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Rockfall Hazard Analysis Using
Computer Simulation of Rockfalls

By

Timothy J. Pfeiffer

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Date: 5/1/89

Signed: Timothy J. Pfeiffer

Timothy J. Pfeiffer

Approved: Jerry D. Higgins

Dr. Jerry D. Higgins

Thesis Advisor

Golden, Colorado

Date: 5/2/89

Dr. Samuel S. Adams

Professor and Head, Department

of Geology and Geological Engineering

DISCLAIMER PAGE

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These programs have been tested and are believed to be reliable engineering tools. No responsibility is assumed by the author, the Colorado School of Mines, or any of its employees for any errors, mistakes or misrepresentations that may occur from any use of these programs.

ABSTRACT

The Colorado Rockfall Simulation Program (CRSP) was developed for the purpose of modeling rockfall behavior and to provide a statistical analysis of probable rockfall events at any given site. This analysis can be used as a tool to study the behavior of rockfalls, 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 video tapes of rockfalls. 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 velocity, friction, and material coefficients are used to model the dynamic interaction of the rock and slope. The statistical variation among rockfalls is modeled by randomly varying the angle at which a rock impacts the slope within limits set by rock size and the slope characteristics. This program provides a site specific analysis of rockfalls by providing estimates of probable velocity and bounce height statistics at various locations on the slope.

This report 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. Adequate theory is presented to give the user the necessary understanding of the theoretical and empirical basis of rockfall modeling. An analysis of the sensitivity of the simulation results to the input parameters should help the user of CRSP to understand the program and its limitations. A step by step guide on using the program and an example problem are presented. Comparisons between CRSP results and rockfall test results provide the user with an idea of what confidence may be expected from simulation results.

TABLE OF CONTENTS

CRSP VERIFICATION AND CALIBRATION

FIELD DATA COLLECTION

ENTERING DATA AND RUNNING CRSP

APPENDICES

LIST OF FIGURES

LIST OF TABLES

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INTRODUCTION

Rockfalls are 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. In this rapid down-slope motion, rockfalls present a common hazard to transportation and structures in steep mountainous terrain. Often, no protective measures are taken, other than posting warning signs. As more transportation routes and structures are placed in areas of rockfall hazards, the need for an understanding of rockfall behavior increases.

The construction of I-70 through Glenwood Canyon, Colorado required rockfall mitigation measures to protect the highway structures and to improve safety to motorists. Conventional design of rockfall protection using ditch design criteria (Ritchie, 1963) was often not applicable for the natural slopes or was aesthetically unacceptable. A reasonable estimate of probable bounce height and velocity of rockfalls was needed input for the design of rockfall fences and alternative rockfall catch ditches in Glenwood Canyon. It was decided that this information could best be provided by a rockfall simulation program for field office PC-compatible style computers.

The Colorado Rockfall Simulation Program (CRSP) was developed to aid in the design of rockfall mitigation by supplying data on probable rockfall bounce height and velocities. The program uses easily identified parameters to produce a rockfall simulation on PC-compatible computers and has proven useful in designing rock cuts, ditches and rockfall fences in Glenwood Canyon. This report presents the results of the development and testing of CRSP, as well as detailed instructions on data collection and using the program.

Development of CRSP began in August, 1985 and was pursued on a part time basis until the fall of 1987. At this time, Federal Highway Administration research money became available for testing and further development of the program. Experimental verification and calibration of CRSP was conducted in conjunction with 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. The program simulates rockfalls at a site based on data on slope irregularities, slope materials, slope profile and rock size. The final product is a reasonably easy to use rockfall simulation program.

Literature Review

The published literature contains abundant studies dealing with slope stability and rockfall mitigation measures, but there are few papers concerning the mechanics of rockfall motion. Since all the rocks cannot be prevented from falling, an understanding of rockfall mechanics is important (Ritchie, 1963).

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 rockfalls. From these observations, Ritchie developed criteria for designing cut slopes and ditches which are widely used today (Nichol and Watters, 1983).

Piteau and Associates (1980) developed and tested a computer rockfall simulation program designed for a mainframe computer. This program used a slope profile divided into straight line segments, termed cells, and the 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 likewise, motion parallel to the slope is attenuated by a tangential coefficient. The slope of each cell can be perturbed to account for surface irregularities and angularity of the rock. The program produces velocity and bounce height probability 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 hazard (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 in rockfalls at a given site. This testing indicated that the rocks bounced less with higher impact angles, so the program reduced the coefficients for larger impact angles.

CRSP incorporates all of the concepts used by previous rockfall 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 previous studies noted a statistical variation of rockfalls caused by irregularities in the slope. CRSP deals with these irregularities by using field measurements of surface roughness. The effect of impact angle noted by Wu (1984) is taken a step further 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. By incorporating all of these concepts and two years of trial use in Glenwood Canyon, CRSP has become a reasonably accurate and easy to use method of investigating rockfall hazards.

General Description of CRSP

CRSP provides estimates of probable rockfall bounce heights and velocities for rockfall on natural or cut slopes. Like any computer simulation model, the accuracy of 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 decide on the quality of the data produced by CRSP.

This report should help the user of the program to choose appropriate input parameters and make decisions concerning the accuracy of the output. It is intended as a guide to the use of CRSP and not as a text on rock slope engineering. The user should have a working knowledge of rock slope stability theory in order to fully benefit from this report and the programs.

CRSP is a compiled basic program designed to run on PC-compatible computers. The following lists the hardware requirements for running CRSP:

360 Kilobyte disk drive
Dot matrix printer with IBM character set
CGA or EGA graphics adapter
Monochrome display screen
8087 Math coprocessor (optional)

A math coprocessor is not required to run the program, but the program runs much faster with a coprocessor.

The CRSP software package includes three programs. CRSP.EXE and CRSPSCR.EXE are the same program except that

CRSPSCR.EXE prints out data only to the screen, while CRSP.EXE prints the data to a printer. Also included is a program called ROCKDATA.EXE which aids in constructing input data files.

CRSP requires the following input data:

1) A slope profile, input as a series of straight line segments called cells, designated by the coordinates of the end points of each line.
2) An estimation of the roughness of the slope surface within each cell.
3) Coefficients that quantify the frictional and elastic properties of the slope.
4) The size, shape and starting location of the rocks involved in the rockfalls.

CRSP uses this input data in a stochastic model to produce statistics on probable rockfall velocity and bounce height.

The following data is output by CRSP:

1) Slope profile showing cell locations and the position of each simulation rock every tenth of a second as it travels down the slope.
2) Maximum and average bounce heights at the end of each cell and for one selected location on the slope.

3) Maximum and average velocities at the end of each cell and at the selected location on the slope.
4) Maximum total kinetic energy of the falling rock at the selected location on the slope.
5) Graph of the distribution of velocities and bounce heights at the selected location on the slope.
6) Graphs of the maximum velocity and bounce height along the slope.

THEORY

The proper use of any computer engineering tool requires an understanding of the basis of the program. This helps the user of the program to choose appropriate input data and recognize reasonable results. While CRSP adds objectivity to the otherwise subjective task of investigating rockfall, many aspects of using CRSP are dependent on the judgement of the investigator, and it is the investigator's responsibility to understand the application and limitations of CRSP. This section of the report should help the investigator to understand the principles behind rockfall modeling and therefore, make better decisions while using CRSP.

Rockfall Parameters

The behavior of rockfalls is influenced by slope geometry, slope material properties, rock geometry and rock material properties (Ritchie, 1963). Rockfalls 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 and rock material properties (Table 1) are used to model rockfall behavior.

Table 1: Parameters determining behavior of rockfalls.

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

Slope geometry parameters influencing the behavior of rockfalls are slope inclination, slope length, surface roughness, and lateral variability of the slope surface. Slope inclination is critical because it 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 (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 rockfalls. Irregularities in the slope surface account for most of the variability observed among rockfalls originating from a single source location. These irregularities, referred to as surface roughness, alter the angle at which the rock impacts the 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.) The variation of the slope angle (θ) is defined in Figure 1. Lateral (cross slope) variations of the slope surface may affect slope inclination, slope length, or surface roughness and thereby influence the rock's speed and direction of travel.

The properties of slope material influence the behavior of a rock rebounding from the slope. Numerical representations of these properties are termed the normal coefficient of restitution (Rn) and the tangential coefficient of frictional resistance (Rt), where the normal direction is perpendicular to the surface, and the tangential direction is parallel to the surface (Piteau and

Associates, 1980; Wu, 1984). The velocity components and coefficients are illustrated in Figure 1.

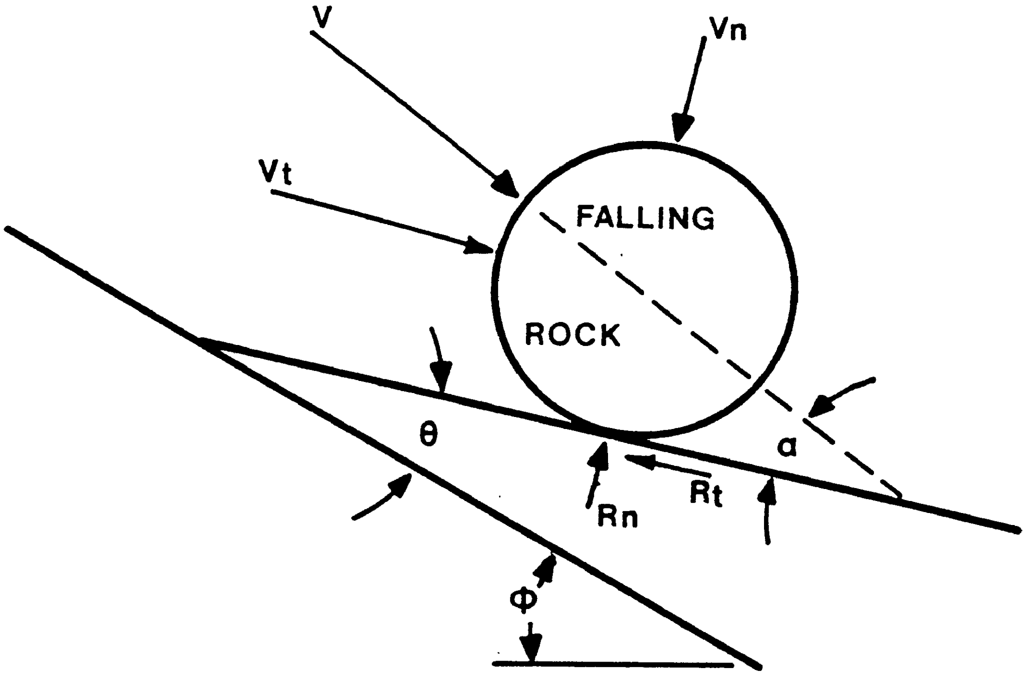

Figure 1: Impact angle (α) defined as a function of rock trajectory, slope angle (Φ), and slope variation (θ).
Vn - Velocity normal to the slope.
Vt - Velocity tangential to the slope.
Rt - Coefficient of frictional resistance tangential to the slope.
Rn - Coefficient of restitution normal to the slope.

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 tangential 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. Rn is a measure of elasticity in collisions normal to the slope, and Rt is a measure of friction parallel to the slope.

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

Assumptions

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

1) The slope profile should follow the most probable rockfall path as established during field investigations; therefore, all the calculations may be in two dimensions.
2) 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 can account for both the rock and slope properties.
3) The worst case scenario is generally that of the largest rock which remains intact while traveling down a slope; therefore, it is assumed that the rock does

not break apart in its fall.

4) 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.
5) 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 disk shaped or cylindrical rocks.
6) Only variations in the slope angle that decrease the slope angle are used, because this situation tends towards the worst case.

CRSP Algorithm

By assigning the rock nominal initial horizontal and vertical velocity components, a rockfall simulation begins within a selected vertical zone representing the source location. 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 (V_1), impact angle (α), and rotational velocity (W_1) 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 (θmax). 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 seen by the rock on impact. Surface roughness (S) and rock radius (R) are used in calculating

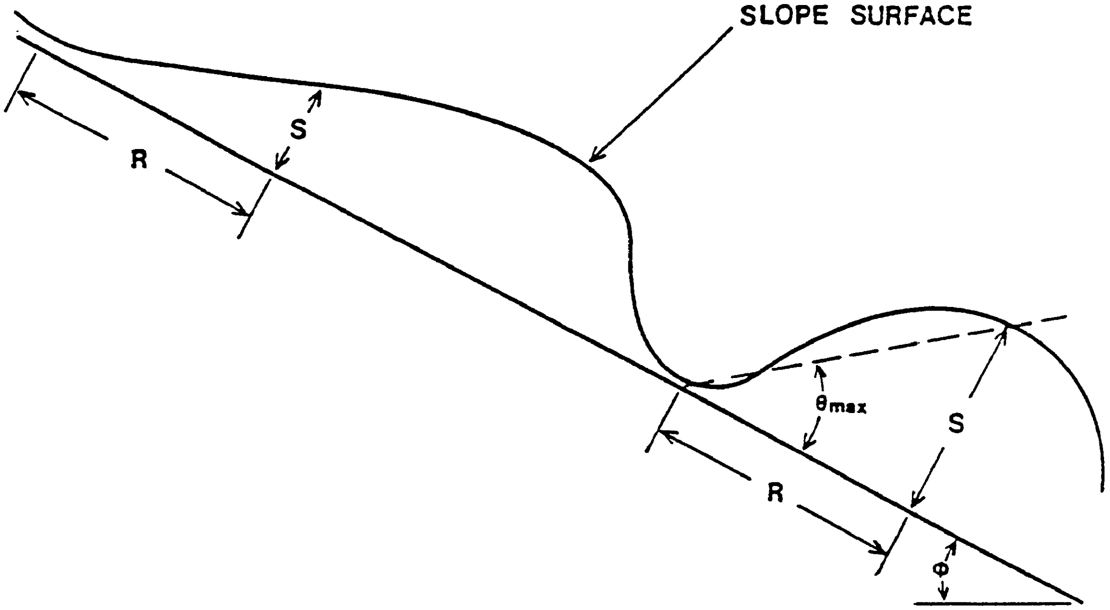

Figure 2: Surface roughness (S) established as the perpendicular variation within a slope distance equal to the radius of the rock (R). Maximum slope variation (θmax) defined by S and R.

the maximum allowable variation in slope angle (Θmax) by:

$$\text{max} = \tan^{-1}(S/R) \qquad \text{Eq. 1}$$

The angle of variation (Θ) is a randomly selected angle, less than max, that determines the variation in the slope angle (Φ). This random variation is largely responsible for the statistical variation of rockfalls modeled by CRSP. The impact angle (α), is used to resolve the incoming velocity (V_1) into velocity components tangential ($Vt_1=V_1\cos\alpha$) and normal ($Vn_1=V_1\sin\alpha$) to the slope surface (Figure 1).

A new tangential velocity is calculated from the conservation of energy considerations in the following equation:

$$\left(\tfrac{1}{2}IW_1^2 + \tfrac{1}{2}MVt_1^2\right) f(F)\ SF = \tfrac{1}{2}IW_2^2 + \tfrac{1}{2}MVt_2^2 \qquad \text{Eq. 2.1}$$

where:

M = rock mass

I = rock moment of inertia

$I = 2MR^2/5$ (sphere)

$I = MR^2/2$ (disk)

$I = MR^2/4 + ML^2/12$ (cylinder L = length)

W_1 = initial rotational velocity

W_2 = final rotational velocity

Vt_1 = initial tangential velocity

Vt_2 = final tangential velocity

$f(F)$ = friction function

$= Rt+(1-Rt)/\{[(Vt_1-W_1R)/20]^2+1.2\}$

SF = scaling factor

$= Rt/\{[Vn_1/(250Rn)]^2+1\}$

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, quantified 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 difference between the velocity at the surface of the rock relative to the ground at the start of the impact. A graph of the friction function is shown in Figure 3.

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 2.1 may be solved for new tangential and rotational velocities by establishing the following

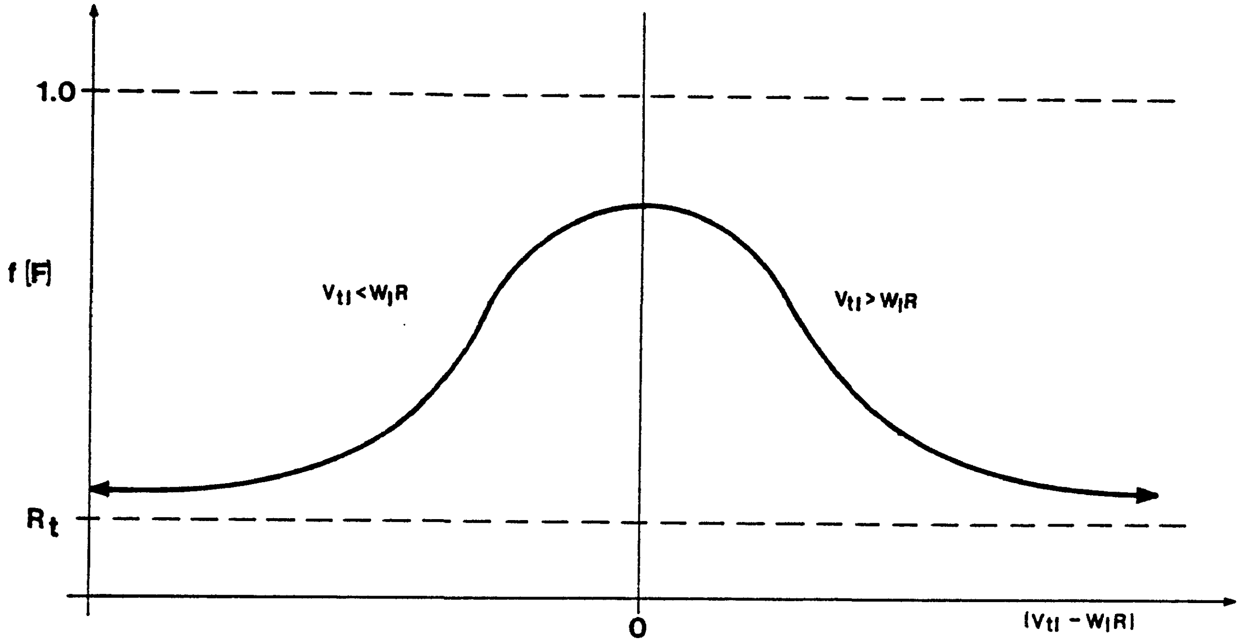

Figure 3: Friction function $f(Rt, Vt_1 - W_1R)$ as a function of the difference between tangential and rotational velocities.

relationship between rotational velocity and tangential velocity:

$$Vt_2 = W_2R \qquad \text{Eq. 2.2}$$

This equation 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 2.2 allows rotational energy to be converted to tangential energy, or tangential energy to be converted to rotational energy. 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 2.1 for the new tangential velocity yields the following equation:

$$Vt_2 = \sqrt{\frac{R^2 (IW_1^2 + MVt_1^2) f(F) SF}{I + MR^2}} \qquad \text{Eq. 2.3}$$

A new normal velocity (Vn_2) is established by the following equation:

$$Vn_2 = \frac{Vn_1 \ Rn}{1 + (Vn_1/30)^2} \qquad \text{Eq. 3}$$

This equation uses the normal coefficient of restitution (Rn) and a velocity dependent scaling factor ($1/(1+Vn_1/30)^2$) to determine the new normal velocity (Vn_2).

