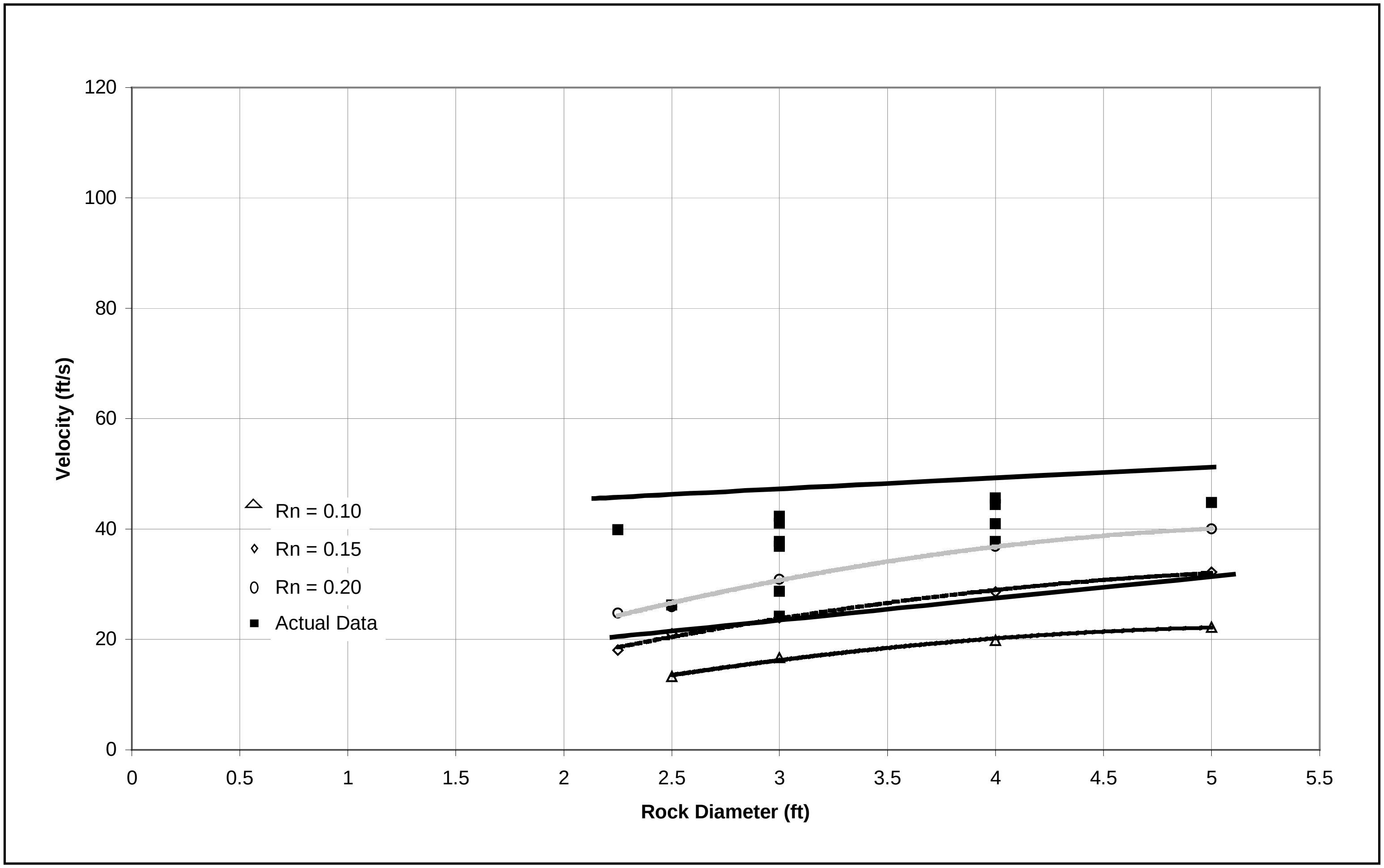


Figure A-28. Envelope of actual velocity and trends (second order polynomial) of CRSP predicted average velocity at R_t of 0.65 and various values of R_n for Rifle test. Surface roughness equals 0.5 feet.

CRSP DATA FORM

LOCATION: ______________________ DATE: ______________________

STATION: ______________________ FILENAME: ______________________

SITE INVESTIGATOR: ______________________

CELL #	DESCRIPTION	SURFACE ROUGHNESS			Rt	Rn	BEGIN X,Y	END X,Y

ANALYSIS POINT: ______________________ STARTING ZONE: ______________________

APPENDIX C—SAMPLE CRSP ANALYSIS USING FILE RIFLE.DAT

CRSP Input File-D:\CRSP\RIFLE.DAT

Input File Specifications

Units of Measure: U.S.
Total Number of Cells: 13
Analysis Point 1 X-Coordinate: 400
Analysis Point 2 X-Coordinate:
Analysis Point 3 X-Coordinate:
Initial Y-Top Starting Zone Coordinate: 330
Initial Y-Base Starting Zone Coordinate: 325

