

Rockfall Hazard Analysis Using the Colorado Rockfall Simulation Program

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The Colorado Rockfall Simulation Program (CRSP) was developed to provide a statistical analysis of probable rockfall behavior at any given site and to be used as a tool to study the behavior of rockfalls, to determine the need for rockfall mitigation, and to aid in the design of rockfall mitigation. The basic theory behind CRSP is summarized, and the results of recent program modifications and calibration are discussed. CRSP uses numerical input values assigned to slope and rock properties to model rockfall behavior. 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 properties 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 slope irregularities. The program provides estimates of probable velocity and bounce height at various locations on a slope. Experimental verification and calibration of CRSP was conducted by analyzing videotapes of rocks traveling down a slope. A comparison of rock velocity and bounce height obtained from the tapes with CRSP prediction indicates reasonable agreement. Also, an evaluation of the sensitivity of input parameters indicates that slope angle and surface roughness are the most important parameters on steep slopes. Design graphs are developed based on CRSP simulations by using surface roughness and slope angle to estimate rock velocity and bounce height on uniform slopes.

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 paper, rockfall refers to rocks traveling in a combination of those modes. Rockfalls in this rapid down-slope motion present a common hazard to transportation and structures in steep mountainous terrain. Often, no protective measures are taken other than posting warning signs. The need for an understanding of rockfall behavior increases as more transportation routes and structures are placed in areas of rockfall hazards.

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 by using ditch-design criteria was often not applicable for the natural slopes or was aesthetically unacceptable considering the intense environmental pressure in Colorado and especially in Glenwood Canyon. 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. This information could best be provided by a rockfall simulation program for field office PC-compatible 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. CRSP simulates rockfalls at a site based on slope irregularities, slope materials, slope profile, and rock size. The final product is a reasonably easy-to-use rockfall simulation program.

The detailed development of the CRSP algorithm has been published previously (1,2). The purpose of this paper is to summarize briefly the basic theory behind the program and to discuss the results of recent work on program modifications and calibration and includes an evaluation of program sensitivity to input parameters, development of design charts for simple rockfall analyses, and presentation of field test results.

Experimental verification and calibration of CRSP was conducted in conjunction with the testing of rockfall fences at a site near Rifle, Colorado. The motion of rocks traveling down a slope and hitting the test fence was recorded on videotape. Researchers at the Colorado School of Mines added graphical data presentations to the program and analyzed the videotapes to aid the verification and calibration of the program (1).

LITERATURE REVIEW

The published literature contains abundant studies that deal with slope stability and rockfall mitigation measures, but there are few papers concerning the mechanics of rockfall motion (2). Because all rocks cannot be prevented from falling, an understanding of rockfall mechanics is important.

A rockfall study was conducted by Ritchie of the Washington Department of Transportation (3) in the 1960s. Ritchie observed the importance of angular momentum and bouncing ledges, or "ski jumps," in rockfalls by studying 16-mm films of rockfall. Criteria were developed from these observations for designing cut slopes and ditches, which are widely used today (4).

Several computer simulation models have been developed to describe rockfall dynamics in an effort to improve rockfall mitigation designs. Piteau and Associates (5) developed and tested a computer rockfall simulation program designed for a mainframe computer that produces velocity and bounce

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height probability distributions from the input coefficients, slope geometry, and probability of surface variations. During the relocation of I-40 in North Carolina, the North Carolina Department of Transportation produced the program ROCKSIM to simulate rockfall and to test the effectiveness of widening the roadway ditch to mitigate rockfall hazard (4,6). Hoek (7) in 1987 also developed a copyrighted computer program to model rockfall. The development of CRSP relied on many of the basic concepts used in some of those programs but with the idea of improving on the individual approaches.

A study conducted by Evans (8) at the University of Arizona compared and tested ROCKSIM, Hoek's program, and CRSP. The study incorporated data from 260 induced rockfall events with eight different slope geometries. Evans found CRSP to be the most consistent at predicting rockfall behavior and incorporated it into a program to aid in the design of rockfall catch benches.

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. Every effort has been made to make the model as accurate as possible, but the program user must decide on the quality of the data produced by CRSP.