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, an iteration is used to find the time elapsed until the next bounce. Elapsed time is calculated from the x,y velocities, gravitational

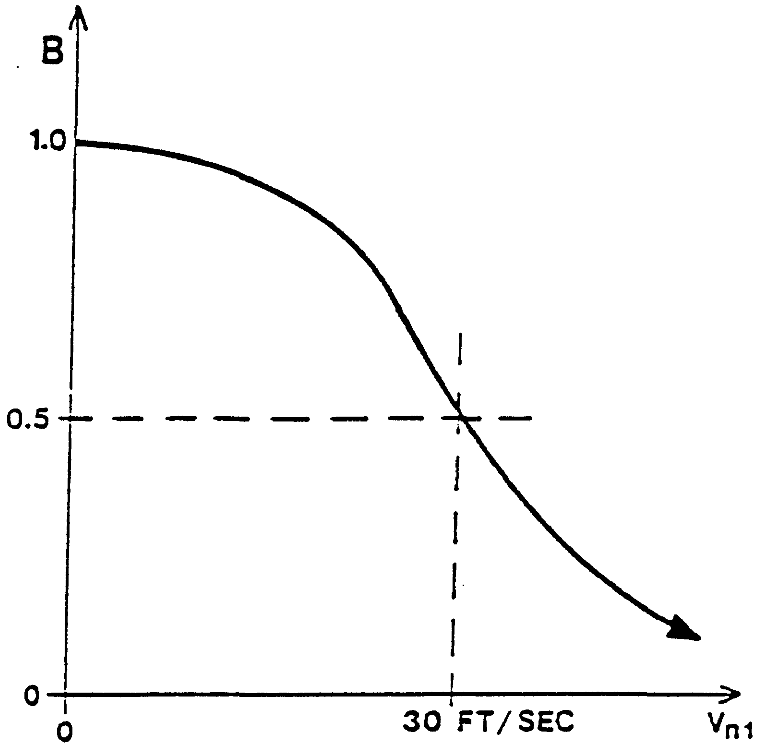

Figure 4: Normal coefficient scaling factor $B = 1/(1+(Vn_1/30)^2)$ as a function of the incoming normal velocity.

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. The effects of the input parameters on both bounce height and velocity predictions often vary because of changes in other input parameters. For example, the effect of surface roughness and surface material coefficients decreases on steeper slopes because the rock bounces less often. Sensitivity to the input parameters was investigated by varying input parameters for idealized situations and recording the effects on the predicted velocity and bounce height values.

As expected, slope angle is an important factor in determining the behavior of rockfalls. Rockfalls will increase in velocity up to an equilibrium velocity where the energy lost in the bounce equals the energy gained since the previous bounce. The relationship between slope angle and equilibrium velocity for various surface roughness conditions is shown in Figure 5. (Figures 5 through 10 appear starting on page 30 because they are used together.) For example, CRSP predicts an average equilibrium velocity for long 35° slopes of between 25 ft/sec and 65 ft/sec depending on surface roughness and rock size. Bounce height will also tend to reach an equilibrium height on long slopes. The relationship between slope angle and bounce height is shown in Figure 6.

Also very important in determining rockfall behavior is surface roughness, because it is used in determining the impact angle. The ratio of the surface roughness to rock size (S/R) is used to determine the maximum variation in the slope (Equation 1); therefore, the effect of surface roughness must be studied by investigating the effect of S/R. An increase in the S/R ratio will generally result in a decrease in velocity and an increase in bounce height on slopes over 45°, but on shallower slopes the decrease in velocity with increasing S/R results in a decrease in bounce height. Graphs illustrating these relationships may be found in Figures 5 and 6.

Material coefficients affect rockfall behavior by determining the amount of energy absorbed during impact; higher coefficient values result in less energy loss during impact. Because material coefficients act only on impact, their effect on bounce height and velocity depends on the number of bounces. On steep slopes, where rocks impact the slope with less frequency, the effect of material coefficients on rockfall behavior becomes negligible. The effect of the coefficients on rockfall behavior is greatest for gradual slopes, where the rockfall velocity is decreasing. On most slopes, changes in material coefficients, within reasonable limits for a specific slope material, will not produce a significant change in results. Simulation results from the West Rifle test site (discussed in the section on CRSP Verification and Calibration) showed that changing coefficients between reasonable limits resulted in only a 15% variation in maximum velocities.

Several factors act to reduce the effect of surface material on rockfall behavior. First, the effect of slope angle and surface roughness is so much greater than the effect of material properties that they obscure the results of changes in material coefficients. Second, the coefficients themselves are modified by factors (discussed in the section describing the algorithm) that tend to further obscure the results of changes in coefficients. Most important of these factors is the velocity normal to the slope at impact. This velocity depends on the impact angle, which is determined by the slope angle, rock radius, and surface roughness. For these reasons, the effect of changes in material coefficients depends largely on the slope configuration. Therefore, the recommended method of determining the sensitivity to changes in material coefficients is to test the effect of coefficient changes at a specific site by varying the input.

Use of Graphs for Estimating Rockfall Bounce Height and Velocity

Graphs showing the sensitivity of CRSP results to changes in the input parameters may be used to make estimates of probable rockfall bounce heights and velocities for uniform slopes and runout zones. Cases with changes in slope angle are too complex for estimates using graphs of velocity and bounce height verses slope angle and S/R ratio. The advantage to using the graphs for simple slopes is that changes in parameters may be quickly evaluated. These graphs also provide a basis for developing a conceptual understanding of the relationships between the input parameters.

The average rockfall equilibrium velocity from the graph in Figure 5 is the average velocity predicted by CRSP after the equilibrium condition is reached). The maximum equilibrium velocity predicted is the velocity of the fastest rock. The graph in Figure 5 is limited to slopes between 30° and 60°. On slopes greater than about 60° the energy lost during the bounce will always be less than the energy gained between bounces, and on slopes of less than about 30° the velocity will decrease until the rock comes to rest. Surface material will have a small effect on the equilibrium velocity. Figure 5 was developed for hard, (rocky slopes. The equilibrium velocity for softer soil slopes of less than about 40° will be about 15% less than predicted by the graph in Figure 5. On slopes steeper than 50° the effect of surface material will be negligible.

The average and maximum equilibrium velocities may be obtained from the graph in Figure 5 for a given slope angle and S/R ratio. For slopes shorter than 300 to 500 feet, the rockfall may not reach the equilibrium condition. In this case the average and maximum velocities may be obtained by multiplying the velocity from Figure 5 by the distance factor obtained for the slope length and angle in Figure 7. (These products are an estimate of the velocities (that would be predicted by CRSP) for uniform slopes.

Rockfall bounce heights behave in a manner similar to velocity. At slope angles below about 45°, rough slopes

(S/R > 1), tend to result in lower bounce heights, but at steeper slope angles the rougher slopes will tend to generate higher bounce heights as shown in Figure 6. This graph may be used to estimate the average and maximum bounce heights for uniform slopes. The bounce height values obtained from the graph in Figure 6 may be corrected for slope length by multiplying by the distance factor obtained from Figure 7.

In addition to velocity and bounce height data for slopes, velocities for the runout zone below the slope may be of interest. An estimate of rockfall velocity in the runout zone may be obtained from the nomograms in Figures 8 and 9, if initial velocity is between 20 and 50 ft/sec. The procedure for estimating rockfall velocities in the runout zone entails the following steps:

1) Estimate the average velocity on the slope from Figures 5 and 6.
2) Estimate the initial velocity within the runout zone using Figure 10. The change in the slope angle at the start of the runout zone results in an increase in the impact angle and, consequently, a reduction in velocity. To obtain the initial velocity in the runout zone, multiply the velocity from step one by the V_2/V_1 value from Figure 10, corresponding to the appropriate

change in slope and slope velocity.

3) To obtain the velocity at a given distance into the runout zone, start with the right side of the nomogram in Figure 8. Find the unadjusted distance on the left side of the nomogram by passing a line through the point in the center corresponding to the appropriate surface conditions in the runout zone.
4) Using the nomogram in Figure 9, pass a line from the unadjusted distance on the right side through the point on the center graph corresponding to the appropriate values of the runout slope angle and the S/R ratio. On the graph at the left side of the nomogram where the projection line crosses the curve corresponding to the initial velocity, the remaining velocity factor is obtained. By multiplying the initial velocity value times this factor the estimated velocity may be obtained for the chosen distance.

The use of this method is restricted to distances where the velocity in the runout zone will fall between 25% and 75% of the initial velocity. It is also restricted to use on slopes between -15° upward and +15° downward. To find the average distance the rocks will travel in the runout zone, start at the left side of the nomogram in Figure 9, where the 0.25 factor crosses the initial velocity and work back through the nomogram to the unadjusted distance. Adjust this distance using Figure 8 and multiply the adjusted distance by 1.3 to produces an estimate of the average distance rockfalls will travel in the runout zone.

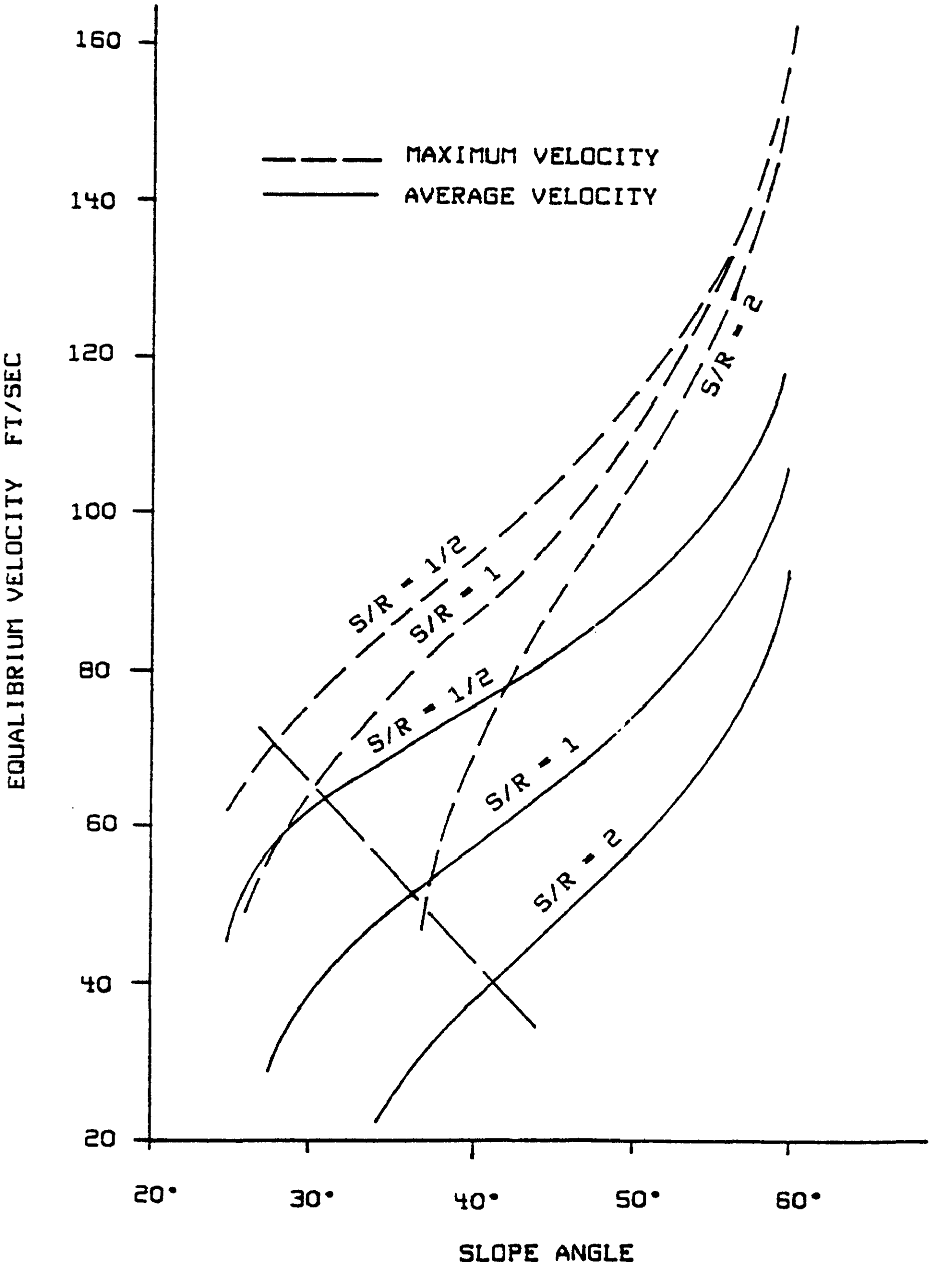

Figure 5: Maximum and average equilibrium velocity verses slope angle for uniform slopes.

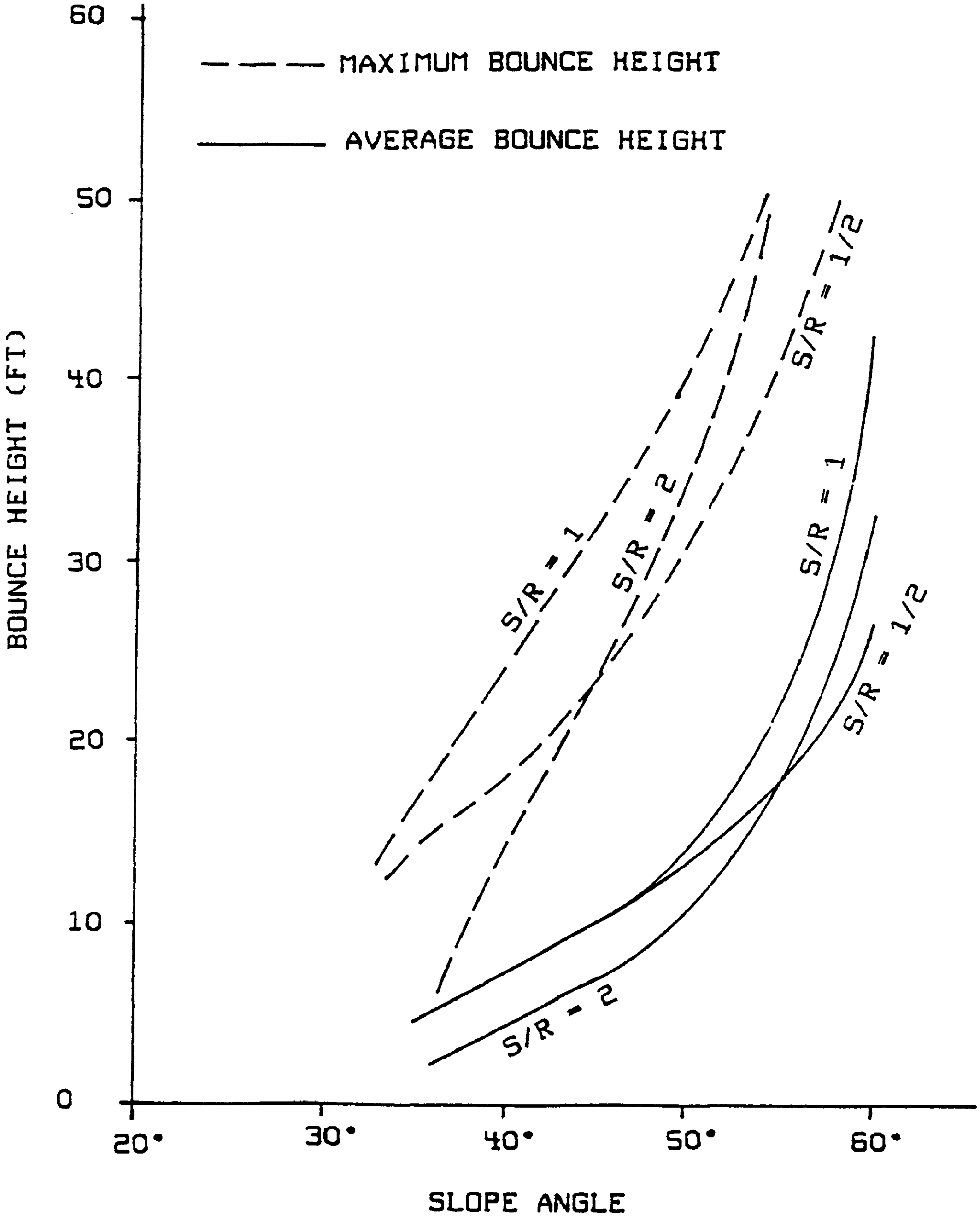

Figure 6: Maximum and average equilibrium bounce heights verses slope angle.

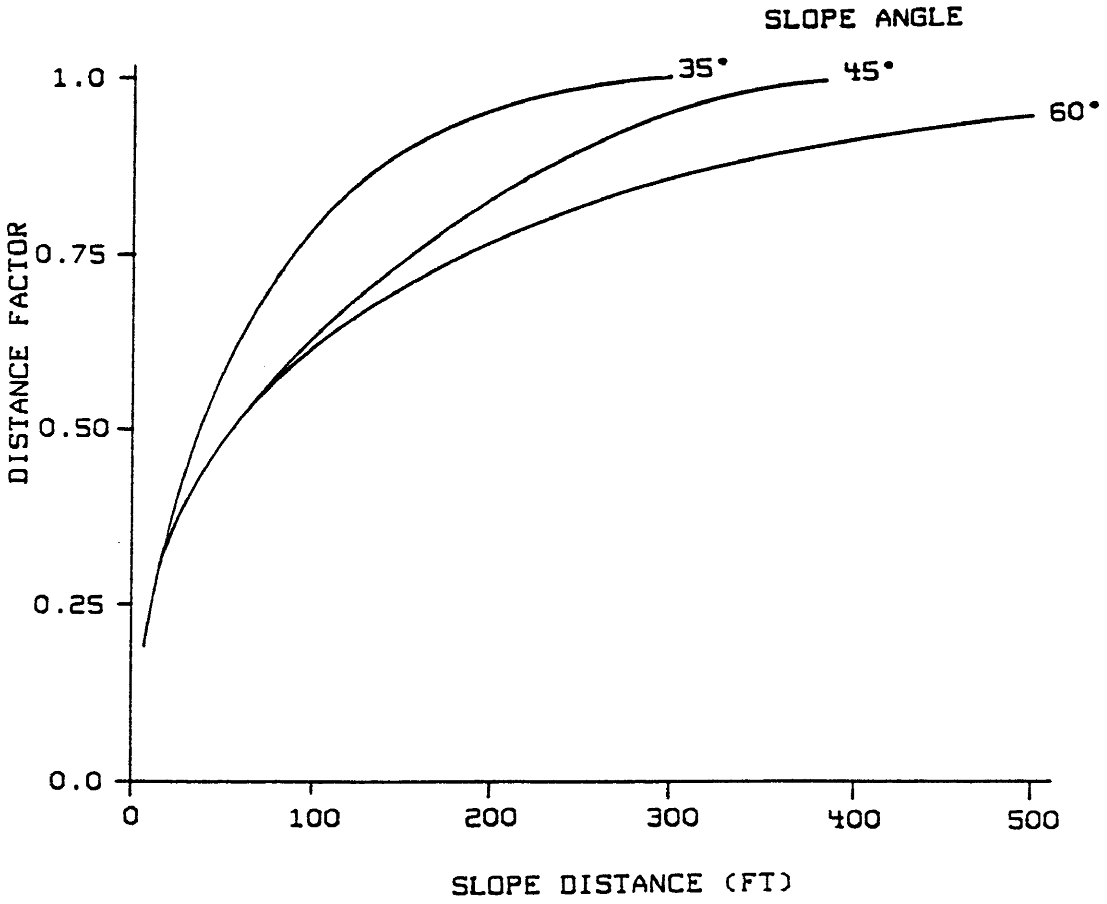

Figure 7: Distance factor indicating the proportion of the equilibrium velocity achieved verseshorizontal slope distance.