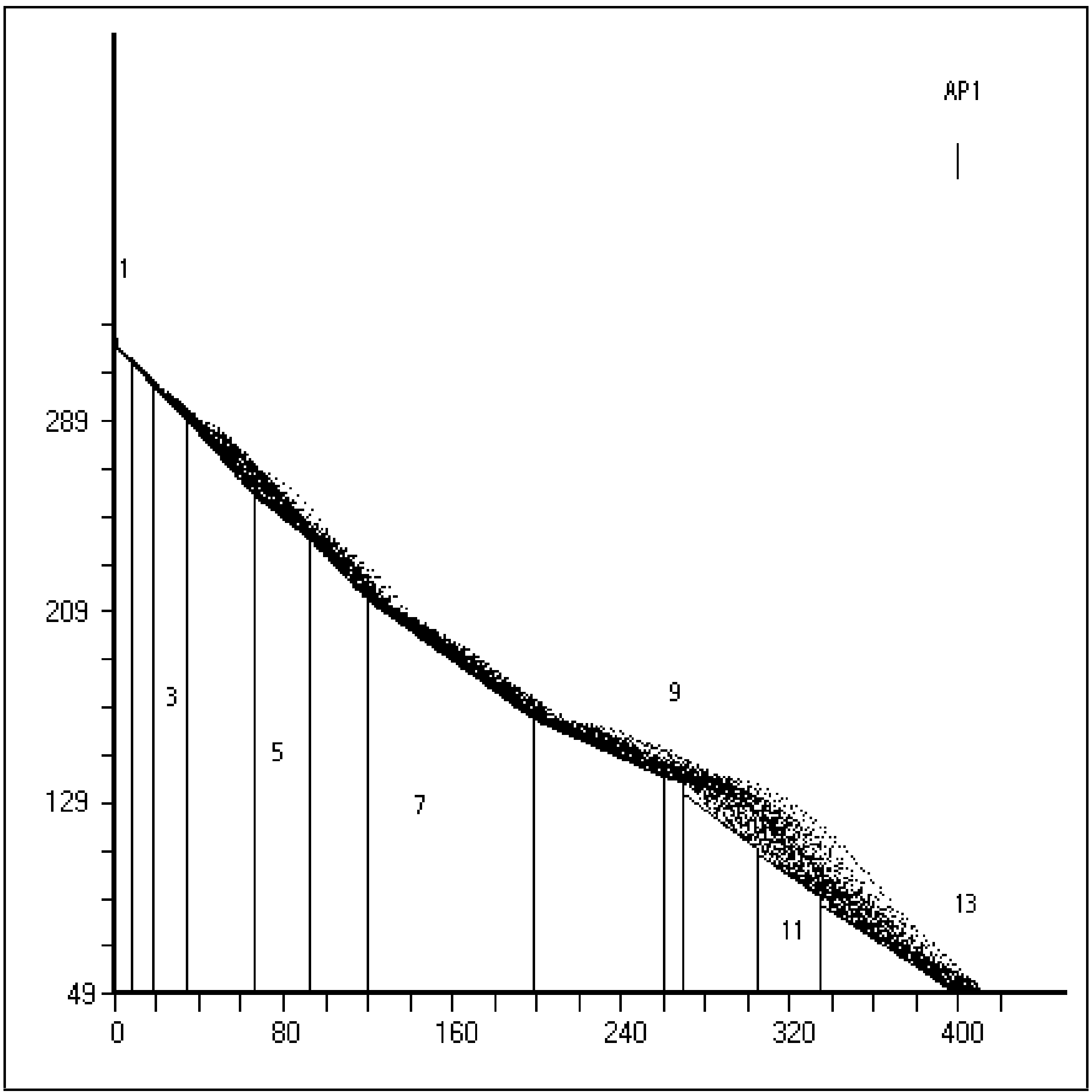
Remarks: NONE

Cell Data

Cell No.	S.R.	Tang. C.	Norm. C.	Begin X	Begin Y	End X	End Y
1	.4	.82	.25	0	320	8	314
2	.6	.84	.32	8	314	18	304
3	.8	.84	.32	18	304	34	290
4	2	.84	32	34	290	66	258
5	.8	.84	.3	66	258	92	240
6	.8	.84	.3	92	240	120	214
7	.8	.83	.3	120	214	199	164
8	1	.82	.33	199	164	260	140
9	.8	.82	.33	260	140	269	138
10	1.4	.84	.34	269	133	305	110
11	1.2	.84	.34	305	108	335	90
12	.8	.84	.34	335	87	396	51
13	.4	.85	.34	396	51	410	49

CRSP Simulation Specifications: Used with D:\CRSP\RIFLE.DAT

Total Number of Rocks Simulated: 100
Starting Velocity in X-Direction: 1 ft/sec
Starting Velocity in Y-Direction: -1 ft/sec
Starting Cell Number: 1
Ending Cell Number: 13
Rock Density: 165 lb/ft^3
Rock Shape: Spherical
Diameter: 4 ft



CRSP Analysis Point 1 Data - D:\CRSP\RIFLE.DAT

Analysis Point 1:

X = 400, Y = 50

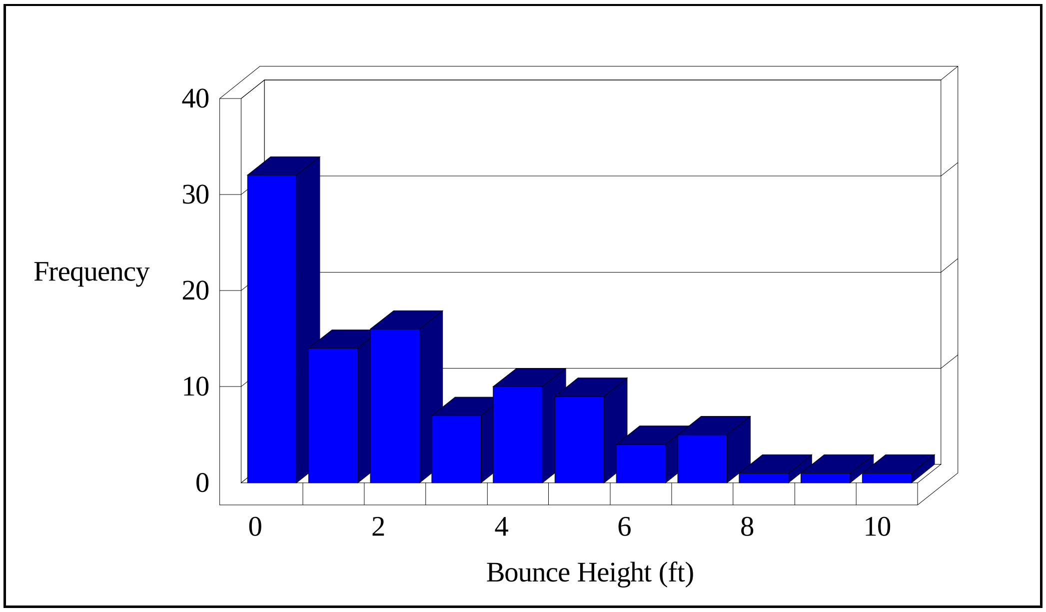
Total Rocks Passing Analysis Point: 100

Cumulative Probability	Velocity (ft/sec)	Energy (ft-lb)	Bounce Ht. (ft)
50%	57.42	381082	0.91
75%	63.32	447260	6.5
90%	68.64	506782	11.53
95%	71.83	542517	14.56
98%	75.4	582624	17.95

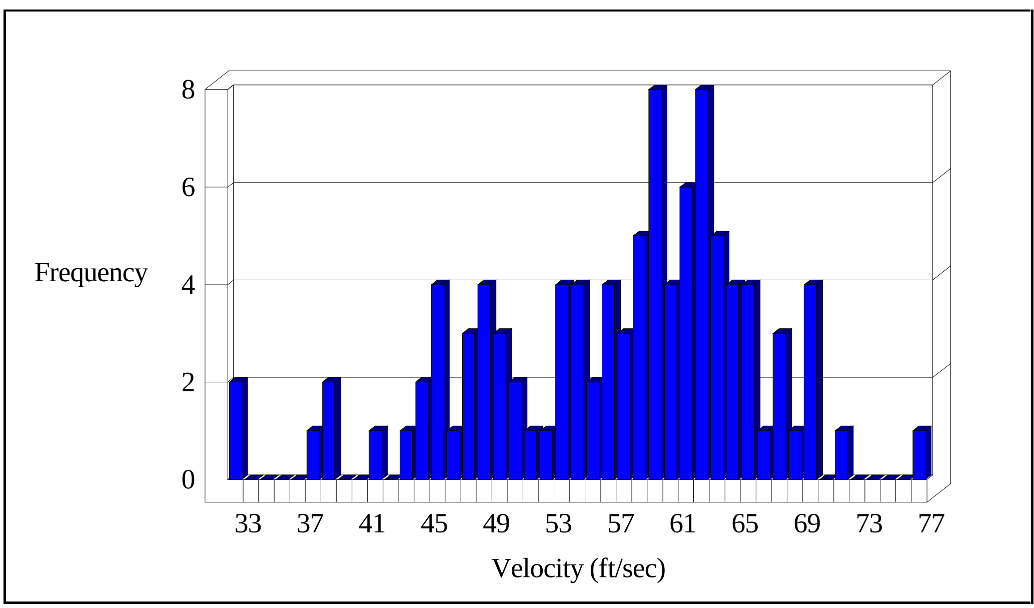
Velocity (ft/sec)	Bounce Height (ft)	Kinetic Energy (ft-lb)
Maximum: 76.74	Maximum: 9.68	Maximum: 612351
Average: 57.42	Average: 2.44	Average: 381082
Minimum: 32.8	G. Mean: .91	Std. Dev.: 98011
Std. Dev.: 8.75	Std. Dev.: 8.29	