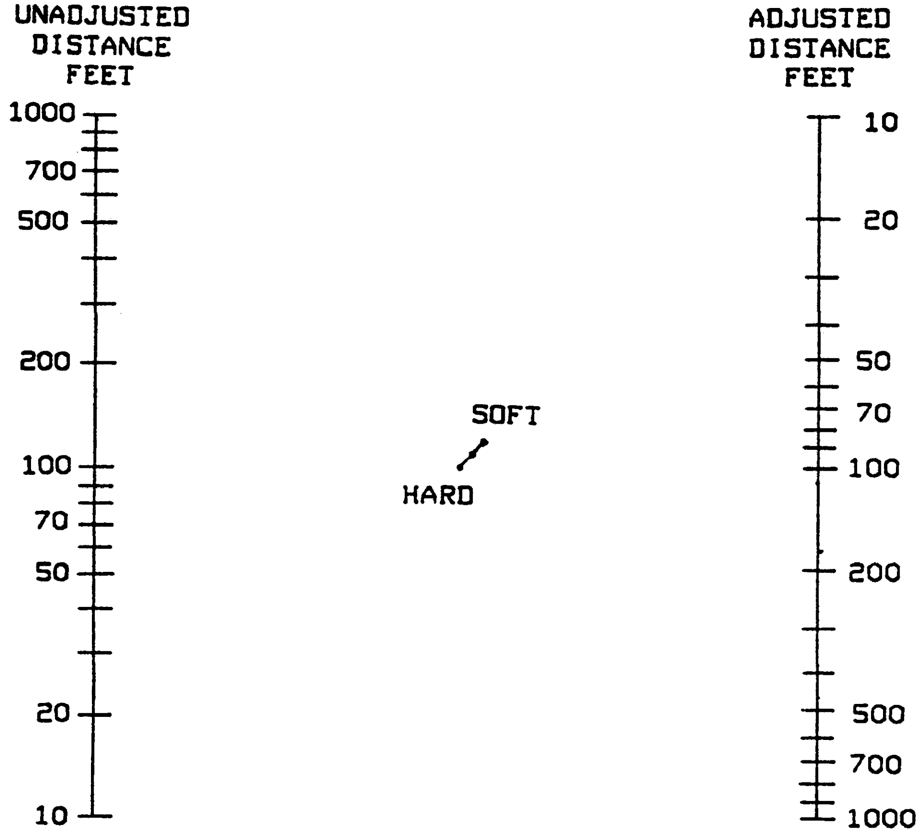

Figure 8: Nomogram for adjusting runout distance for surface material properties.

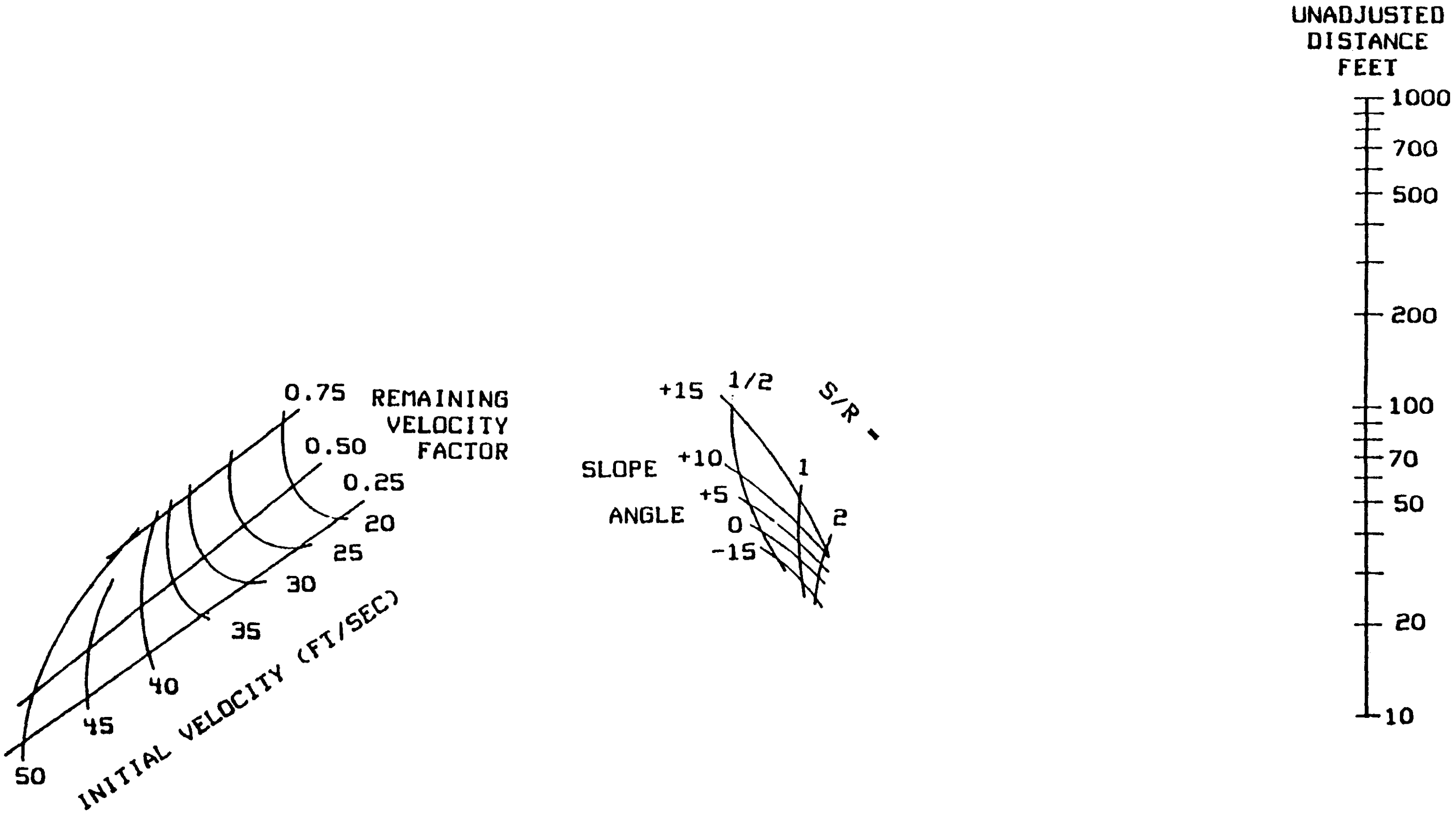

Figure 9: Nomogram for finding runout distances and velocities on slopes between -15° downward and +15° upward for rocks with initial velocities between 25 and 50 ft/sec.

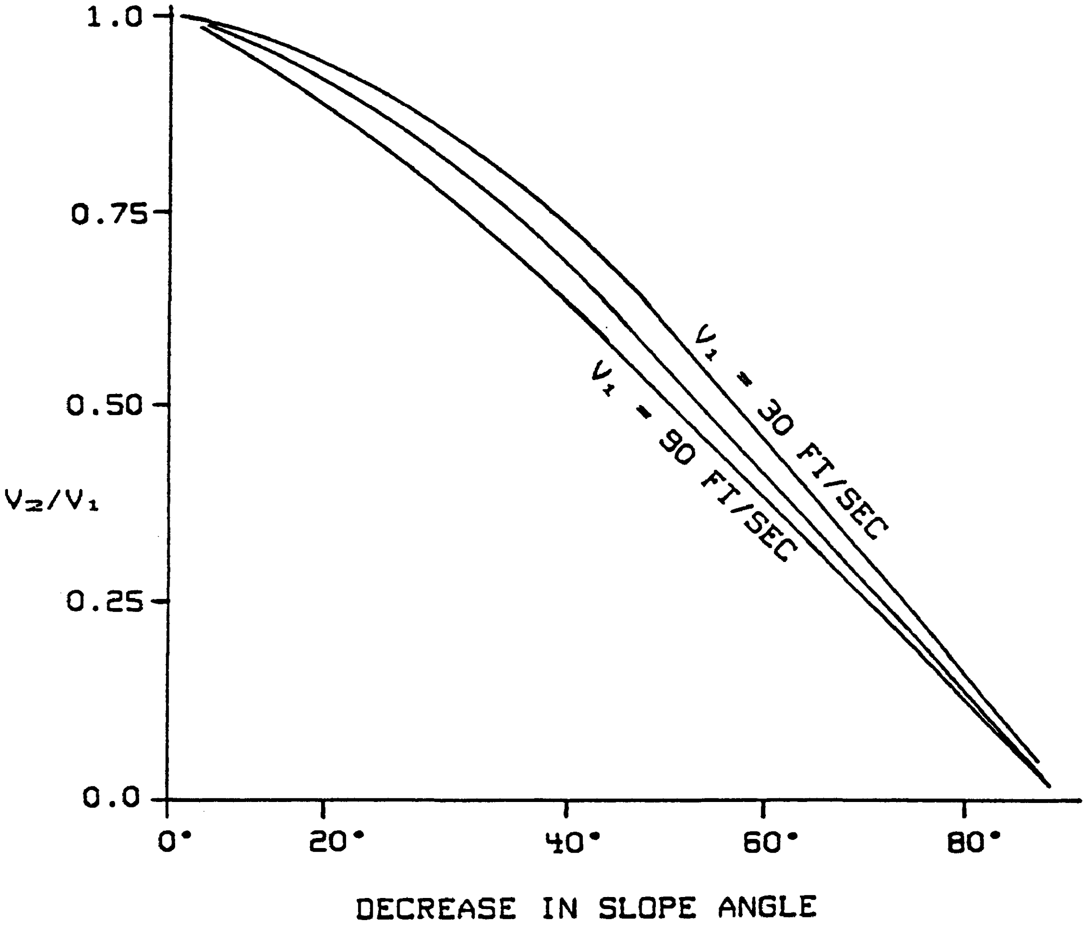

Figure 10: Change in velocity verses decrease in slope angle.

CRSP VERIFICATION AND CALIBRATION

West Rifle Test Site

In order to test rockfall fence designs and collect data on rockfalls for verification and calibration of CRSP, rocks were rolled down a 300 foot high hillside near Rifle, Colorado. The test hillside consisted of thin desert soil with rocky ledges (Figure 11). The very sparse vegetation visibly had little effect on the behavior of the rockfalls.

All of the rockfalls were initiated from the same point, but the topography of the upper slope resulted in a wide dispersion. Data could only be obtained for the rocks that traveled down the most direct path to the gully on the lower part of the slope. Two slope profiles were constructed representing possible paths that the rocks could take. For the comparison between the experimental results and simulation results, the slope profile that produced the worst case values was used. Figure 12 shows the slope profile used for this site. From videotapes of the rockfalls, the time for each rock to travel through two sections of the hillside was collected. These data were

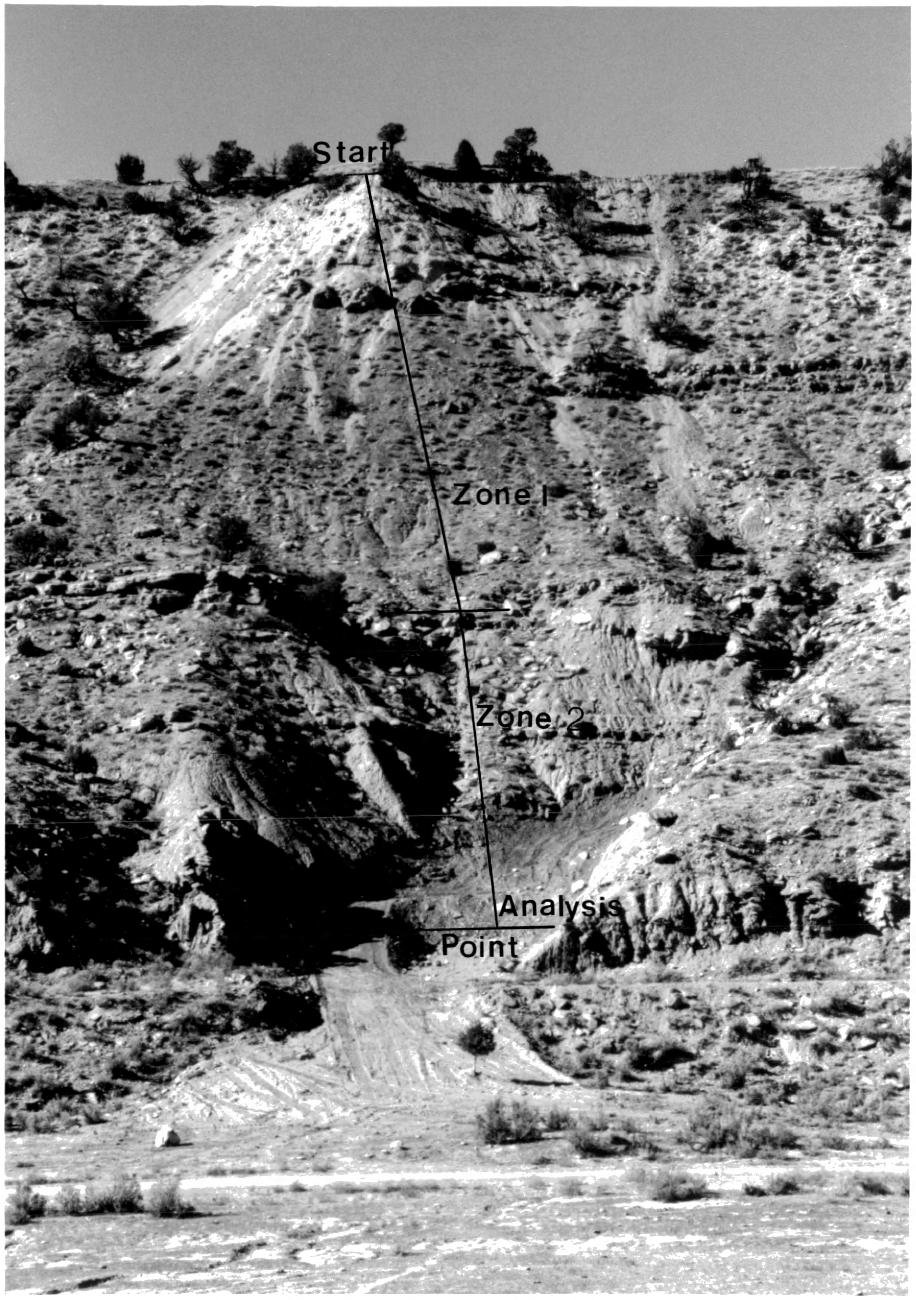

Figure 11: Slope used for CRSP testing near Rifle, Colorado.

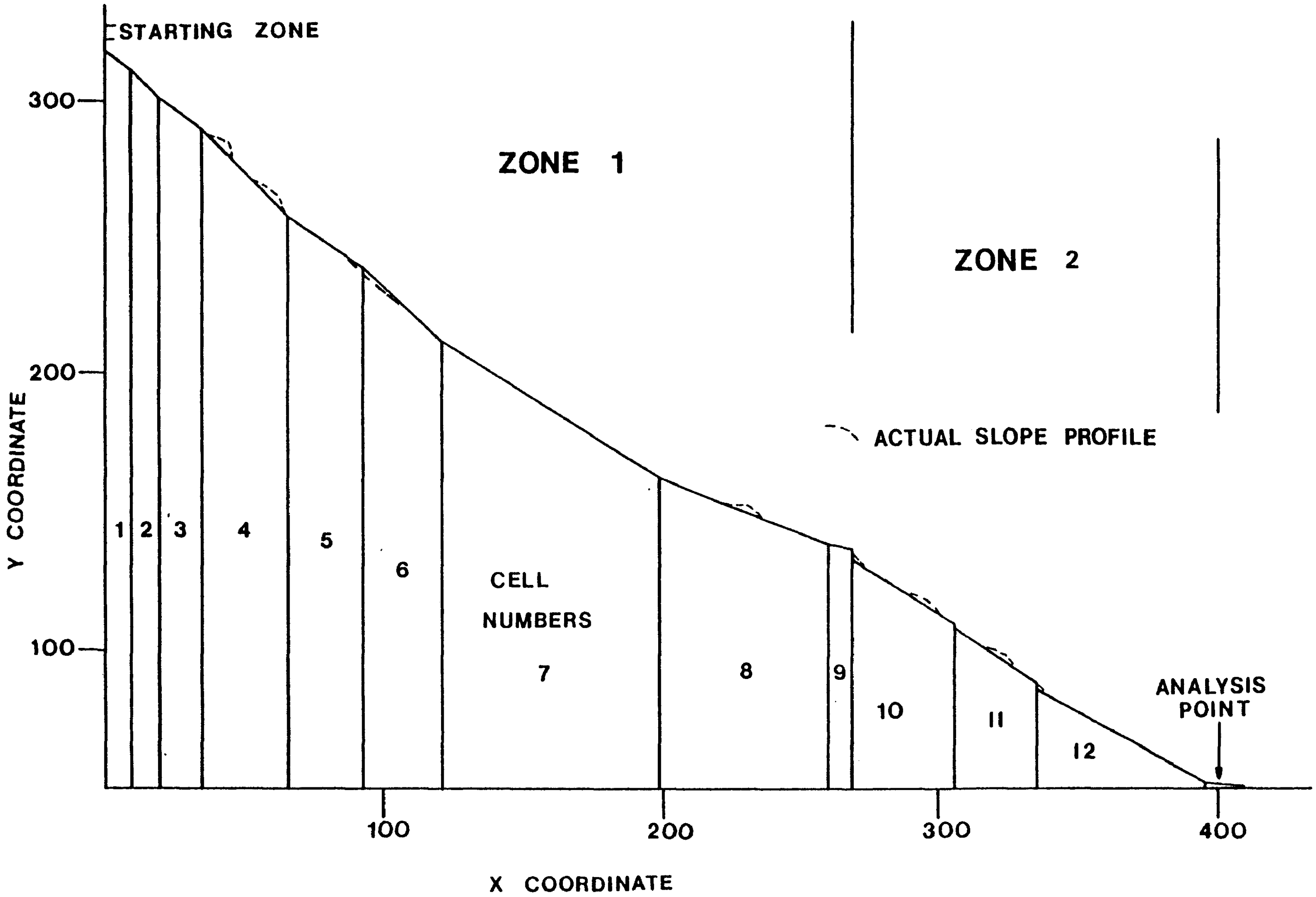

Figure 12: Slope profile of West Rifle test site.

compared to data generated by CRSP, which was modified to present data on the time it takes for the rock to traverse the same sections of the slope.

Videotapes of the rocks traveling down the slope were used to collect data on rockfall behavior. Test data obtained at the West Rifle test site were used to establish the constants used in the bounce calculation equations. Before incorporating the test data, CRSP predicted a maximum bounce height of 12 ft and a maximum velocity of 78 ft./sec. near the base of the slope. Testing indicated that in this case the bounce height prediction was very close, but the measured velocity was higher. The experimental data was used to adjust the constants used in the friction function and scaling factors until the simulation data fit with the experimental values for travel time, number of bounces and bounce height.

Cell input values were chosen according to the guidelines presented in the section on field data collection. The input values presented in Table 2 were used to produce the statistics for the comparison in Table 3. Because CRSP attempts to represent worst case situations, only data from the fastest 50% of the rocks rolled were used in the comparison. The CRSP values shown represent the

Table 2: Input values used in the West Rifle simulations.

CELL #	SURFACE ROUGHNESS	TANGENTIAL COEFFICIENT	NORMAL COEFFICIENT	BEGIN X,Y	END X,Y
1	0.4	0.82	0.25	0,320	8,314
2	0.6	0.84	0.32	8,314	18,304
3	0.8	0.84	0.32	18,304	34,290
4	2.0	0.84	0.32	34,290	66,258
5	0.8	0.84	0.30	66,258	92,240
6	0.8	0.84	0.30	92,240	120,214
7	0.8	0.83	0.30	120,214	199,164
8	1.0	0.82	0.33	199,164	260,140
9	0.8	0.82	0.33	260,140	269,138
10	1.4	0.84	0.34	269,133	305,110
11	1.2	0.84	0.34	305,108	335,90
12	0.8	0.84	0.34	335,87	396,51
13	0.4	0.85	0.34	396,51	410,49

Table 3: Comparison of field data from the West Rifle test site with data generated by CRSP.