Remarks: NONE

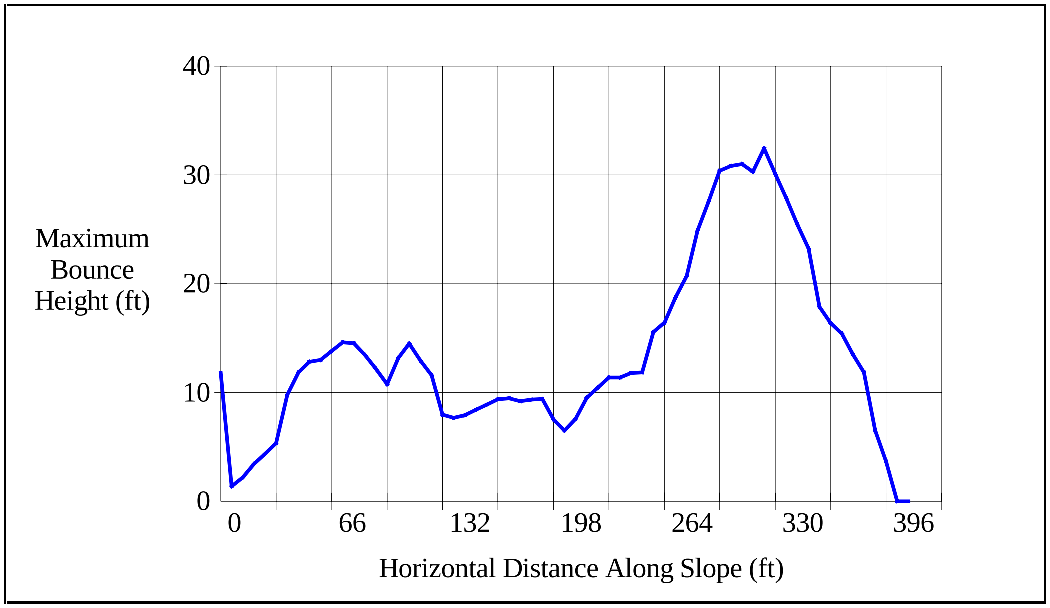
Bounce Height Distribution—RIFLE.DAT



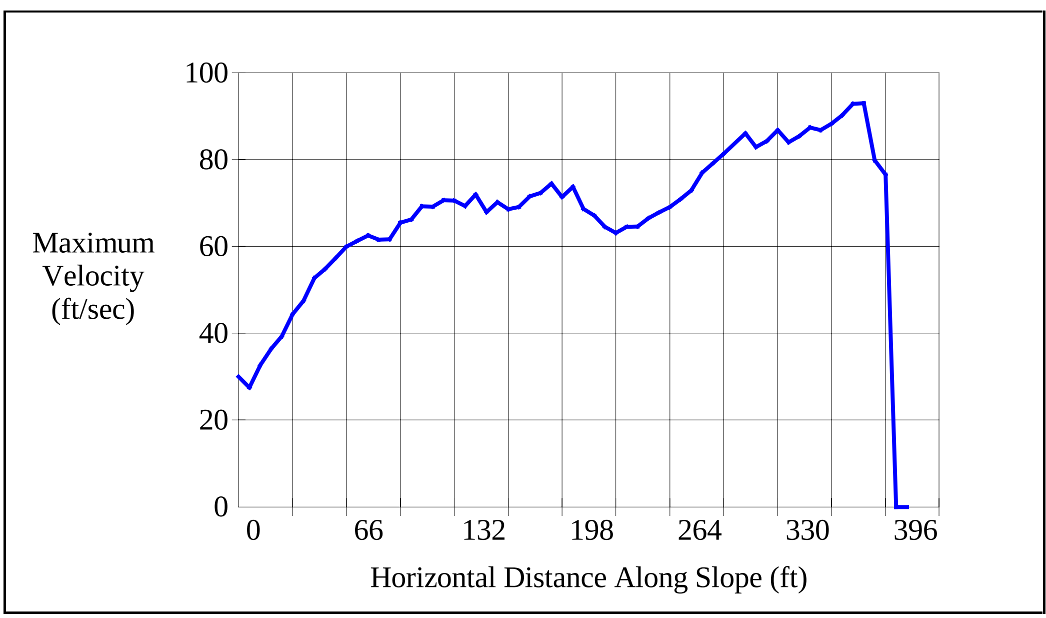
Analysis Point 1 Velocity Distribution—\RIFLE.DAT



Bounce Height Graph—RIFLE.DAT



Velocity Graph—RIFLE.DAT



CRSP Data Collected at End of Each Cell - D:\CRSP\RIFLE.DAT

Velocity Units: ft/sec   Bounce Height Units: ft

Cell #	Max. Vel.	Avg. Vel.	S.D. Vel.	Max. Bounce Ht.	Avg. Bounce Ht.
1	21	19	1	0	0
2	32	27	1.43	2	0
3	40	34	2.18	5	1
4	55	42	6.73	13	6
5	59	45	5.78	13	2
6	65	55	5.24	14	4
7	73	58	5.81	9	2
8	65	51	6.5	12	3
9	67	49	6.63	10	3
10	79	58	7.47	27	12
11	82	62	10.24	30	8
12	91	62	7.14	13	3
13	75	52	8.61	4	1