	ZONE 1		ZONE 2		ANALYSIS POINT
	TIME SEC.	# OF BOUNCES	TIME SEC.	# OF BOUNCES	BOUNCE HEIGHT
FIELD DATA					
SAMPLE SIZE	(23)	(21)	(19)	(18)	(17)
AVERAGE	8.72	12.6	2.58	2.0	2.53
RANGE	7.8-9.8	10-16	2.2-2.9	1-4	0-11
STANDARD DEVIATION	.61	1.43	.23	.88	3.36
CRSP DATA					
AVERAGE	8.40	12.6	2.62	1.5	2.45
RANGE	7.8-10.5	10-16	2.2-3.4	1-3	0-11
STANDARD DEVIATION	.95	1.85	.38	.64	2.43

simulation values produced after calibration of the constants used in the bounce calculations.

The effect of varying the input parameters on rockfall velocity and bounce height at the analysis point is shown in Table 4. The input values from Table 2 were varied for the sensitivity analysis. Spherical rocks with a 2.2 ft radius were used for all of the simulations except for the rock size comparison tests. For this comparison, surface roughness values were changed to be appropriate for the rock size indicated. The combined effect of changes in surface roughness and rock size is responsible for the inconsistent influence of rock size on maximum velocity.

Because these simulation results were produced from input data collected with unusual care, simulation data for other sites could not be expected to be as comparable to the actual rockfalls, but note that similar conclusions may be reached by using any of the simulation results in Table 4. One conclusion that could be reached from the simulation results that agrees with observations of the testing is that any protective structures should be located at least 30 feet from the base of the slope where the bounce heights are lower. Even if CRSP simulation data does not closely agree with the actual rockfalls at a site, the simulation data may

Table 4: Effect of changes in input values on CRSP results at the analysis point.

	MAXIMUM VELOCITY FT/SEC	AVERAGE VELOCITY FT/SEC	MAXIMUM BOUNCE HEIGHT	AVERAGE BOUNCE HEIGHT
TABLE 2 VALUES	92	65	11	2
COEFFICIENTS				
NORMAL + .02	96	66	10	3
NORMAL - .02	78	62	8	2
TANGENTIAL + .02	94	66	14	2
TANGENTIAL - .02	92	64	9	2
SURFACE ROUGHNESS				
+ .2 FT	93	60	13	2
- .2 FT	96	70	10	2
ROCK RADIUS				
1.0 FT	93	60	12	3
1.5 FT	80	61	13	2
2.0 FT	80	63	12	2
2.5 FT	97	68	10	2

still help the investigator come to proper conclusions. A complete printout of the West Rifle simulation results is presented in Appendix B.

The graphs in Figures 5 and 6 may be used to obtain reasonable velocity estimates for the upper seven cells. If a uniform slope is assumed for the upper portion of the West Rifle test site, then by using the graphs in Figures 5 and 6, an average velocity of 59 ft/sec is obtained, whereas the simulation program yields a value of 57 ft/sec. Because of irregularities on the lower slope at the test site, these graphs do not apply for estimating velocity at the base of the slope.

CRSP Comparisons

In an effort to ascertain 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 ditch design criteria (Ritchie, 1963). Slope profiles of the slopes used for comparison with CALTRANS field trials are shown in Figure 13. Table 5 shows a comparison between data obtained in field trials by CALTRANS and CRSP simulation using slope descriptions provided by CALTRANS. CRSP predictions tend more toward a worst case than do the field tests, but the overall conclusions were similar. CRSP simulation results for rocks falling into ditches designed according to Ritchie's criteria are shown in Table 6. CRSP results predict the effectiveness of the ditches with a few exceptions. While Ritchie's study does not specifically address the effect of rock size on the effectiveness of the recommended ditches, CRSP predicts that the effectiveness of a 1 1/4 H : 1 V backsloped ditch is reduced for large rocks rolling down slopes less than about 50°.

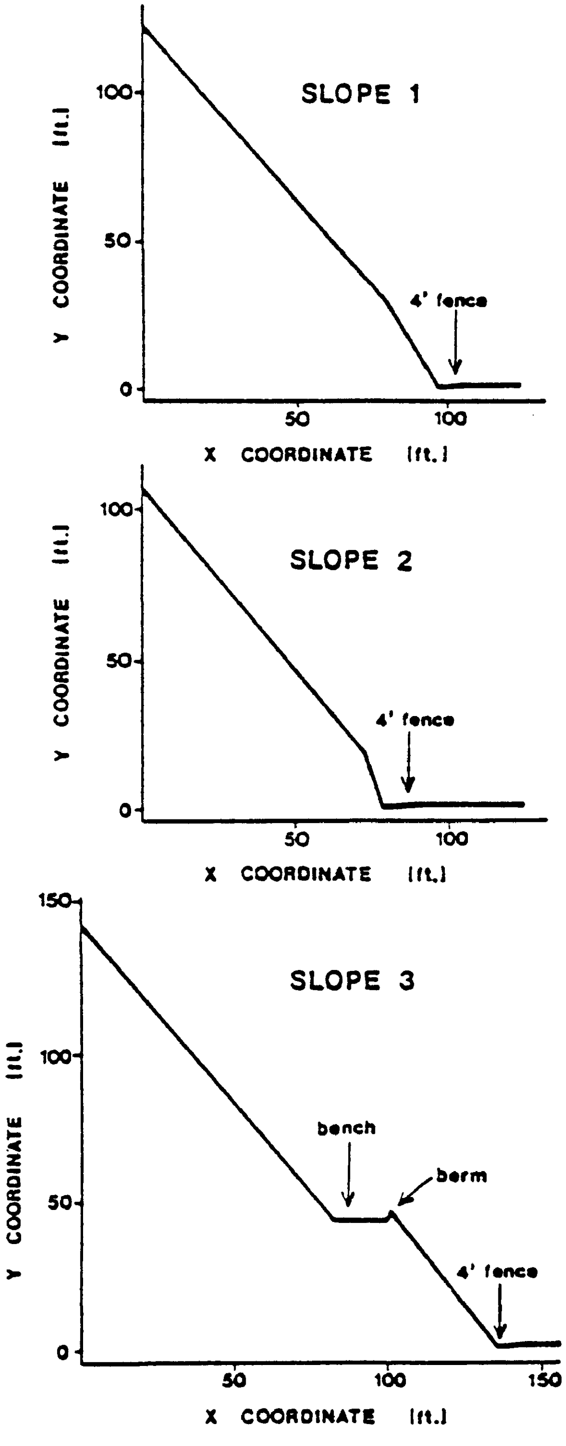

Figure 13: Slope profiles drawn from data gathered by the California Department of Transportation.

Table 5: Comparison of California Department of Transportation test results with CRSP statistical data for the slopes in Figure 13.

CALIFORNIA DEPARTMENT OF TRANSPORTATION TEST ROLL	CRSP MODEL
SLOPE 1	
8 ROCKS .52-1.41 FT. DIAMETER	100 SPHERICAL ROCKS 1 FT. DIAMETER
2 rocks (25%) over 4′ fence.	25 rocks (25%) over fence (5′ maximum bounce height).
All rocks going over the fence roll into the roadway.	All rocks impact the shoulder and roll onto the roadway.
10.5′ maximum impact distance from toe of slope.	10′ maximum impact distance from toe of slope.
Conclusion: Fence should be 10′ from slope.	Conclusion: Fence should be 10′ from slope. Avoid paved shoulder.
SLOPE 2	
10 ROCKS .38-1.02 FT. DIAMETER	100 SPHERICAL ROCKS 1 FT. DIAMETER
7 rocks (70%) over 4′ fence.	75 rocks (75%) over 4′ fence (9′ maximum bounce height).
5 rocks (50%) into roadway.	70 rocks (70%) into roadway.
12′ impact from toe of slope. slope.	10′ impact from toe of
Conclusion: Fence should be 10′ from slope.	Conclusion: Fence should be 10′ from toe of slope.

Table 5: (Continued)

SLOPE 3

20 ROCKS .7-1.24 FT. DIAMETER	100 SPHERICAL ROCKS 1.2 FT. DIAMETER
13 rocks (65%) stopped by berm.	27 rocks (27%) stopped by berm.
2 rocks (10%) over 4′ fence.	16 rocks (16%) over fence (25% of rocks passing over berm). 30′ maximum bounce height at fence. 9′ maximum bounce height at edge of roadway.
Conclusion: Place fence on bench. 4′ fence at grade will not stop all the rocks.	Conclusion: Place fence on bench. An impractical 10′ fence at the edge of roadway would be required to stop all the rocks. A 6′ fence located 3′ from the toe of the slope would stop 95% or more of the rocks from the berm or above.

Table 6: Comparison of CRSP results with Ritchie′s Catch ditch design.

SLOPE	RITCHIE DITCH DESIGN CRITERIA WIDTH	DEPTH	CRSP PREDICTION % STOPPING BEFORE ROADWAY
1/10:1	20′	4′	90%
1/4:1	25′	6′	89%
1/2:1	25′	8′	100%
3/4:1	15′	6′	93%
1:1	15′	6′	99%
	(4′ DIAMETER ROCK)		26%

(2′ DIAMETER ROCK USED EXCEPT AS NOTED)

FIELD DATA COLLECTION

Identification of Rockfall Hazards

Since rockfall hazard investigations are usually 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, a good way to begin the identification of hazard areas may be by examining accident records or talking to maintenance personnel. This often provides good information on where and how often dangerous rockfalls occur. Location of rockfall hazard areas may also be done by looking for evidence of recent rockfalls. While a single rock falling from a cliff may not leave an identifiable scar, most rockfalls 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. Often rockfall areas will coincide with other hazards such as debris flows and snow avalanches.)

(After locating rockfall hazard areas and before proceeding with data collection for CRSP analysis), some preliminary assessment of the site may simplify the investigation. If the budget only allows for placing "WATCH FOR FALLING ROCKS" signs, then a more thorough investigation is probably not warranted. If lives or expensive structures are at risk, then CRSP analysis of the site may be used as a tool for planning cost effective rockfall mitigation.

CRSP Input Data Collection

Input data for CRSP consists of rock size, surface roughness of the slope, coefficients representing the materials in the slope and coordinates of the cells defining the slope profile. Selection of input parameters begins with identification of the rockfall path between the source area and 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. This profile may be obtained from surveying the slope or detailed 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 may 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 may be done safely. If the rockfall path is not accessible, then the data may need 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 input parameters. The data forms in Appendix A 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.

1) Rock Size Determination

The size of the rocks involved in rockfalls depends on the size of blocks in the source area and on the durability of the rocks. While it is conceivable that a rock that 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 may make a good choice for rock size. If no rocks are available at the base of the path, then a rock size may be determined from the size of blocks found in the source area. The rock size or sizes selected will be used later for determination of surface roughness.

(2) Cell Boundary Selection

Cell boundaries are used to define the slope profile and areas of uniform slope characteristics. Cells are input into CRSP as the X,Y coordinates of the end points and may have any slope, but the beginning X coordinate must equal the ending X coordinate of the proceeding cell and the beginning Y coordinate must be less than or equal to the ending Y coordinate of the proceeding cell. This allows vertical zones representing cliffs between cells.

Cell boundaries are selected where changes in slope occur 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 makes 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. 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.)

(3) 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 theory. Surface roughness is an estimation of how much the slope angle may vary within the radius of the rock (Figure 2). The beginning rockfall investigator may want to take some measurements of surface roughness. This may be done by stretching a string down the slope and measuring the distance to the slope perpendicular to the string. The variation of this measurement, within the rock radius, 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. 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.

4) Tangential Coefficient

The tangential coefficient of friction 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, influences the tangential coefficient. A range of probable values should be selected (for each cell for use in a sensitivity analysis of the slope). Table 7 shows suggested values for various slope materials.

Tangential coefficient values for slopes with vegetation more than a few feet tall is difficult to assess, because, while the coefficient for an individual rock may be low, the first rocks down the hill clear a path for the next rocks in the rockfall.

Table 7: Suggested tangential coefficient input values.

Tangential Coefficient Rt	Description of slope
0.87 - 0.92	Smooth hard surfaces such as pavement or smooth bedrock surfaces.
0.83 - 0.87	Most bedrock surfaces and talus with no vegetation.
0.82 - 0.85	Most talus slopes with some low vegetation.
0.80 - 0.83	Vegetated talus slopes and soil slopes with scarce vegetation.
0.78 - 0.82	Brush covered soil slope.

5) Normal Coefficient

The normal coefficient of restitution is a measure of the change in the velocity normal to the slope before impact compared to the normal velocity after impact. The normal coefficient is determined by the rigidity of the slope surface. Table 8 lists ranges of suggested values for different materials.

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

Table 8: Suggested normal coefficient input values.

Normal Coefficient Rn	Description of slope
0.37 - 0.42	Smooth hard surfaces and paving.
0.33 - 0.37	Most bedrock and boulder fields.
0.30 - 0.33	Talus and firm soil slopes.
0.28 - 0.30	Soft soil slopes.

ENTERING DATA AND RUNNING CRSP

Data File Construction

Before constructing the input data file, it is convenient to arrange the field data into the following form to simplify data entry:

1) Set up the slope profile on a cartesian coordinate system with the starting zone at X=0. The Y coordinates may start and end at any positive value. Elevation above sea level is often a convenient Y coordinate.
2) Number the cells from left to right and select coordinates for the end point of each cell.
3) CRSP provides a detailed statistical analysis of the rockfall for one analysis point on the slope. This point is usually chosen at the position where mitigation is being considered.
4) A vertical zone from which the rockfall simulation is initiated is selected on the Y axis.
5) CRSP reads all of the coordinate data as integers.

CRSP requires an input file containing the field data. This file contains the slope profile and cell data. The data file can be constructed using the program ROCKDATA or any file construction program that creates ASCII files. The data file must be in the required form shown below:

line 1
Cn,Xan,Y1,Y2
Cn = number of cells used in the simulation
Xan = X coordinate of the analysis point
Y1 = Y coordinate of the base of the starting zone
Y2 = Y coordinate of the top of the starting zone
line 2
C#,SR,Rt,Rn,Xs,Ys,Xe,Ye
C# = cell number
SR = surface roughness in feet
Rt = tangential coefficient
Rn = normal coefficient
Xs = X coordinate of the start of the cell
Ys = Y coordinate of the start of the cell
Xe = X coordinate of the end of the cell
Ye = Y coordinate of the end of the cell
Repeat line 2 for each cell

ROCKDATA simplifies the data entry by asking the user for the data and performing some simple checks to see if the data being entered is possible. ROCKDATA is an executable program which may be started by entering ROCKDATA <R>. A question will appear asking for the name of the file you wish to create. The data entry process using rockdata is shown below.

```
ROCKDATA <R>
FILE NAME ?
RKDATA.EXT <R>  (Enter data file name)
C#,Xan,Y1,Y2 ?
(Enter data separated by commas) <R>
C#,SR,Rt,Rn,Xs,Ys,Xe,Ye ?
(Enter data separated by commas) <R>
```

The program will automatically terminate and return you to the system when data entry is complete.

Running CRSP

Two versions of CRSP are available. CRSP prints data on a printer and CRSPSCR prints the same data on the screen. In all other ways the two programs are the same and only one set of instructions is needed. CRSP is an executable program and is started by entering CRSP <R> or CRSPSCR <R>. The program will display a message and ask for the data file name. The procedure for running CRSP is as follows:

```
CRSP <R>
```

ENTER FILE NAME ?

RKDATA.EXT <R>

(Enter data file name. If the data file is not located on the default drive then a drive will need to be specified)

CRSP ASSUMES THE FOLLOWING VALUES

100 SIMULATION ROCKS

SPHERICAL ROCKS AT 165 LB/CF

INITIAL X,Y VELOCITY = 1,-1 FT/SEC

DO YOU WISH TO CHANGE ANY OF THESE VALUES Y/N ?

If you respond **N <R>**

RADIUS OF ROCK ?

#. <R>

(Enter the radius of the rock in feet to be used in the simulation)

If you respond **Y <R>**

ENTER NUMBER OF SIMULATION ROCKS ?

<R>

(Enter the number of rocks to be used in the simulation)

ENTER INITIAL X,Y VELOCITY ?

VX,VY <R>

(Enter the starting velocities separated by a comma)

```
ENTER ROCK DENSITY IN LB/CF ?
### <R>
SELECT ROCK SHAPE
1=CYLINDER 2=DISK 3=SPHERE ?
# <R>
```

(Enter the number corresponding to the desired shape)

Enter the requested dimensions separated by a comma. The shape is used to determine the mass and moment of inertia of the rock. The moment of inertia defined for a cylinder is end for end rotation and the moment of inertia defined for a disk is for rolling like a wheel.

After entering the last of the data the program will print out the initial data to the default printer and display the slope profile on the screen. CRSPSCR will print the input data on the screen and pause until any key is pressed. The axes of the slope profile are marked with a short line every ten feet for scale. The cell numbers appear along the bottom of the screen if space permits and are designated on the slope profile by a vertical line extending down from the slope profiles. The analysis point is designated by a vertical line extending up from the slope profile. Dots will appear in characteristic parabolic arcs above the slope profile. Each dot represents the position of the simulation rocks every tenth of a second; therefore, the farther the dots are apart, the greater the velocity. A counter located near the top center of the screen displays the number of simulations completed. As the simulation progresses, the dots will form a speckled pattern above the slope profile representing the distribution of simulation rocks by position and time. Note that a gap in the pattern may appear at cell boundaries, this is because the program restarts the simulation at each cell boundary.

A hard copy of this display may be made using the MS-DOS utility program GRAPHICS, available with later versions of MS-DOS. GRAPHICS must be loaded from the MS-DOS disk before running CRSP. If this program has been loaded, then a printout of the graphic display may be made with a screen print (PrtSc).

After the simulation is completed the program will pause showing the graphic display. To continue execution of the program, press any key. A printout will be made of the data collected during the simulation. If the printer is set up with the IBM character set, bar graphs of velocity and bounce height distribution at the analysis point will be constructed. Also graphs of the maximum velocity and bounce heights versus the X position are displayed. These graphs and the tables provide statistical data on the expected velocity and bounce height for rockfalls at the site.

Data Interpretation

Before designing mitigation based on the results of a rockfall simulation, the investigator must decide on the accuracy of the results. The first test of accuracy is whether the results seem reasonable based on the investigator's experience and judgement. If the results do not seem reasonable or do not agree with observations at the site, then the input parameters should be re-examined for accuracy and the applicability of CRSP simulations reconsidered for the site in question. If the values seem reasonable, then additional simulations should be conducted using input values within a realistic range of values. In many cases, the simulation results will fall within a small range; however, if the range is large, then the investigator must use engineering judgement to decide on which value to use depending on the required conservativeness of the design.

The effectiveness of ditches and berms may be tested by running a simulation using the appropriate berm or ditch configuration. Small berms and steep backslopes may not work because of limited precision. CRSP data may be used to help locate rockfall fences by identifying areas where the bounce heights are minimal. Fences may be designed using the velocity and total kinetic energy at the fence location. <u>Remember that CRSP is a stochastic model; therefore, the statistics, not the actual bounce positions and trajectories, should be used for design.</u>

EXAMPLE

In March, 1985 rockfall events damaged portions of two retaining walls under construction on I-70 in Glenwood Canyon, Colorado. The first event consisted of one 128 cubic foot block of quartzite, and the second, two weeks later, consisted of an estimated twenty to thirty irregular blocks of quartzite ranging in volume from three to fifteen cubic feet.

The severity of rockfall damage prompted a study of the area to determine the likelihood and impact of future rockfall. The rockfall path was traced to the base of quartzite cliffs 750 feet above I-70 (Figure 14). The source area was investigated and an evaluation was made of potential rockfall size and frequency. Due to the jointed and weathered nature of the rock over a wide area, it was decided that the source area could produce more rockfalls. Although the frequency of such events is not expected to be great, the potential for damage is considerable.

The investigation of the rockfall site provided information necessary for computer analysis. A slope profile of the rockfall path was made by plane table mapping (Figure 15). Further field investigations identified and

Figure 14: Path of rockfall events.

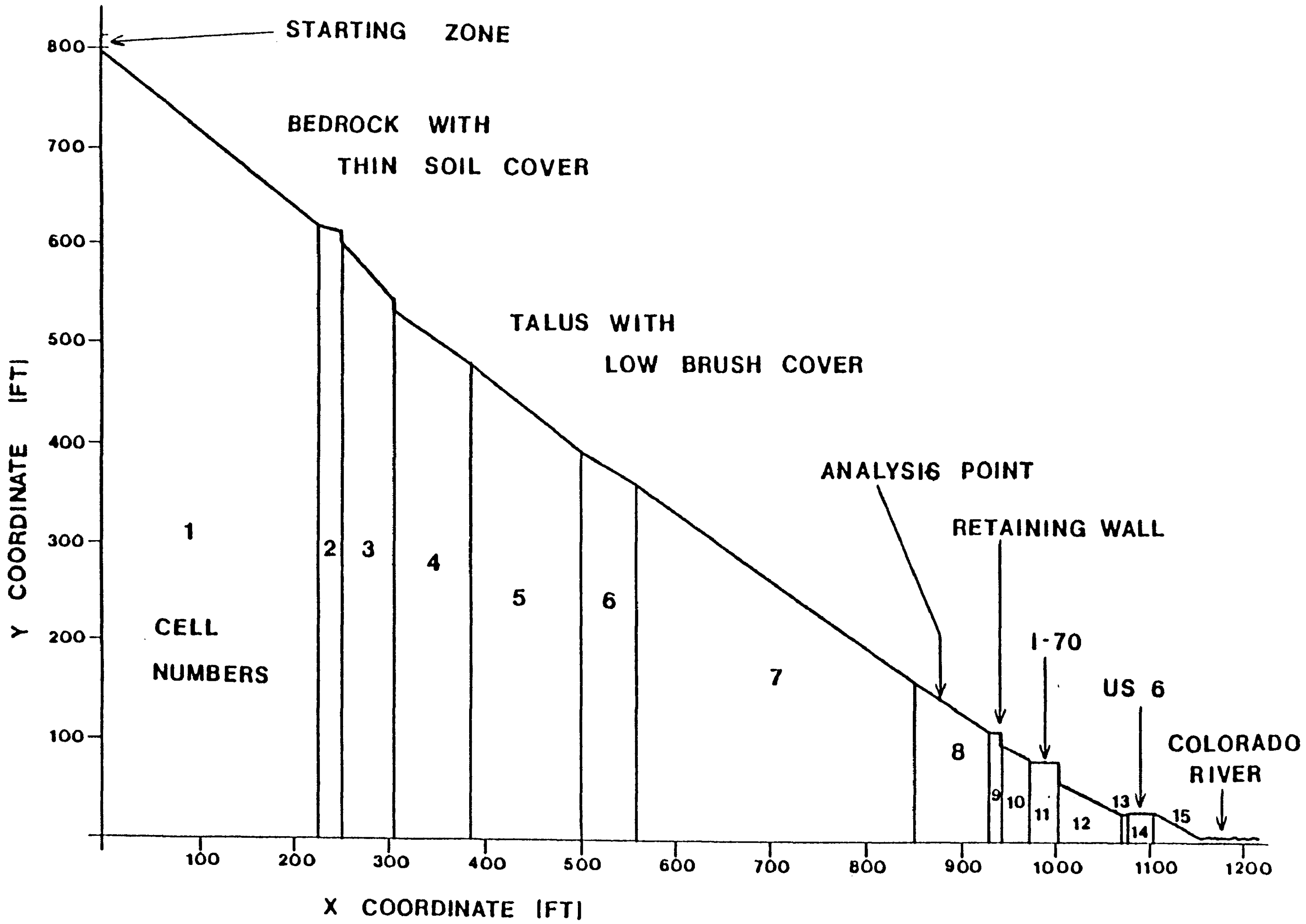

Figure 15: Slope profile of example area in Glenwood Canyon

located slope materials on the slope profile. The upper one third of the slope is granitic bedrock with sparse vegetation and a thin soil cover. The remainder of the slope above I-70 is talus with scattered areas of low shrubs. The slope profile was divided into fifteen cells, with each cell being assigned a surface roughness, a normal coefficient, and a tangential coefficient. The simulation was started from the zone above the uppermost cell representing the area where future rockfalls were expected to originate. The slope profile is shown in Figure 15, and the input file is shown in Table 9. A complete CRSP printout of the rockfall simulation is presented in Appendix C.

Table 9: Input file for Glenwood Canyon example.

```
15,885,800,810
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
13,.2,.82,.32,1069,25,1075,27
14,.1,.9,.4,1075,27,1104,27
15,1,.82,.32,1104,27,1153,4
```

Another example printout of a hypothetical slope is presented in Appendix C to illustrate the effect of benches with berms. This example models a 45° slope with ten foot wide benches and one foot high berms.

CONCLUSIONS

CRSP is used in Glenwood Canyon on a daily basis as part of a comprehensive rockfall program. Simulation results are used to help determine rockfall hazard severity and determine necessary rockfall fence capacities. Also, CRSP is used to help plan rock cut and ditch configurations that are both safe and aesthetically acceptable. The use of CRSP in Glenwood Canyon provides an objective means to help evaluate rockfall hazards.

While determining input values and using the output data requires judgement, the computer analysis adds objectivity to an otherwise largely subjective investigation of rockfall hazard. Because this computer program provides a site specific analysis of rockfall, it may help identify areas where roadside ditches can be narrowed or alternate rockfall mitigation measures should be considered. Rockfall simulation may also see applications in open pit mines and hillside property development.

Computer analysis of a site is rapid, inexpensive and allows for consideration of numerous alternatives. Increased use of computer analyses for rockfall studies can improve the state of the art in rockfall hazard investigation and mitigation.

Increased use of CRSP will identify many areas where the program may be improved. The current version of CRSP relies on minimal field data for calibration and verification; therefore, more testing and theoretical studies of bouncing rocks are needed to improve the bounce calculations. Also, with more widespread use, rockfall investigators will find new and better ways to present rockfall simulation data. Other obvious areas for improvement would include a metric version and a version for plotters. These changes will come about as they are needed.

CRSP Application in Glenwood Canyon

CRSP has been used extensively to aid in the design of rockfall mitigation for Interstate 70 in Glenwood Canyon. The steep canyon slopes above the road lead to frequent rockfalls in the 15 mile-long canyon. Some of the rockfalls originate high on the canyon slopes. Also of significance are rockfalls from rock cuts and natural cliffs near the roadway. Rockfall hazards from high on the canyon slopes may be reduced using catch fences designed with the aid of CRSP, but the rockfall hazard associated with rock slopes closer to the highway require other mitigation methods.

An important aspect of the highway design was concern for aesthetics and the environment. This concern required minimizing disturbance to natural slopes and constructing rock cuts to look natural. Rock cuts were constructed with a minimal ditch, irregular cut faces, and without presplitting. Traditional rock slope design considerations for rockfall call for even, presplit slopes and large ditches. Before the development of CRSP, there were no practical methods available to assess the rockfall hazard associated with irregular slopes. Without a means to assess the hazard, rock cuts and ditches were constructed on the basis of aesthetics with little regard for safety from rockfall. Often ditches were constructed sloping into the roadway, allowing rocks to roll into the roadway.

With the development of CRSP, the hazards associated with irregular rock cuts and natural rock slopes could be better assessed. CRSP use allows compromises between the landscape architect's aesthetic concerns and concerns for rockfall safety. Rock cuts could be constructed that were safe, while still incorporating planted benches and the irregular shape needed to have the appearance of a natural rock slope. The effect of proposed bench locations on rockfalls could be modeled, and usually a compromise could be reached on the location of the bench, in order to avoid launching rocks into the roadway. Generally this meant that benches could be located high on the slope, just above the ditch area, or elsewhere if a minimum bench width was maintained. CRSP results often aided in reaching a compromise on ditch configurations. Wider ditches were acceptable to the landscape plan if some variety could be incorporated into the visible area of the ditch. Rock ledges and irregular shaped slopes within the ditch area could be modeled with CRSP and located so as not to create a rockfall hazard. Usually this required several feet of backslope and no features over a specified height in the ditch. The addition of the graphics display to the program proved to be a convincing visual aid.

At some locations, CRSP would indicate rockfalls could present a hazard to the roadway, but wider ditches or reshaping of the slope did not present a practical solution. In these cases CRSP was used to evaluate alternative methods of rockfall mitigation located above the roadway. In many cases no practical solutions were available and some risk was accepted.

Implementation

CRSP may be used in many situations encountered during construction in steep terrain. With a little practice, most geologists and engineers with field data collection experience should be able to effectively use the program and the methods outlined in this report. The experience gained from using CRSP in Glenwood Canyon indicates that the program is useful in designing rock cuts and ditches. Various combinations of cut slope and ditch configurations are tested until a configuration is found that is both acceptable to the landscape architects and safe regarding rockfalls. CRSP is also used in Glenwood Canyon to determine bounce heights and velocities for natural rockfalls to help design mitigation. Many smaller projects should also find rockfall simulations useful.

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

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Appendix A
CRSP Data Forms

CRSP DATA FORM

LOCATION: ____________________

STATION: ____________________

DATE: ______________

FILE NAME: ____________________

SITE INVESTIGATOR: ______________

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

ANALYSIS POINT: ____________________

STARTING ZONE: ____________________

Appendix A
CRSP Data Forms

CRSP Site Profile

Location: ______________

Station: ______________

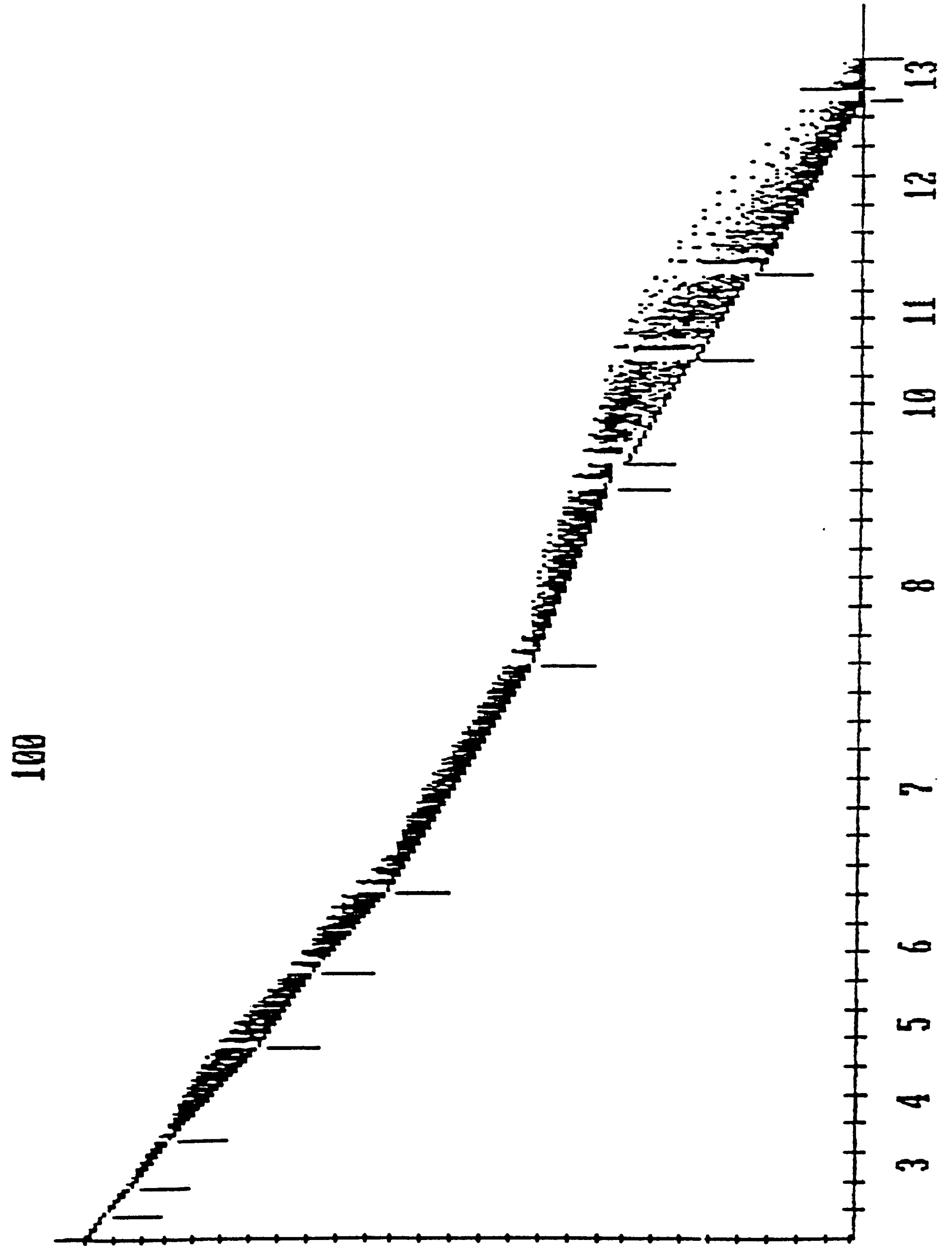
File Name: ______________

Site Investigator: ______________

Appendix B
West Rifle Test Site Printout

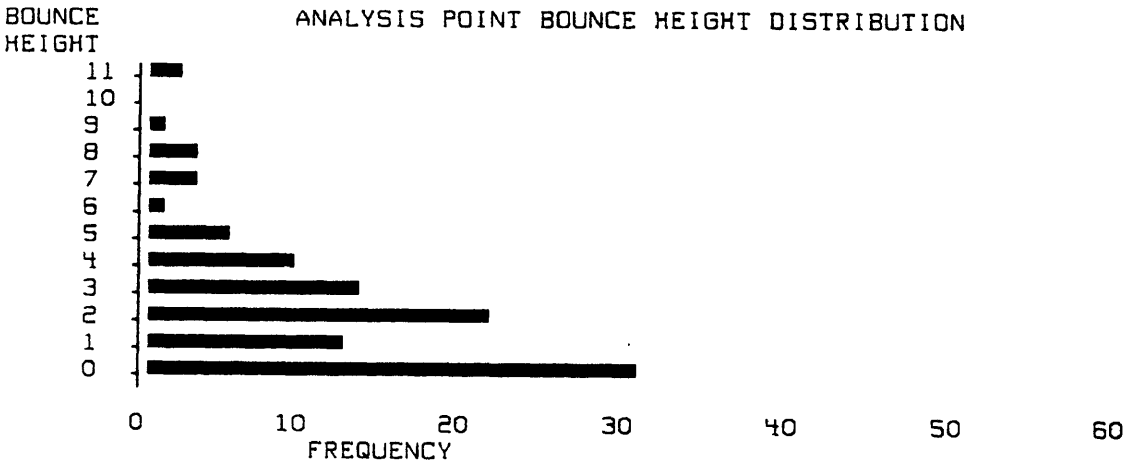
```
                    COLORADO ROCKFALL SIMULATION PROGRAM


FILE NAME B.T

ROCK STATISTICS
 7358 LB SPHERICAL ROCK   2.2  FT RADIUS

    NUMBER OF CELLS      13
    NUMBER OF ROCKS      100
    ANALYSIS POSITION    400
    INITIAL Y ZONE       325 TO 330
    INITIAL X VELOCITY   1  FT/SEC
    INITIAL Y VELOCITY  -1  FT/SEC

                         TANGENTIAL      NORMAL
           SURFACE       COEFFICIENT   COEFFICIENT     BEGINNING       ENDING
CELL #     ROUGHNESS                   RESTITUTION       X,Y            X,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
```

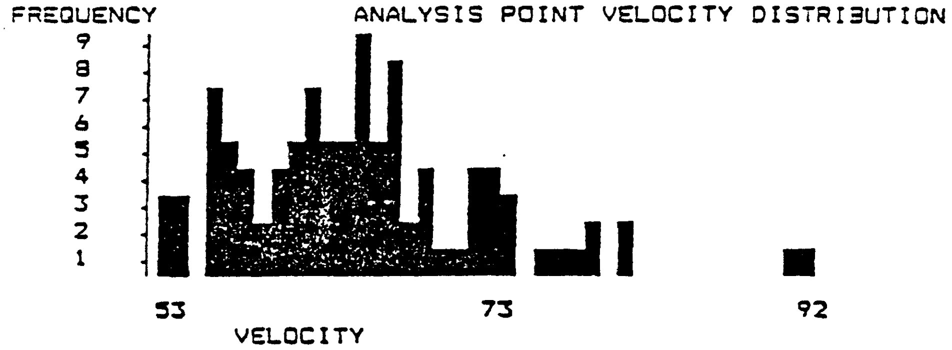
Appendix B
West Rifle Test Site Printout



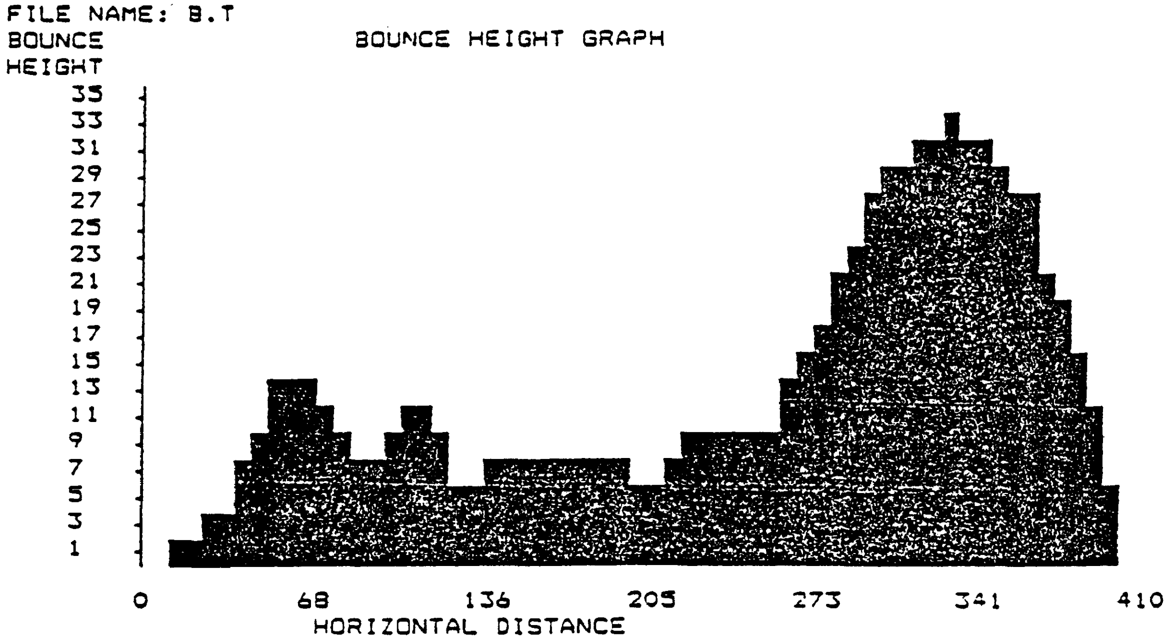
Appendix B
West Rifle Test Site Printout