CRSP Rocks Stopped Data - D:\CRSP\RIFLE.DAT

X Interval	Rocks Stopped
0 To 10 ft	0
10 To 20 ft	0
20 To 30 ft	0
30 To 40 ft	0
40 To 50 ft	0
50 To 60 ft	0
60 To 70 ft	0
70 To 80 ft	0
80 To 90 ft	0
90 To 100 ft	0
100 To 110 ft	0
110 To 120 ft	0
120 To 130 ft	0
130 To 140 ft	0
140 To 150 ft	0
150 To 160 ft	0
160 To 170 ft	0
170 To 180 ft	0
180 To 190 ft	0
190 To 200 ft	0
200 To 210 ft	0
210 To 220 ft	0
220 To 230 ft	0
230 To 240 ft	0
240 To 250 ft	0
250 To 260 ft	0
260 To 270 ft	0
270 To 280 ft	0
280 To 290 ft	0
290 To 300 ft	0
300 To 310 ft	0
310 To 320 ft	0
320 To 330 ft	0
330 To 340 ft	0
340 To 350 ft	0
350 To 360 ft	0
360 To 370 ft	0
370 To 380 ft	0
380 To 390 ft	0
390 To 400 ft	0
400 To 410 ft	0

APPENDIX D—SAMPLE CRSP ANALYSIS USING FILE GLENWOOD.DAT

CRSP Input File -D:\CRSP\GLENWOOD.DAT

Input File Specifications

Units of Measure: U.S.
Total Number of Cells: 15
Analysis Point 1 X-Coordinate: 885
Analysis Point 2 X-Coordinate:
Analysis Point 3 X-Coordinate:
Initial Y-Top Starting Zone Coordinate: 810
Initial Y-Base Starting Zone Coordinate: 800

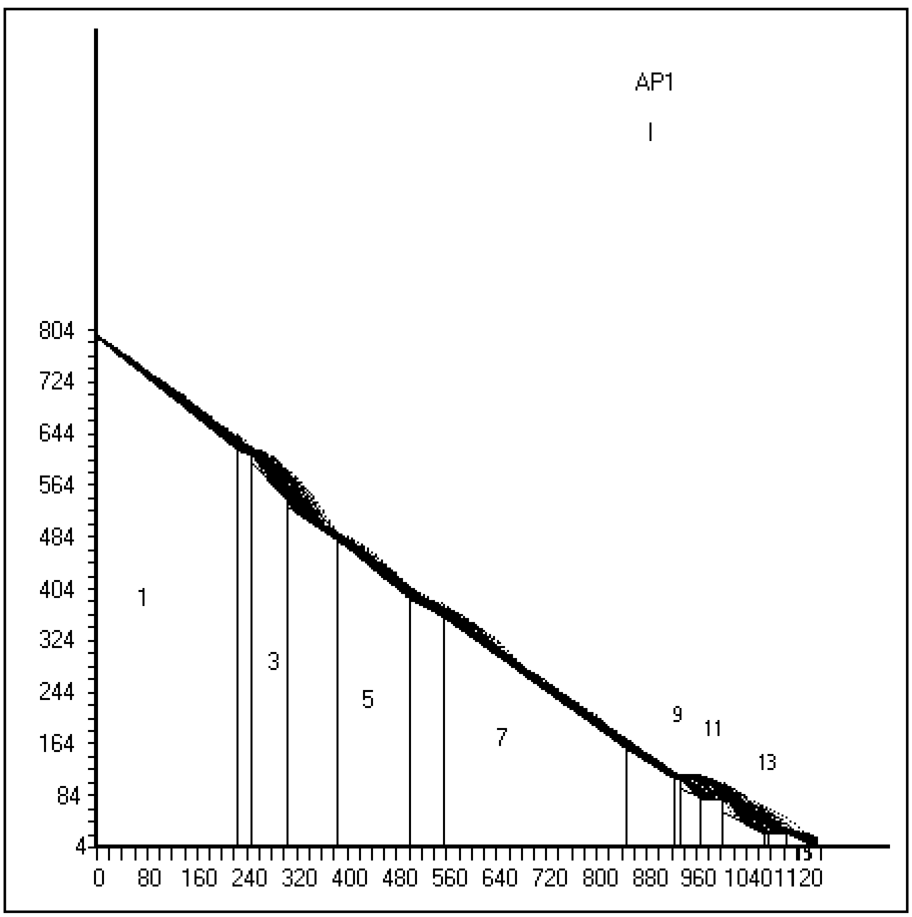
Remarks:

Cell Data

Cell No.	S.R.	Tang. C.	Norm. C.	Begin X	Begin Y	End X	End Y
1	1.5	.85	.35	0	794	224	620
2	1.8	.85	.35	224	620	248	610
3	2.5	.85	.35	248	600	306	540
4	1.0	.81	.32	306	530	385	480
5	1.0	.81	.32	385	480	500	390
6	1.2	.81	.32	500	390	557	360
7	.70	.80	.31	557	360	848	157
8	.60	.80	.31	848	157	925	110
9	1.0	.82	.31	925	110	933	110
10	.5	.80	.32	933	95	968	80
11	.1	.9	.4	968	78	1002	78
12	1	.8	.32	1002	60	1069	25
13	.2	.82	.32	1069	25	1075	27
14	.1	.9	.4	1075	27	1104	27
15	1	.82	.32	1104	27	1153	4