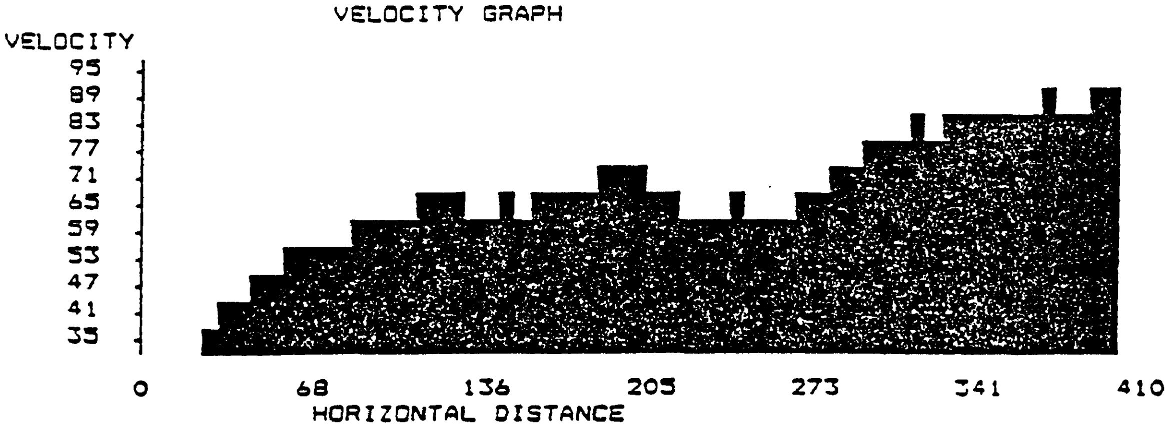
```
FILE NAME: B.T
    ANALYSIS POINT                             X= 400  Y= 50
    MAXIMUM VELOCITY                            92 FT/SEC
    AVERAGE VELOCITY                            65 FT/SEC
    MINIMUM VELOCITY                            53 FT/SEC
    STANDARD DEVIATION (VELOCITY)               7.68
    AVERAGE BOUNCE HEIGHT                       2 FEET
    MAXIMUM BOUNCE HEIGHT                       11 FEET
    MAXIMUM KINETIC ENERGY                      973205  FT LB
```





Appendix B
West Rifle Test Site Printout





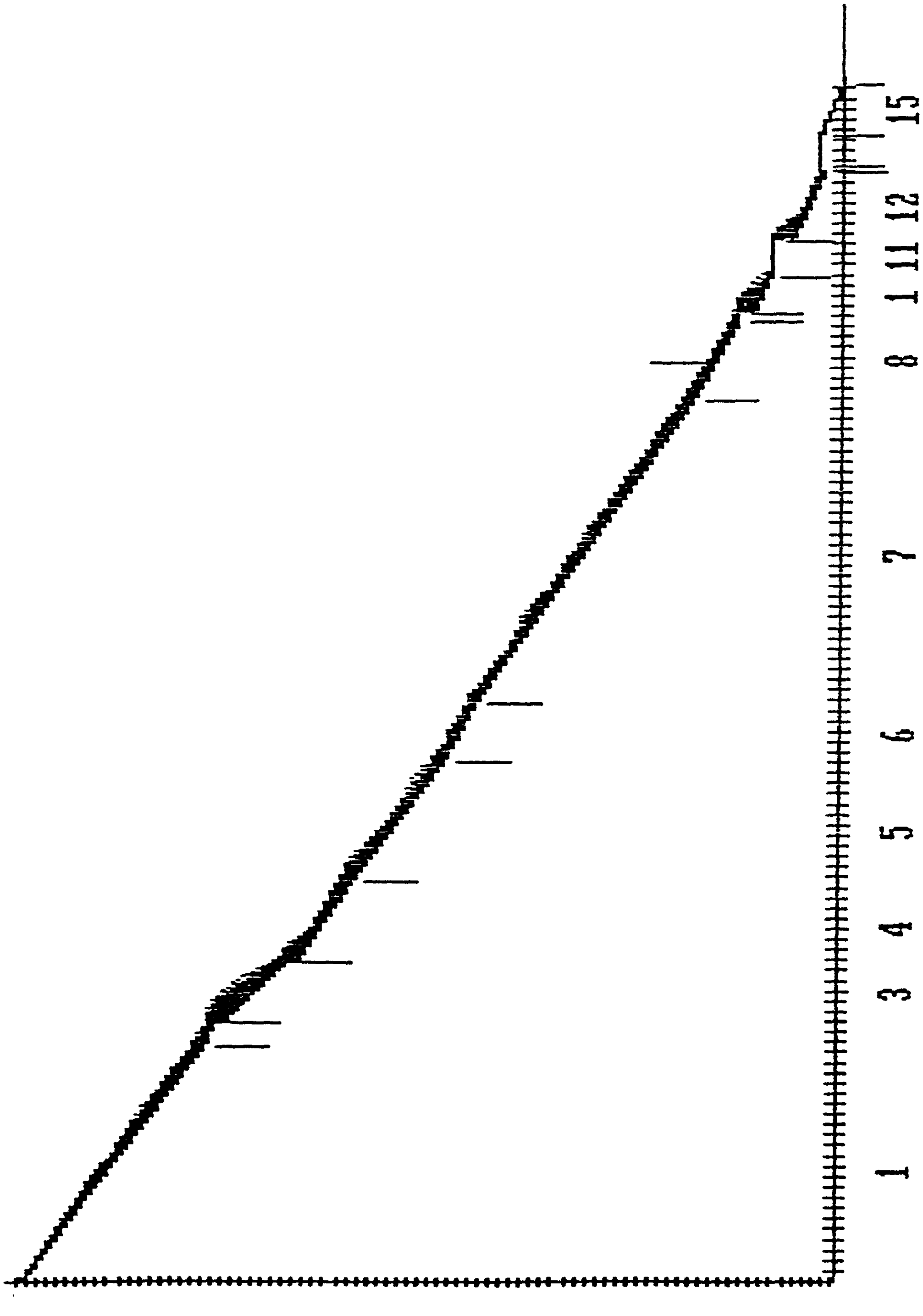
Appendix B
West Rifle Test Site Printout

```
FILE NAME: B.T
         MAXIMUM     AVERAGE     STANDARD    AVERAGE            MAXIMUM
CELL #   VELOCITY    VELOCITY    DEVIATION   BOUNCE              BOUNCE
         (FT/SEC)    (FT/SEC)    VELOCITY    HEIGHT (FT)      HEIGHT (FT)

  1        21          17          1.39       0                  0
  2        30          26          1.79       0                  2
  3        38          33          2.07       1                  4
  4        55          42          6.23       6                  14
  5        57          45          5.69       2                  8
  6        67          54          5.63       4                  12
  7        72          57          5.56       3                  9
  8        63          54          5.24       3                  10
  9        65          52          6.14       2                  10
  10       78          60          8.55       11                 27
  11       81          66          8.99       8                  31
  12       90          63          7.51       3                  15
  13       71          53          7.5        1                  6
```

Appendix C
Glenwood Canyon Example Printout

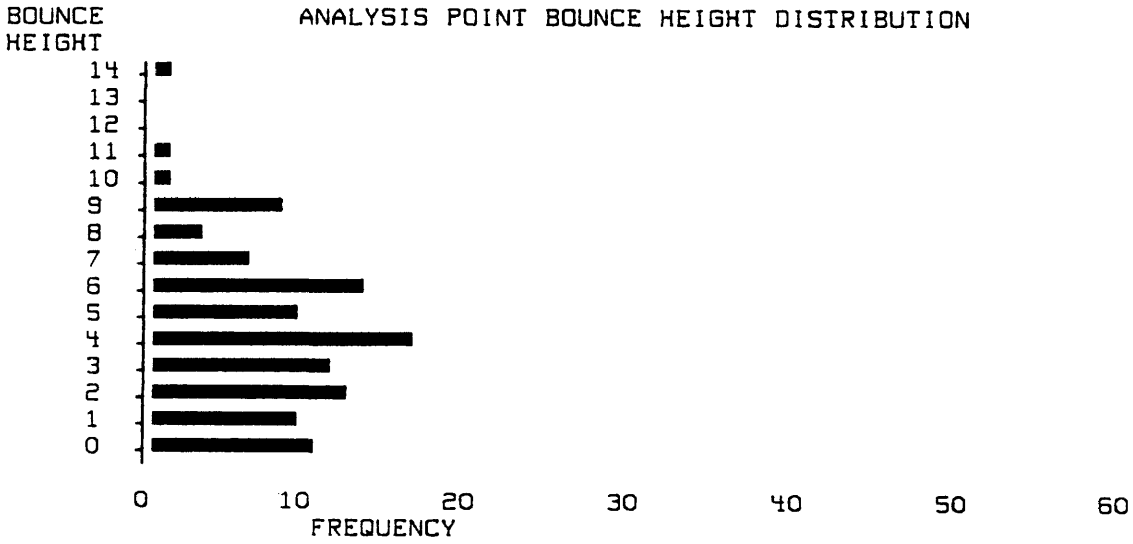
```
                     COLORADO ROCKFALL SIMULATION PROGRAM


FILE NAME RKD\R62.5

ROCK STATISTICS
 3761 LB DISK SHAPED ROCK  RADIUS= 2.2  THICKNESS= 1.5

    NUMBER OF CELLS       15
    NUMBER OF ROCKS       100
    ANALYSIS POSITION     885
    INITIAL Y ZONE        800 TO 810
    INITIAL X VELOCITY    1  FT/SEC
    INITIAL Y VELOCITY   -1  FT/SEC

                          TANGENTIAL       NORMAL
            SURFACE       COEFFICIENT    COEFFICIENT       BEGINNING        ENDING
CELL #      ROUGHNESS                    RESTITUTION         X,Y             X,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             .81             .32         306 , 530        385 , 480
 5            1             .81             .32         385 , 480        500 , 390
 6            1.2           .81             .32         500 , 390        557 , 360
 7            .7            .8              .31         557 , 360        848 , 157
 8            .6            .8              .31         848 , 157        925 , 110
 9            1             .82             .31         925 , 110        933 , 110
 10           .5            .8              .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
```

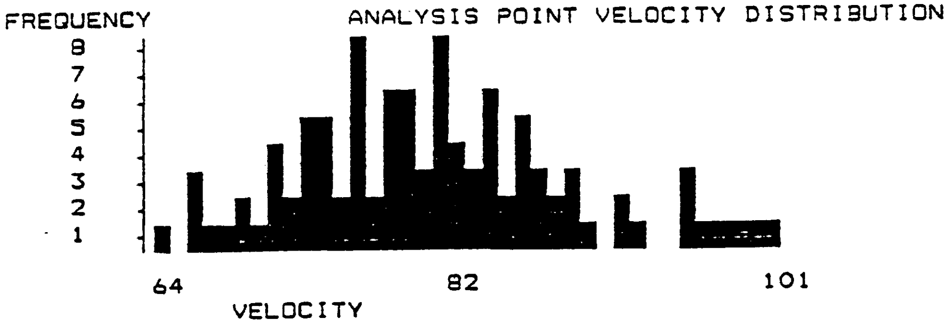
Appendix C
Glenwood Canyon Example Printout



Appendix C
Glenwood Canyon Example Printout

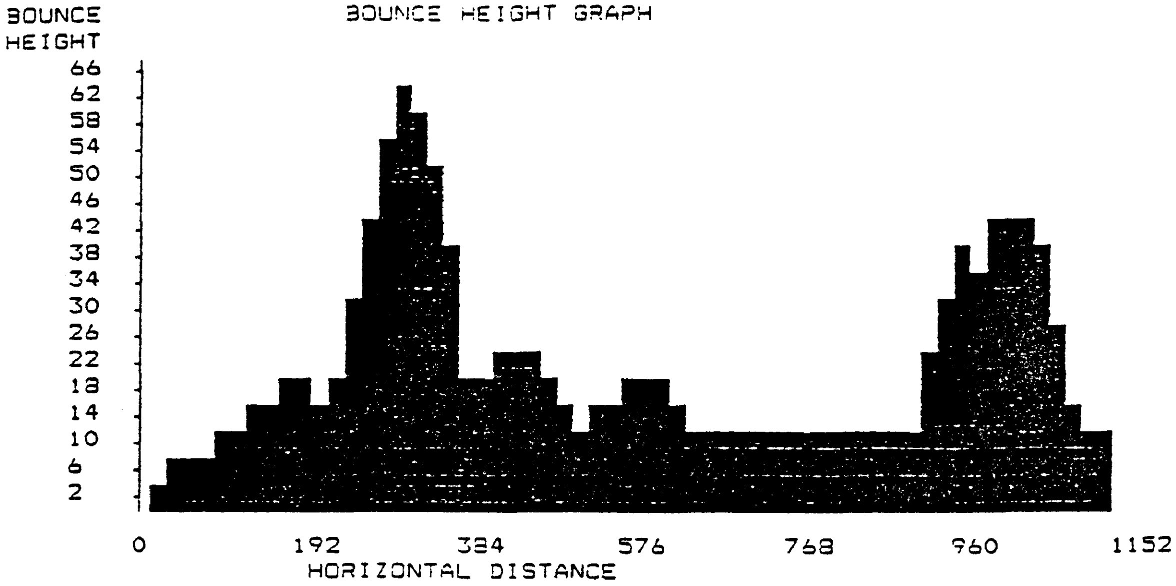
```
FILE NAME: RKD\R62.5
    ANALYSIS POINT                                  X= 885  Y= 134
    MAXIMUM VELOCITY                                 101 FT/SEC
    AVERAGE VELOCITY                                 80 FT/SEC
    MINIMUM VELOCITY                                 64 FT/SEC
    STANDARD DEVIATION (VELOCITY)                    8.18
    AVERAGE BOUNCE HEIGHT                            4 FEET
    MAXIMUM BOUNCE HEIGHT                            14 FEET
    MAXIMUM KINETIC ENERGY                           599596  FT LB
```

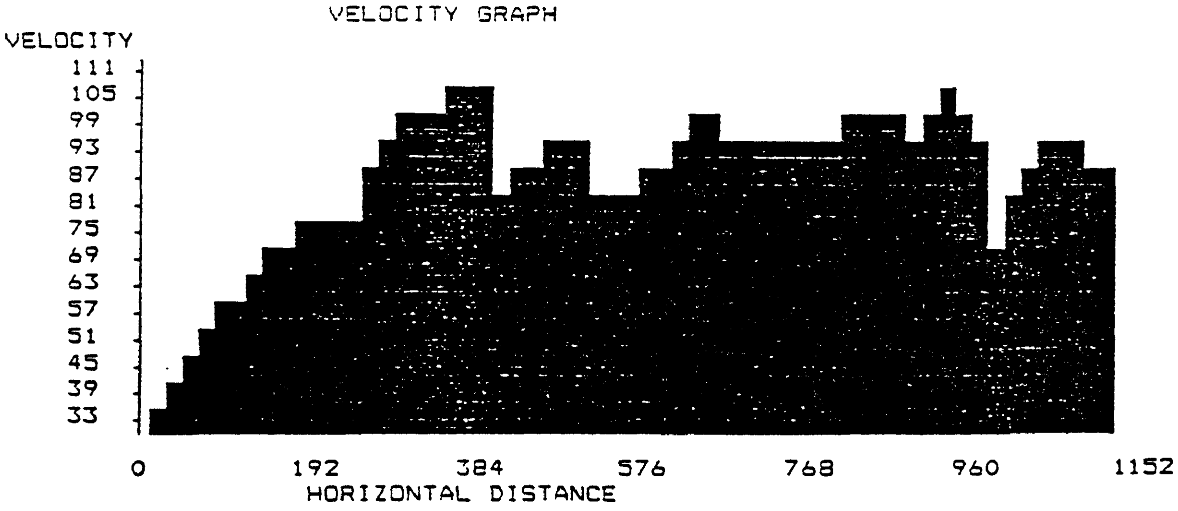




Appendix C
Glenwood Canyon Example Printout

FILE NAME: RKD\R62.5


BOUNCE HEIGHT GRAPH


VELOCITY GRAPH

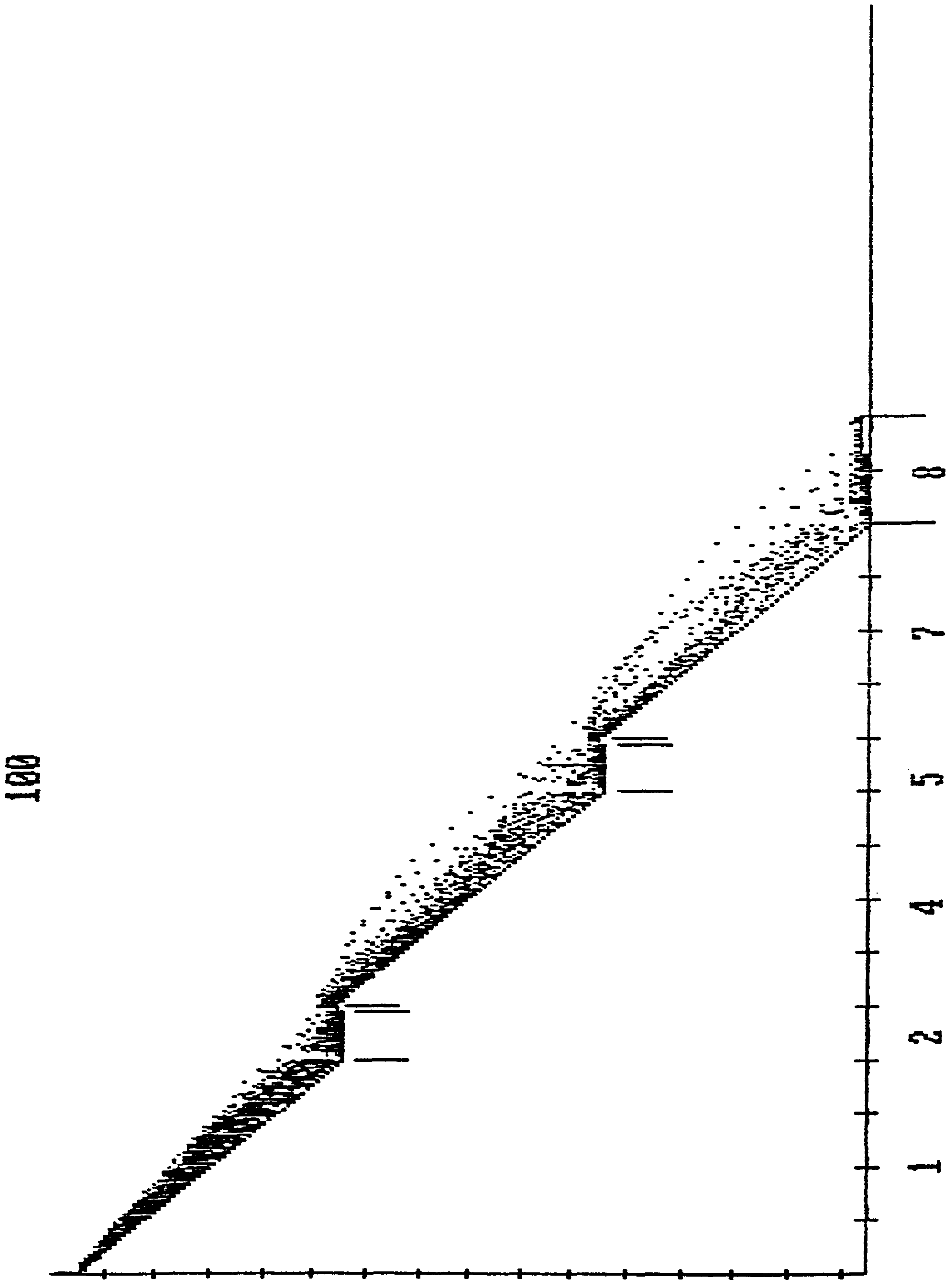
Appendix C
Glenwood Canyon Example Printout

```
FILE NAME: RKD\R62.5
           MAXIMUM       AVERAGE      STANDARD     AVERAGE               MAXIMUM
CELL #     VELOCITY      VELOCITY     DEVIATION    BOUNCE                 BOUNCE
           (FT/SEC)      (FT/SEC)     VELOCITY     HEIGHT  (FT)       HEIGHT  (FT)

  1           76            57           8.74        6                      18
  2           70            47          11.29        3                      10
  3           95            69          13.67        19                     55
  4           107           56          11.56        3                      23
  5           94            70           8.78        6                      16
  6           77            60           7.13        6                      16
  7           98            80           7.09        5                      13
  8           98            80           6.49        3                      12
  9           100           60          18.04        1                      7
  10          98            62          19.08        20                     37
  11          71            56          11.29        6                      27
  12          92            64          16.16        15                     39
  13          94            55          24.35        11                     34
  14          86            44          19.83        1                      15
  15          76            48          13.11        4                      14
```