CRSP Simulation Specifications: Used with D:\CRSP\GLENWOOD.DAT

Total Number of Rocks Simulated: 100
Starting Velocity in X-Direction: 1 ft/sec
Starting Velocity in Y-Direction: -1 ft/sec
Starting Cell Number: 1
Ending Cell Number: 15
Rock Density: 165 lb/ft^3
Rock Shape: Spherical
Diameter: 4. ft



CRSP Analysis Point 1 Data - D:\CRSP\GLENWOOD.DAT

Analysis Point 1:

X = 885, Y = 134

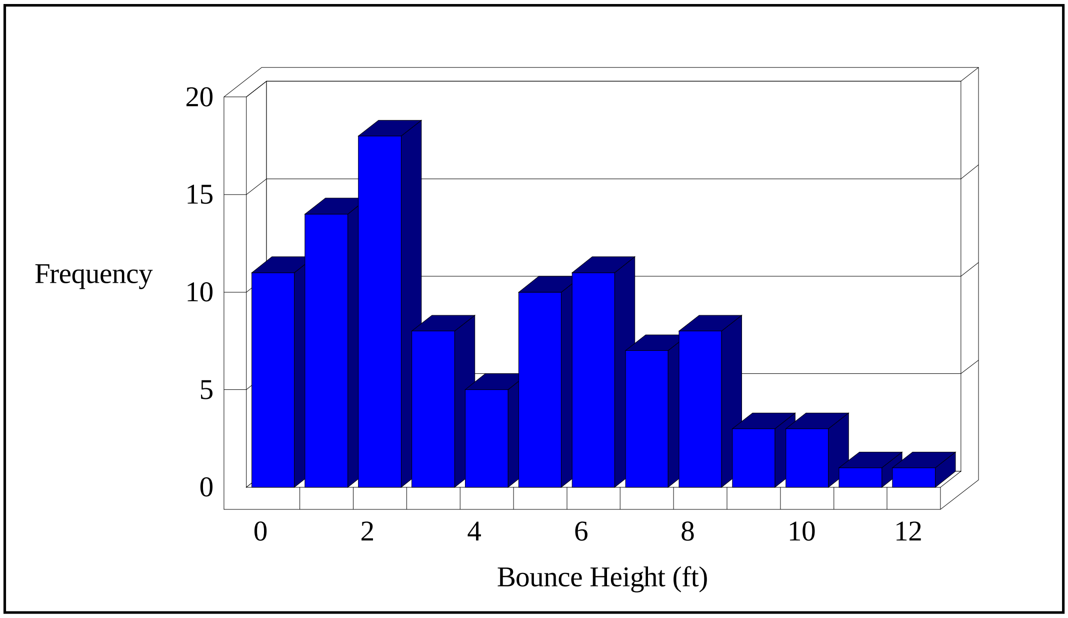
Total Rocks Passing Analysis Point: 100

Cumulative Probability	Velocity (ft/sec)	Energy (ft-lb)	Bounce Ht. (ft)
50%	79.41	717679	2.24
75%	84.86	803370	5.61
90%	89.77	880444	8.63
95%	92.71	926716	10.45
98%	96.01	978649	12.49

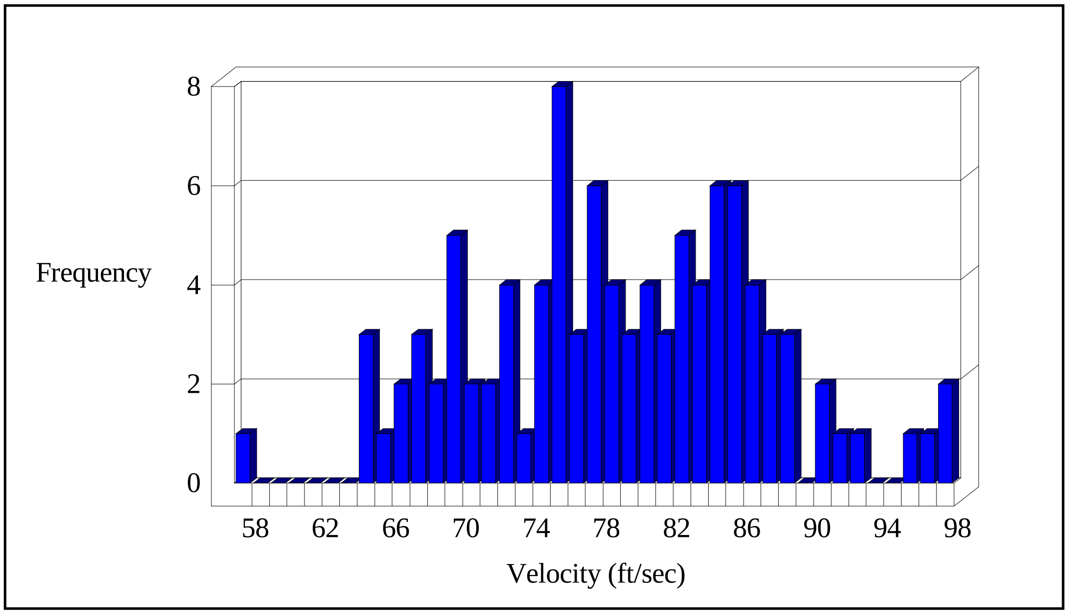
Velocity (ft/sec)	Bounce Height (ft)	Kinetic Energy (ft-lb)
Maximum: 98	Maximum: 11.81	Maximum: 1018981
Average: 79.41	Average: 3.99	Average: 717679
Minimum: 58.31	G. Mean: 2.24	Std. Dev.: 126912
Std. Dev.: 8.07	Std. Dev.: 4.98	