Appendix C
Benched Slope Example Printout

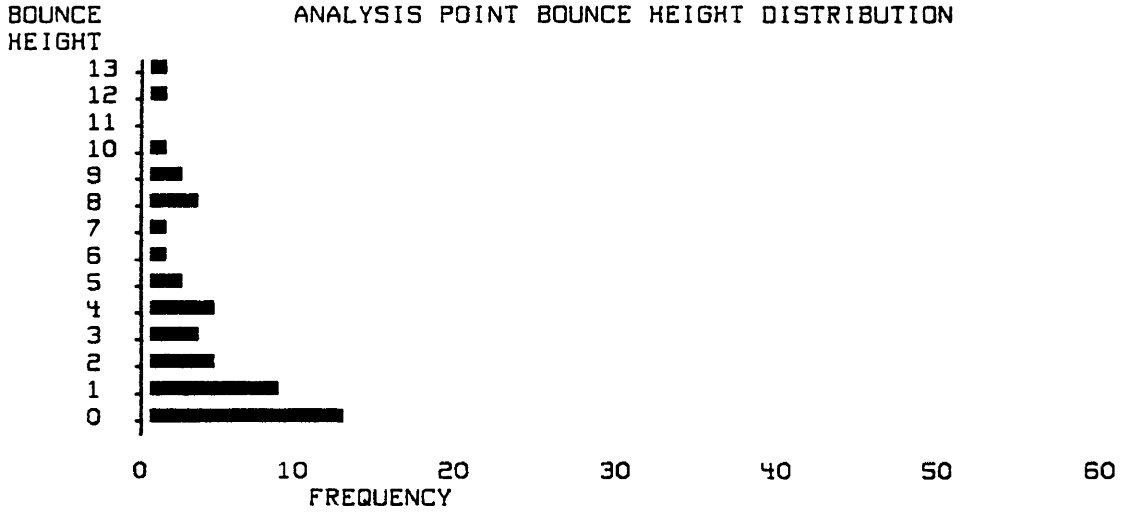
```
                    COLORADO ROCKFALL SIMULATION PROGRAM


FILE NAME RKD\TEST.2

ROCK STATISTICS
 86 LB SPHERICAL ROCK    .5  FT RADIUS

    NUMBER OF CELLS       8
    NUMBER OF ROCKS       100
    ANALYSIS POSITION     95
    INITIAL Y ZONE        150 TO 155
    INITIAL X VELOCITY    1  FT/SEC
    INITIAL Y VELOCITY   -1  FT/SEC

                         TANGENTIAL      NORMAL
              SURFACE    COEFFICIENT    COEFFICIENT      BEGINNING       ENDING
CELL #       ROUGHNESS                 RESTITUTION        X,Y            X,Y

 1              1           .85            .35           0 , 150        40 , 100
 2             .5           .82            .28           40 , 100       49 , 100
 3             .5           .82            .28           49 , 100       50 , 101
 4              1           .85            .35           50 , 101       90 , 50
 5             .5           .82            .28           90 , 50        99 , 50
 6             .5           .82            .28           99 , 50        100 , 51
 7              1           .85            .35           100 , 51       140 , 0
 8             .5           .82            .28           140 , 0        160 , 2
```

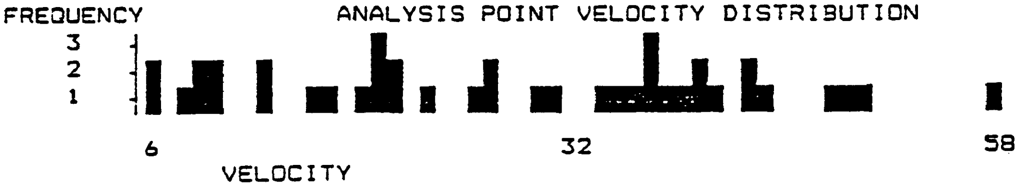
Appendix C
Benched Slope Example Printout



Appendix C
Benched Slope Example Printout

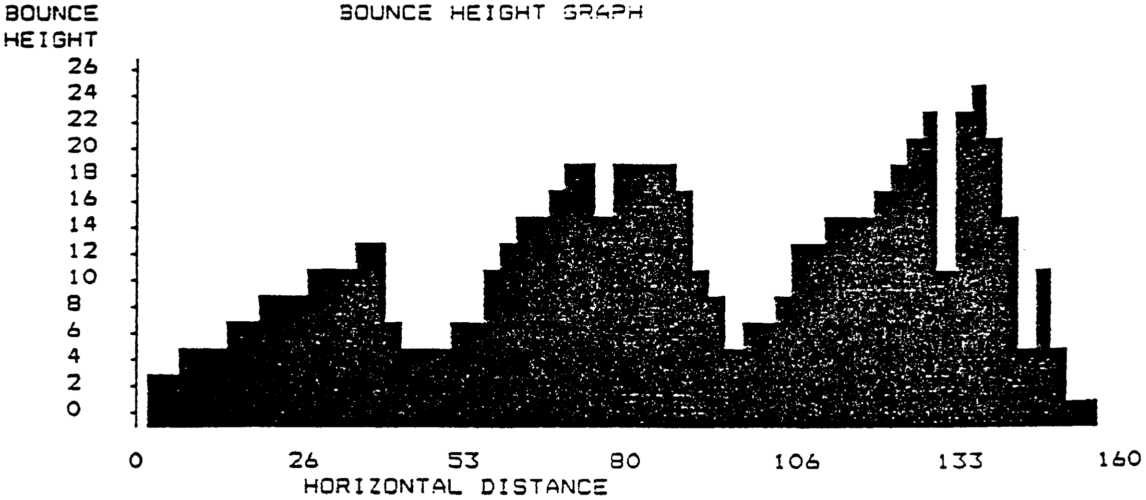
```
FILE NAME: RKD\TEST.2
    ANALYSIS POINT                                  X= 95   Y= 50
    MAXIMUM VELOCITY                                 58 FT/SEC
    AVERAGE VELOCITY                                 28 FT/SEC
    MINIMUM VELOCITY                                 6 FT/SEC
    STANDARD DEVIATION (VELOCITY)                    14.03
    AVERAGE BOUNCE HEIGHT                            2 FEET
    MAXIMUM BOUNCE HEIGHT                            13 FEET
    MAXIMUM KINETIC ENERGY                           4540  FT LB
```

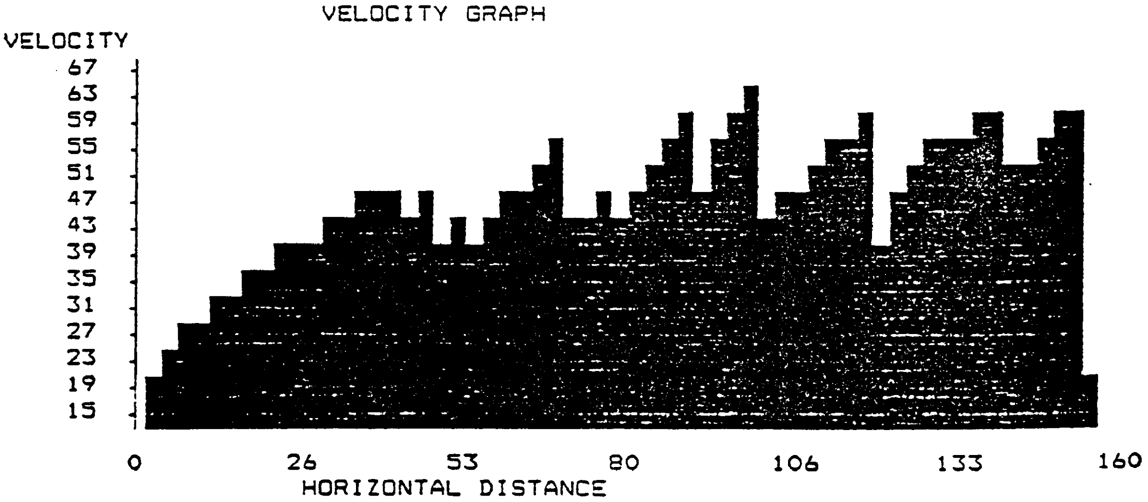




Appendix C
Benched Slope Example Printout

FILE NAME: RKD\TEST.2





Appendix C
Benched Slope Example Printout

```
FILE NAME: RKD\TEST.2
         MAXIMUM      AVERAGE      STANDARD     AVERAGE          MAXIMUM
CELL #   VELOCITY     VELOCITY     DEVIATION    BOUNCE            BOUNCE
         (FT/SEC)     (FT/SEC)     VELOCITY     HEIGHT (FT)    HEIGHT (FT)

  1         51           32           9.38        4                13
  2         49           15          10.38        0                 4
  3         40           11           8.42        0                 3
  4         58           33          11.03        6                20
  5         62           19          13.77        1                 9
  6         63           17          15.73        0                 7
  7         63           40          11.56        7                25
  8         20           13           6.27        1                 3

    X INTERVAL      ROCKS STOPPED

 0  TO  10  FEET              5
 40  TO  50  FEET             48
 50  TO  60  FEET             2
 90  TO  100  FEET            19
 100  TO  110  FEET           1
 140  TO  150  FEET           5
 150  TO  160  FEET           13
```

Appendix D
CRSP Basic Source Code

```
10 REM ***** COLORADO ROCKFALL SIMULATION PROGRAM CRSP *****
20   '         MODELS THE TRAJECTORY OF ROCKS ON IRREGULAR
SLOPES
30   '        USES SLOPE PROFILE, SURFACE ROUGHNESS, SURFACE
MATERIAL PROPERTIES
40   '        ROCK SIZE, AND ROCK SHAPE TO PRODUCE A
STATISTICAL ANALYSIS OF
50   '        ROCKFALL BEHAVIOR ON THE SLOPE
60   '  WRITTEN AND DEVELOPED BY TIM PFEIFFER FOR THE
COLORADO DEPARTMENT OF
70   '  HIGHWAYS   1988
80 '
90 '
100 CLEAR : CLS
110 PRINT "**** COLORADO ROCKFALL SIMULATION PROGRAM ****"
120 PRINT : PRINT "WRITTEN AND DEVELOPED FOR THE COLORADO
DEPARTMENT OF HIGHWAYS"
130 PRINT "          BY TIM PFEIFFER   1988": PRINT : PRINT
140 PRINT "THIS PROGRAM HAS BEEN TESTED AND IS BELIEVED TO
BE A RELIABLE ENGINEERING TOOL"
150 PRINT "NO RESPONSIBILITY IS ASSUMED BY THE AUTHOR FOR
ANY ERRORS, MISTAKES "
160 PRINT "MISREPRESENTATIONS THAT MAY OCCUR FROM ANY USE OF
THE PROGRAM": PRINT : PRINT : PRINT
170 '
180 REM ******** PROGRAM INITIALIZATION ******************
190 '
200 DEFINT I-L, N    'SETS INTEGER VARIABLES
210 INPUT "ENTER FILE NAME"; A$    'SLOPE DATA FILE
220 IAB = 16: IBC = 32: CD = 1.5708: IVANN = 1000: VX = 1:
VY = -1: IRD = 165: INR = 100: ICHOICE = 3'DEFAULT VALUES
AND CONSTANTS
230 OPEN A$ FOR INPUT AS #1
240 INPUT #1, N, IXAN, IYB, IYC
250 DIM ICV(N), ICVM(N), IMCBH(N), MAXA(N), CVT(N), ICVN(N),
R(N), ICC(N), IIBH(62), IV(62)
260 DIM SRD(N), RT(N), RN(N), IXS(N + 1), IYS(N), IXE(N),
IYE(N), ICBHA(N)
270 '         DEFAULT VALUES
280 PRINT "CRSP ASSUMES THE FOLLOWING VALUES"
290 PRINT "100 SIMULATION ROCKS"
300 PRINT "SPHERICAL ROCKS AT 165 LB/CF"
310 PRINT "STARTING VELOCITIES X=1 Y=-1"
```

Appendix D
CRSP Basic Source Code

```
320 INPUT "DO YOU WISH TO CHANGE ANY OF THESE VALUES Y/N";
B$
330 IF B$ = "Y" OR B$ = "y" THEN GOSUB 3060 ELSE GOSUB 3330
340 DIM IBH(100), IVELN(150)
350 '
360 LPRINT TAB(20); "COLORADO ROCKFALL SIMULATION PROGRAM":
LPRINT : LPRINT : LPRINT
370 LPRINT "FILE NAME "; A$
380 '
390 REM ************** DATA ENTRY **************
400 '
410 LPRINT : LPRINT "ROCK STATISTICS"
420 ON ICHOICE GOTO 440, 450, 460
430 '
440 LPRINT INT(M * 32); "LB DISK SHAPED ROCK  RADIUS="; RXD;
" THICKNESS="; THICK: GOTO 470
450 LPRINT INT(M * 32); "LB CYLINDRICAL ROCK  "; RADI; " BY
"; LENG: GOTO 470
460 LPRINT INT(M * 32); "LB SPHERICAL ROCK  "; RXD; " FT
RADIUS"
470 LPRINT
480 '   PRINTOUT OF SIZE AND SHAPE OF ROCK USED IN
SIMULATION
490 LPRINT "    NUMBER OF CELLS      "; N
500 LPRINT "    NUMBER OF ROCKS      "; INR
510 LPRINT "    ANALYSIS POSITION    "; IXAN
520 LPRINT "    INITIAL Y ZONE       "; IYB; "TO"; IYC
530 YX = (IYC - IYB) / INR
540 LPRINT "    INITIAL X VELOCITY  "; VX; " FT/SEC": LPRINT
"    INITIAL Y VELOCITY  "; VY; " FT/SEC": LPRINT
550 '         CELL DATA TABLE
560 LPRINT TAB(24); "TANGENTIAL"; SPC(6); "NORMAL"
570 LPRINT SPC(12); "SURFACE"; SPC(4); "COEFFICIENT";
SPC(4); "COEFFICIENT"; SPC(4); "BEGINNING"; SPC(6); "ENDING"
580 LPRINT "CELL #    ROUGHNESS                 RESTITUTION
     X,Y          X,Y": LPRINT
590 '         CELL DATA INPUT AND PRINTOUT
600 FOR I = 1 TO N
610 INPUT #1, ICELL, SRD(I), RT(I), RN(I), IXS(I), IYS(I),
IXE(I), IYE(I)
620 IF IXAN > IXS(I) AND IXAN < IXE(I) THEN IYAN = IYS(I) -
((IXAN - IXS(I)) / (IXE(I) - IXS(I))) * (IYS(I) - IYE(I))
```

Appendix D
CRSP Basic Source Code

```
630  LPRINT TAB(1); I; TAB(13); SRD(I); TAB(26); RT(I);
TAB(41); RN(I); TAB(53); IXS(I); ","; IYS(I); TAB(67);
IXE(I); ","; IYE(I)
640 MAXA(I) = ATN(SRD(I) / RXD)'MAXIMUM VARIATION IN SLOPE
650 NEXT I
660 '
670 CLOSE #1
680 LPRINT CHR$(12);
690 LRC = IXE(N) / 10 + 1: SCA = 60 / IXE(N): DIM IRSC(LRC +
1)' DEFINES INCREMENTS
700 '
710 GOSUB 3400 'SCREEN GRAPHICS SUBROUTINE
720 '
730 REM ********* ROCK BOUNCE *************
740 '       SIMULATION OF ROCKS TRAVELING DOWN A SLOPE
750 '
760 '
770 FOR K = 1 TO INR'NEW ROCK
780 LOCATE 1, 30: PRINT K
790 ITK = 0: YI = IYB + YX * K: VXI = VX: X = IXS(1): VYI =
VY: W = VX / RXD: J = 0'INITIAL  VALUES FOR NEW ROCK
800 J = J + 1'CELL COUNT FOR NEW CELL
810 A = (IYS(J) - IYE(J)) / (IXE(J) - IXS(J)): SA =
ATN(A)'SLOPE
820 '
830 REM ********* FLIGHT TIME BETWEEN BOUNCES ******
840 '       DETERMINES TIME BETWEEN BOUNCES
850 '
860 T = 0
870 I = INT(XT * SCA): IIBH = YT - (IYS(J) - (XT - IXS(J)) *
A): IV = SQR((VYI - IBC * T) ^ 2 + VXI ^ 2)
880 IF IIBH > IIBH(I) AND IV > 4 THEN IIBH(I) = IIBH' FINDS
MAXIMUM BOUNCE HEIGHTS
890 IF IV > IV(I) THEN IV(I) = IV' FINDS MAXIMUM VELOCITY
900 T = T + .1: YT = YI + VYI * T - IAB * T ^ 2: XT = X +
VXI * T' NEW TIME AND X,Y POSITION
910 IF XT > IXAN AND ITK = 0 THEN GOSUB 1380'DETERMINES IF
ROCK HAS PAST AN. POINT
920 IF XT > IXE(J) THEN 1230'DETERMINES IF ROCK HAS LEFT
CELL
930 IF YT > (IYS(J) - (XT - IXS(J)) * A) THEN IX = XT * SCX
+ 5: IY = (IYC - YT) * SC + 10: PSET (IX, IY): GOTO 870'
PLOTS POINT EVERY .1 SEC. ON SCREEN
```