Remarks:

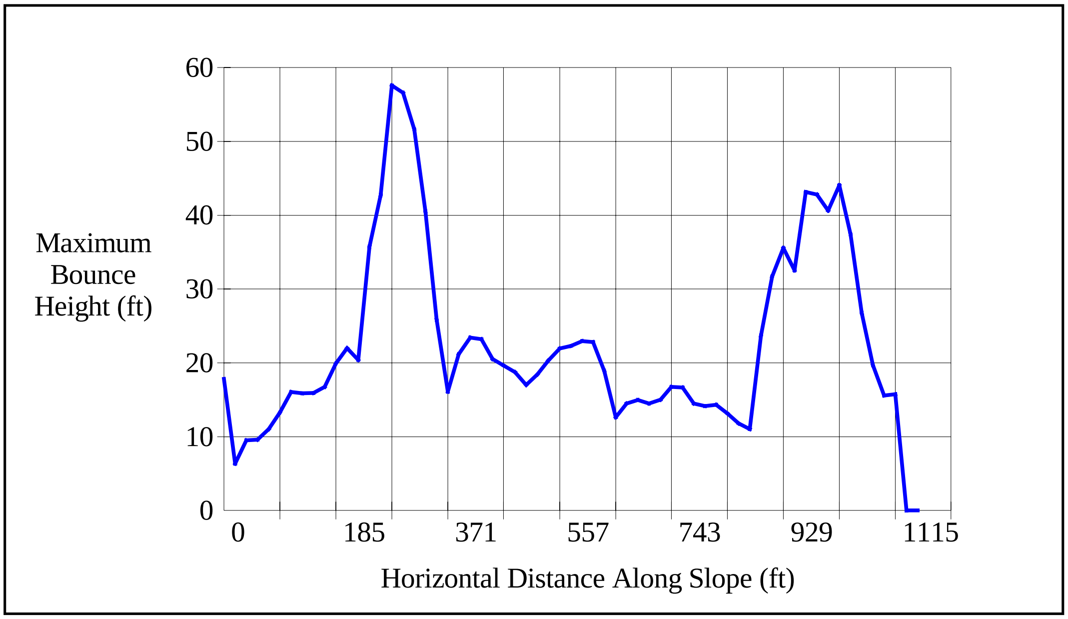
Bounce height Distribution—GLENWOOD.DAT



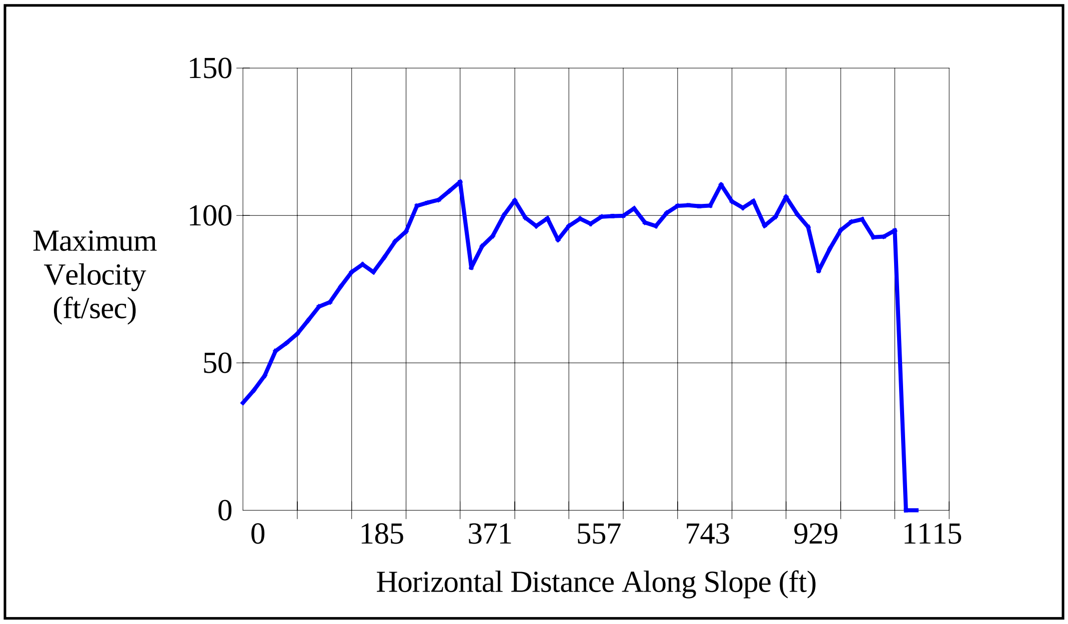
Analysis Point 1 Velocity Distribution—D:\CRSP\GLENWOOD.DAT



Bounce Height Graph—GLENWOOD.DAT



Velocity Graph—GLENWOOD.DAT



CRSP Data Collected at End of Each Cell - D:\CRSP\GLENWOOD.DAT

Velocity Units: ft/sec Bounce Height Units: ft

Cell #	Max. Vel.	Avg. Vel.	S.D. Vel.	Max. Bounce Ht.	Avg. Bounce Ht.
1	81	56	10.2	21	7
2	75	48	11.27	13	4
3	96	68	14.52	48	19
4	104	56	11.15	11	3
5	97	68	11.67	19	7
6	85	60	8.81	18	5
7	105	81	8.56	14	5
8	94	80	7.07	11	4
9	94	61	17.11	6	1
10	104	64	19.05	34	19
11	69	57	10.83	25	6
12	93	65	16.39	44	15
13	94	54	24.07	39	10
14	86	44	20.05	23	1
15	94	48	14.34	16	3

CRSP Rocks Stopped Data - D:\CRSP\GLENWOOD.DAT

X Interval	Rocks Stopped
0 To 10 ft	0
10 To 20 ft	0
20 To 30 ft	0
30 To 40 ft	0
40 To 50 ft	0
50 To 60 ft	0
60 To 70 ft	0
70 To 80 ft	0
80 To 90 ft	0
90 To 100 ft	0
100 To 110 ft	0
110 To 120 ft	0
120 To 130 ft	0
130 To 140 ft	0
140 To 150 ft	0
150 To 160 ft	0
160 To 170 ft	0
170 To 180 ft	0
180 To 190 ft	0
190 To 200 ft	0
200 To 210 ft	0
210 To 220 ft	0
220 To 230 ft	0
230 To 240 ft	0
240 To 250 ft	0
250 To 260 ft	0
260 To 270 ft	0
270 To 280 ft	0
280 To 290 ft	0
290 To 300 ft	0
300 To 310 ft	0
310 To 320 ft	0
320 To 330 ft	0
330 To 340 ft	0
340 To 350 ft	0
350 To 360 ft	0
360 To 370 ft	0
370 To 380 ft	0
380 To 390 ft	0
390 To 400 ft	0
400 To 410 ft	0
410 To 420 ft	0
420 To 430 ft	0
430 To 440 ft	0
440 To 450 ft	0
450 To 460 ft	0
460 To 470 ft	0
470 To 480 ft	0
480 To 490 ft	0
490 To 500 ft	0
500 To 510 ft	0
510 To 520 ft	0
520 To 530 ft	0
530 To 540 ft	0
540 To 550 ft	0
550 To 560 ft	0
560 To 570 ft	0
570 To 580 ft	0
580 To 590 ft	0
590 To 600 ft	0
600 To 610 ft	0
610 To 620 ft	0
620 To 630 ft	0
630 To 640 ft	0
640 To 650 ft	0
650 To 660 ft	0
660 To 670 ft	0
670 To 680 ft	0
680 To 690 ft	0
690 To 700 ft	0
700 To 710 ft	0
710 To 720 ft	0
720 To 730 ft	0
730 To 740 ft	0
740 To 750 ft	0
750 To 760 ft	0
760 To 770 ft	0
770 To 780 ft	0
780 To 790 ft	0
790 To 800 ft	0
800 To 810 ft	0
810 To 820 ft	0
820 To 830 ft	0
830 To 840 ft	0
840 To 850 ft	0
850 To 860 ft	0
860 To 870 ft	0
870 To 880 ft	0
880 To 890 ft	0
890 To 900 ft	0
900 To 910 ft	0
910 To 920 ft	0
920 To 930 ft	0
930 To 940 ft	0
940 To 950 ft	0
950 To 960 ft	0
960 To 970 ft	0
970 To 980 ft	0
980 To 990 ft	0
990 To 1000 ft	0
1000 To 1010 ft	0
1010 To 1020 ft	0
1020 To 1030 ft	0
1030 To 1040 ft	0
1040 To 1050 ft	0
1050 To 1060 ft	0
1060 To 1070 ft	0
1070 To 1080 ft	0
1080 To 1090 ft	0
1090 To 1100 ft	1
1100 To 1110 ft	0
1110 To 1120 ft	0
1120 To 1130 ft	0
1130 To 1140 ft	0
1140 To 1150 ft	0
1150 To 1153 ft	0