Appendix D
CRSP Basic Source Code

```
940 ’         DETERMINE TIME BETWEEN BOUNCES TO .005 SEC.
950 T = T - .1
960 T = T + .01
970 YT = YI + VYI * T - IAB * T ^ 2: XT = X + VXI * T
980 IF YT > (IYS(J) - (XT - IXS(J)) * A) THEN 960
990 T = T - .005
1000 ’    DETERMINATION OF BOUNCE COORDINATES
1010 XT = X + VXI * T: YT = IYS(J) - (XT - IXS(J)) * A
1020 IF SQR((XT - X) ^ 2 + (YT - YI) ^ 2) > RXD THEN X = XT:
GOTO 1080
1030 ’    CALCULATIONS FOR ROLLING ROCKS
1040 IF ITK = 0 AND (X + RXD) > IXAN THEN X = IXAN: YI =
IYS(J) - (X - IXS(J)) * A: GOSUB 1380
1050 IF XT < IXE(J) AND (X + RXD) > IXE(J) THEN X = IXE(J):
YI = IYE(J): GOTO 1230
1060 X = X + RXD: YT = IYS(J) - (X - IXS(J)) * A
1070 ’
1080 VYI = VYI - IBC * T: YI = YT’NEW Y VELOCITY AND
POSITION
1090 ’
1100 REM ************** BOUNCE CALCULATION ************
1110 ’      DETERMINES INTERACTION WITH SLOPE
1120 ’
1130 FA = ABS(ATN(VYI / VXI)): AIC = RND(1) * MAXA(J)
1140 AI = FA - (SA - AIC)’ANGLE THAT ROCK STRIKES SLOPE
1150 VEL = SQR(VYI ^ 2 + VXI ^ 2)’VELOCITY BEFORE BOUNCE
1160 ’   DETERMINATION OF NEW TANGENTIAL VELOCITY AND NORMAL
VELOCITY
1170 D = VEL * SIN(AI): VN = D * RN(J) / ((D / 30) ^ 2 + 1):
VBT = VEL * COS(AI): TE = DIL * W ^ 2 + M * VBT ^ 2: FF =
RT(J) / ((D / (250 * RN(J))) ^ 2 + 1) + (1 - RT(J)) / (((VBT
- W * RXD) / 20) ^ 2 + 1.2)
1180 VT = SQR(RXD ^ 2 * TE * FF / (DIL + M * RXD ^ 2)): W =
VT / RXD’NEW ROTATIONAL VELOCITY
1190 ’   DETERMINATION OF NEW X,Y VELOCITIES
1200 V = SQR(VN ^ 2 + VT ^ 2): AL = ATN(VN / VT) + AIC: VXI
= V * COS(AL - SA): VYI = V * SIN(AL - SA)
1210 IF VEL < 3 OR VXI < 0 THEN IRSC(INT(X / 10)) =
IRSC(INT(X / 10)) + 1: IRSC = 1 : GOTO 1350 ELSE
860’DETERMINES IF ROCK HAS STOPPED
1220 ’
1230 REM ******** END OF CELL DATA COLLECTION **********
```

Appendix D
CRSP Basic Source Code

```
1240 '  COLLECTS VELOCITY AND BOUNCE HEIGHT DATA AT THE END
OF EACH CELL
1250 '
1260 AT = (IXE(J) - X) / VXI: YA = YI + VYI * AT - IAB * AT
^ 2'DETERMINES Y COORDINATE
1270 IF YA < (IYE(J) - .5) THEN 950
1280 YI = YA: VYI = VYI - IBC * AT: ICV = SQR(VYI ^ 2 + VXI
^ 2): CVT(J) = CVT(J) + ICV: R(J) = R(J) + ICV ^ 2: ICC(J) =
ICC(J) + 1
1290 ICBH = YI - IYE(J): ICBHA(J) = ICBHA(J) + ICBH
1300 IF ICV > ICVM(J) THEN ICVM(J) = ICV'FINDS MAXIMUM
VELOCITY AT END OF CELL
1310 IF ICBH > IMCBH(J) THEN IMCBH(J) = ICBH'FINDS MAXIMUM
BOUNCE HEIGHT
1320 X = IXS(J + 1)
1330 IF J < N THEN 800
1340 '
1350 NEXT K
1360 GOTO 1510
1370 '
1380 REM ******* ANALYSIS POINT DATA COLLECTION **********
1390 '   COLLECTS VELOCITY AND BOUNCE HEIGHT DATA AT THE
ANALYSIS POINT
1400 '
1410 AT = (IXAN - X) / VXI: VYA = VYI - IBC * AT: IVAN =
SQR(VYA ^ 2 + VXI ^ 2): YN = YI + VYI * AT - IAB * AT ^ 2:
IH = YN - IYAN: ICA = ICA + 1'COLLECTS STATISTICAL DATA
1420 IF IH > IHM THEN IHM = IH' FINDS MAXIMUM BOUNCE HEIGHT
1430 IF IVAN > IVANM THEN IVANM = IVAN: WA = W'FINDS MAXIMUM
VELOCITY
1440 IF IVAN < IVANN THEN IVANN = IVAN'FINDS MINIMUM
VELOCITY
1450 VANA = VANA + IVAN: U = U + IVAN ^ 2: IHA = IHA + IH:
ITK = 1
1460 IF IH < 1 THEN IH = 0
1470 IBH(IH) = IBH(IH) + 1: IVELN(IVAN) = IVELN(IVAN) + 1'
DATA FOR GRAPH
1480 RETURN
1490 '
1500 REM ********* DATA OUTPUT *******************
1510 '  PRINTOUT OF DATA COLLECTED DURING SIMULATION
1520 '
1530 C$ = INKEY$: IF C$ = "" THEN 1530
```

Appendix D
CRSP Basic Source Code

```
1540  '
1550 LPRINT "FILE NAME: "; A$
1560 REM ************ ANALYSIS POINT DATA ************
1570 ' PRINTOUT OF DATA COLLECTED AT ANALYSIS POINT
1580 '
1590 IF ICA = 0 THEN LPRINT "NO ROCKS PAST ANALYSIS POINT":
GOTO 2220
1600 VAV = VANA / ICA: IHAA = IHA / ICA
1610 STT = SQR((U - ICA * VAV ^ 2) / (ICA - 1))'STANDARD
DEVIATION OF THE VELOCITY
1620 IF IVANN = 1000 THEN IVANN = 0
1630 TKE = .5 * IVANM ^ 2 * M + .5 * IL * WA ^ 2'TOTAL
KINETIC ENERGY
1640 '
1650 LPRINT "    ANALYSIS POINT       "; TAB(48); "X="; IXAN;
" Y="; IYAN
1660 LPRINT "    MAXIMUM VELOCITY    "; TAB(48); IVANM;
"FT/SEC"
1670 LPRINT "    AVERAGE VELOCITY    "; TAB(48); INT(VAV +
.5); "FT/SEC"
1680 LPRINT "    MINIMUM VELOCITY    "; TAB(48); IVANN;
"FT/SEC"
1690 LPRINT "    STANDARD DEVIATION (VELOCITY)"; TAB(48);
INT((STT + .005) * 100) / 100
1700 LPRINT "    AVERAGE BOUNCE HEIGHT"; TAB(48); IHAA;
"FEET"
1710 LPRINT "    MAXIMUM BOUNCE HEIGHT"; TAB(48); IHM;
"FEET"
1720 LPRINT "    MAXIMUM KINETIC ENERGY "; TAB(48);
INT(TKE); " FT LB": LPRINT : LPRINT
1730 '
1740 REM ********** BOUNCE HEIGHT GRAPH ***************
1750 ' PRINT GRAPH OF BOUNCE HEIGHT VS FREQUENCY AT ANALYSIS
POINT
1760 '
1770 LPRINT "BOUNCE"; SPC(12); "ANALYSIS POINT BOUNCE HEIGHT
DISTRIBUTION": LPRINT "HEIGHT"
1780 IB = IHM
1790 ' ROWS FOR # OF ROCKS AT A GIVEN BOUNCE HEIGHT
1800 FOR J = 0 TO IHM
1810 LPRINT TAB(5); IB; TAB(9); CHR$(180);
1820 ' PRINTS 1 COLUMN FOR EACH ROCK
1830 FOR K = 1 TO IBH(IB)
```

Appendix D
CRSP Basic Source Code

```
1840 LPRINT CHR$(223);
1850 IF K = 65 THEN LPRINT IBH(IB): GOTO 1880
1860 NEXT K
1870 '
1880 IB = IB - 1
1890 NEXT J
1900 ' LABEL AXIS
1910 LPRINT
1920 LPRINT : LPRINT TAB(9); "0"; TAB(18); "10"; TAB(28);
"20"; TAB(38); "30"; TAB(48); "40"; TAB(58); "50"; TAB(68);
"60"
1930 LPRINT TAB(20); "FREQUENCY": LPRINT
1940 '
1950 REM ******** VELOCITY GRAPH *************
1960 '       PRINTS GRAPH OF FREQUENCY VS VELOCITY AT
ANALYSIS POINT
1970 '
1980 LPRINT "FREQUENCY"; SPC(12); "ANALYSIS POINT VELOCITY
DISTRIBUTION"
1990 'FINDS NUMBER OF ROCKS AT A GIVEN VELOCITY
2000 FOR J = IVANN TO IVANM
2010 IF IVELN(J) > LIN THEN LIN = IVELN(J)
2020 NEXT J
2030 '
2040 L = LIN: IK = IVANM - IVANN: IKH = IK / 2
2050 IF IK > 65 THEN IK = 65: IVANN = IVANM - 65
2060 'ROWS FOR # OF OCCURRENCES AT THE GIVEN VELOCITY
2070 FOR J = 1 TO LIN
2080 LPRINT TAB(4); L; TAB(9); CHR$(180);
2090 'COLUMNS FOR VELOCITY VALUES
2100 FOR K = IVANN TO IVANM
2110 IF IVELN(K) >= L THEN LPRINT CHR$(219);  ELSE LPRINT
SPC(1);
2120 NEXT K
2130 '
2140 L = L - 1
2150 NEXT J
2160 'LABEL AXIS
2170 LPRINT : LPRINT
2180 IF IK > 10 THEN LPRINT TAB(9); IVANN; TAB(IKH + 9);
IVANN + IKH; TAB(IK + 9); IVANM
2190 IF IK <= 10 THEN LPRINT TAB(9); IVANN; TAB(IK + 9);
IVANM
```

Appendix D
CRSP Basic Source Code

```
2200 LPRINT TAB(15); "VELOCITY": LPRINT CHR$(12): LPRINT
"FILE NAME: "; A$
2210 '
2220 REM ********* BOUNCE HEIGHT INTERVAL GRAPH ************
2230 '    GRAPH OF BOUNCE HEIGHT VS X POSITION
2240 '
2250 LPRINT "BOUNCE"; SPC(15); "BOUNCE HEIGHT GRAPH": LPRINT
"HEIGHT"
2260 NH = NH + 1
2270 ' SCALES GRAPH FOR MAXIMUM OF 20 ROWS
2280 FOR J = 1 TO 59
2290 IF IIBH(J) > 20 * NH THEN 2260
2300 IF IIBHM < IIBH(J) THEN IIBHM = IIBH(J)
2310 NEXT J
2320 '
2330 I = IIBHM + 1
2340 'ROWS FOR MAXIMUM BOUNCE HEIGHTS
2350 FOR J = 1 TO ((IIBHM + NH) / NH)
2360 LPRINT TAB(4); I; TAB(9); CHR$(180);
2370 'COLUMNS FOR X POSITION
2380 FOR K = 1 TO 59
2390 IF IIBH(K) > I THEN LPRINT CHR$(219);  ELSE LPRINT
SPC(1);
2400 NEXT K
2410 '
2420 I = I - NH
2430 NEXT J
2440 'LABEL AXIS
2450 LPRINT
2460 LPRINT : LPRINT TAB(9); "0"; TAB(18); INT(10 / SCA);
TAB(28); INT(20 / SCA); TAB(38); INT(30 / SCA); TAB(48);
INT(40 / SCA); TAB(58); INT(50 / SCA); TAB(68); INT(60 /
SCA)
2470 LPRINT TAB(20); "HORIZONTAL DISTANCE": LPRINT : LPRINT
2480 '
2490 REM ************ VELOCITY INTERVAL GRAPH **************
2500 '     GRAPH OF VELOCITY VS X POSITION
2510 '
2520 LPRINT SPC(20); "VELOCITY GRAPH": LPRINT "VELOCITY"
2530 NS = NS + 2
2540 ' SCALES GRAPH FOR MAXIMUM OF 20 ROWS
2550 FOR J = 1 TO 59
2560 IF IV(J) > 20 * NS THEN GOTO 2530
```

Appendix D
CRSP Basic Source Code

```
2570 IF IV(J) > IVMA THEN IVMA = IV(J)
2580 IF IVM < IV(J) THEN IVM = IV(J)
2590 NEXT J
2600 '
2610 II = IVM + 1
2620 ' ROWS OF MAXIMUM VELOCITY
2630 FOR J = NS TO INT((IVMA + NS) / NS)
2640 LPRINT TAB(4); II; TAB(9); CHR$(180);
2650 ' COLUMNS FOR X POSITION
2660 FOR K = 1 TO 59
2670 IF IV(K) > II THEN LPRINT CHR$(219);  ELSE LPRINT
SPC(1);
2680 NEXT K
2690 '
2700 II = II - NS
2710 NEXT J
2720 'LABEL AXIS
2730 LPRINT
2740 LPRINT : LPRINT TAB(9); "0"; TAB(18); INT(10 / SCA);
TAB(28); INT(20 / SCA); TAB(38); INT(30 / SCA); TAB(48);
INT(40 / SCA); TAB(58); INT(50 / SCA); TAB(68); INT(60 /
SCA)
2750 LPRINT TAB(20); "HORIZONTAL DISTANCE": LPRINT CHR$(12):
LPRINT "FILE NAME: "; A$
2760 '
2770 REM ************ CELL DATA OUTPUT *****************
2780 ' PRINTOUT OF DATA COLLECTED AT THE END OF EACH CELL
2790 '
2800 LPRINT TAB(10); "MAXIMUM"; TAB(22); "AVERAGE"; TAB(34);
"STANDARD"; TAB(46); "AVERAGE"; TAB(63); "MAXIMUM"
2810 LPRINT "CELL #"; TAB(10); "VELOCITY"; TAB(22);
"VELOCITY"; TAB(34); "DEVIATION";
2820 LPRINT TAB(46); "BOUNCE"; TAB(64); "BOUNCE"
2830 LPRINT TAB(10); "(FT/SEC)"; TAB(22); "(FT/SEC)";
TAB(34); "VELOCITY"; TAB(46);
2840 LPRINT "HEIGHT (FT)"; TAB(61); "HEIGHT (FT)": LPRINT
2850 '
2860 FOR I = 1 TO N
2870 IF ICC(I) = 0 THEN LPRINT I; "   NO ROCKS PASSED
POINT": GOTO 2950
2880 MN = CVT(I) / ICC(I)
2890 IF ICC(I) < 5 THEN SD = 0: GOTO 2910
2900 SD = SQR((R(I) - ICC(I) * MN ^ 2) / (ICC(I) - 1))
```

Appendix D
CRSP Basic Source Code

```
2910 IF ICVN(I) = 1000 THEN ICVN(I) = 0
2920 STAN = INT((SD + .005) * 100) / 100’STANDARD DEVIATION
OF THE VELOCITY
2930 LPRINT SPC(1); I; TAB(12); ICVM(I); TAB(23); INT(MN);
TAB(36);
2940 LPRINT STAN; TAB(47); INT(ICBHA(I) / ICC(I)); TAB(65);
IMCBH(I)
2950 NEXT I
2960 ’
2970 REM ********* ROCK STOP PRINTOUT **************
2980 ’ PRINTS OUT # OF ROCKS STOPPED PER 10’ INCREMENT
2990 ’
3000 IF IRSC > 0 THEN LPRINT : LPRINT TAB(5); "X INTERVAL";
TAB(20); "ROCKS STOPPED": LPRINT
3010 FOR J = 0 TO LRC - 1
3020 IF IRSC(J) > 0 THEN LPRINT 10 * J; " TO "; 10 * (J +
1); " FEET"; TAB(30); IRSC(J)
3030 NEXT J
3040 GOTO 3780
3050 ’
3060 REM **** DEFAULT VALUE SETTING ************
3070 ’ CHANGES DEFAULT VALUES FOR ROCK CONSTANTS
3080 ’
3090 INPUT "ENTER THE NUMBER OF SIMULATION ROCKS"; INR
3100 INPUT "ENTER THE STARTING VELOCITIES X,Y "; VX, VY
3110 INPUT "ENTER ROCK DENSITY IN LB/CF"; IRD
3120 PRINT "SELECT ROCK SHAPE"
3130 INPUT "1=DISK  2=CYLINDER  3=SPHERE"; ICHOICE
3140 ’
3150 ON ICHOICE GOSUB 3190, 3260, 3330
3160 ’
3170 RETURN
3180 ’
3190 REM ********* CALCULATIONS FOR DISK ****************
3200 ’  DETERMINES MASS AND INERTIA FOR DISK SHAPED ROCK
3210 ’
3220 INPUT "ENTER  RADIUS,THICKNESS  FOR DISK"; RXD, THICK
3230 M = IRD * RXD ^ 2 * THICK / 10.19: DIL = M * RXD ^ 2 /
2
3240 RETURN
3250 ’
3260 REM ********* CALCULATIONS FOR CYLINDER ************
3270 ’ MASS AND INERTIA OF CYLINDER
```

Appendix D
CRSP Basic Source Code

```
3280 '
3290 INPUT "ENTER  RADIUS,LENGTH FOR CYLINDER "; RADI, LENG
3300 M = IRD * RADI ^ 2 * LENG / 10.19: DIL = M * RADI ^ 2 /
4 + M * LENG ^ 2 / 12: RXD = LENG / 2
3310 RETURN
3320 '
3330 REM ****** CALCULATIONS FOR SPHERE ****************
3340 ' MASS AND INERTIA OF SPHERE
3350 '
3360 INPUT "ENTER RADIUS OF ROCK"; RXD
3370 M = IRD * RXD ^ 3 / 7.64: DIL = M * RXD ^ 2 / 2.5
3380 RETURN
3390 '
3400 REM *************** SCREEN GRAPHICS *************
3410 ' PRINTS SLOPE PROFILE ON SCREEN
3420 '
3430 IYLEAST = IYC
3440 ' FINDS LOWEST POINT ON SLOPE
3450 FOR J = 1 TO N
3460 IF IYS(J) < IYLEAST THEN IYLEAST = IYS(J)
3470 IF IYE(J) < IYLEAST THEN IYLEAST = IYE(J)
3480 NEXT J
3490 '
3500 IYR = IYC - IYLEAST' VERTICAL RANGE
3510 '    SELECTS SCALE FOR GRAPH
3520 IF (635 / (IXE(N) * 2.5)) < (165 / IYR) THEN SC = 635 /
(IXE(N) * 2.5) ELSE SC = 165 / IYR
3530 SCX = SC * 2.5' X AXIS SCALE
3540 '
3550 CLS : SCREEN 2: WIDTH 80   'INITIALIZE SCREEN
3560 'PRINT CELL LOCATIONS AND LABELS
3570 FOR J = 1 TO N
3580 IX = IXE(J) * SCX + 5: IY = (IYC - IYE(J)) * SC + 13:
LINE (IX, IY)-(IX, (IY + 10))
3590 IF ((IXE(J) - IXS(J)) * SCX) > 16 THEN LX = (IXS(J) +
IXE(J)) * SCX / 16: LOCATE 24, LX: PRINT J;
3600 NEXT J
3610 '   ANALYSIS POINT MARK AND BORDER
3620 IX = IXAN * SCX + 5: IY = (IYC - IYAN) * SC + 8: LINE
(IX, IY)-(IX, (IY - 10))
3630 LINE (5, 10)-(5, 175): LINE (5, 175)-(635, 175)
3640 FOR J = 1 TO INT(IXE(N) / 10)
3650 IX = J * 10 * SCX + 5: LINE (IX, 173)-(IX, 177)
```

Appendix D
CRSP Basic Source Code

```
3660 NEXT J
3670 FOR J = 1 TO INT(IYR / 10)
3680 IY = J * 10 * SC + 10: LINE (3, IY)-(7, IY)
3690 NEXT J
3700 '   SLOPE PROFILE
3710 FOR J = 1 TO N
3720 IX1 = IXS(J) * SCX + 5: IY1 = (IYC - IYS(J)) * SC + 10
3730 IX2 = IXE(J) * SCX + 5: IY2 = (IYC - IYE(J)) * SC + 10
3740 LINE (IX1, IY1)-(IX2, IY2)
3750 NEXT J
3760 '
3770 RETURN
3780 LPRINT CHR$(12)
3790 END
```