CRSP requires the following input data:

- A slope profile, input as a series of straight line segments called cells, designated by the coordinates of the end points of each line;
- An estimation of the roughness of the slope surface within each cell;
- Estimated coefficients that quantify the frictional and elastic properties of the slope; and
- The size, shape, and starting location of 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 are produced by CRSP:

- Slope profile showing cell locations and the position of each simulation rock every tenth of a second as it travels down the slope;
- Maximum and average bounce heights at the end of each cell and for one selected location on the slope;
- Maximum and average velocities at the end of each cell and at the selected location on the slope;
- Maximum total kinetic energy of the falling rock at the selected location on the slope;
- Histograms of the distribution of velocities and bounce heights at the selected location on the slope; and
- 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 that enables 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. The theory behind CRSP has been discussed in detail in previous papers (1,2). However, it is important to provide a general discussion of theory here for the reader who is unfamiliar with the earlier work.

Rockfall Parameters

The behavior of rockfalls is influenced by slope geometry, slope material properties, rock geometry, and rock material properties (1,5). Rockfalls originating from the same source location may behave very differently as a result of the interaction of those factors. Parameters that quantify the factors listed are used in CRSP to model rockfall behavior (Table 1).

TABLE 1 PARAMETERS DETERMINING BEHAVIOR OF ROCKFALLS (2)

Factor	Parameter
Slope Geometry	Slope Inclination Slope Length Surface Roughness
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 inclination, slope length, and surface roughness are slope geometry parameters influencing the behavior of rockfalls. 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 then by 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. Those irregularities, referred to in this paper as surface roughness, alter the angle at which the rock hits the surface. It is this impact angle that largely determines the character of the bounce (4). CRSP models the effects of surface roughness by randomly varying the slope angle between limits defined by the rock size and surface roughness. The surface roughness and maximum variation of the slope angle (Θ_{max}) is defined in Figure 1.

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 (R_n) and the tangential coefficient of frictional resistance (R_t), where the normal direction is perpendicular to the surface and the tangential direction is parallel to the surface (3,4). The velocity components (V_n, V_t), coefficients (R_n, R_t), impact angle (α), and slope variation (Θ) are illustrated in Figure 2.

Separate normal and tangential coefficients are necessary owing to the different mechanisms involved in resisting motion normal and tangential to the slope to determine new velocity components for a rock following impact. When a rock bounces on a slope, kinetic energy is lost owing to inelastic components of the collision and friction. The primary mechanism in resisting motion parallel to the slope is sliding or rolling friction, but the elasticity of the slope determines the motion normal to the slope. R_n is a measure of elasticity in collisions normal

to the slope, and R_t is a measure of friction parallel to the slope. Tables 2 and 3 present the suggested ranges of coefficients for use with CRSP developed by observation and literature review (1,2).

Assumptions

For a natural slope the 11 parameters in Table 1 typically have a wide range of values and would be difficult to analyze as independent variables. It is convenient to reduce the number of variables by means of the following simplifying assumptions:

- Lateral slope variability need not be considered because the slope profile follows the most probable rockfall path as established by field investigations.
- Coefficients assigned to the slope material can account for both the rock and slope properties because the rock type is constant for each analysis and the range of slope material properties is much greater than that of rock material properties.
- The worst-case scenario is generally that of the largest rock that remains intact while traveling down a slope. Therefore, it is assumed the rock does not break apart in its fall.
- Rock size and mass are assumed constant for analysis of rockfall from a given source. This is justified by the worst-case assumption.
- A sphere may be used to determine a rock's volume and inertia because a sphere yields a maximum volume for a given radius that will tend toward a worst case.

Algorithm

Kinetic energy is lost in any nonperfectly elastic collision. In the case of a rock hitting 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 (R_t)

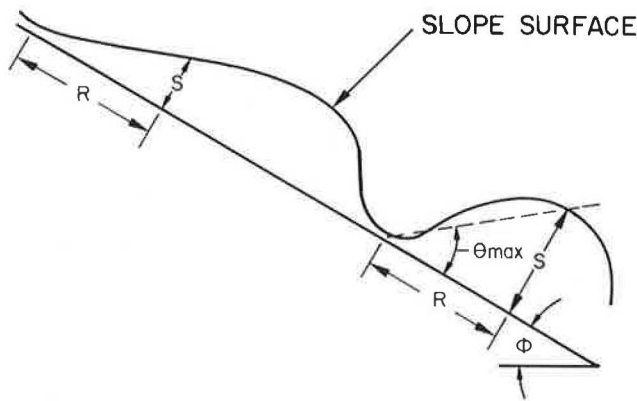


FIGURE 1 Surface roughness (S) established as the perpendicular variation within a slope distance equal to the radius of the rock (R). Maximum slope variation (Θ_{max}) defined by S and R .

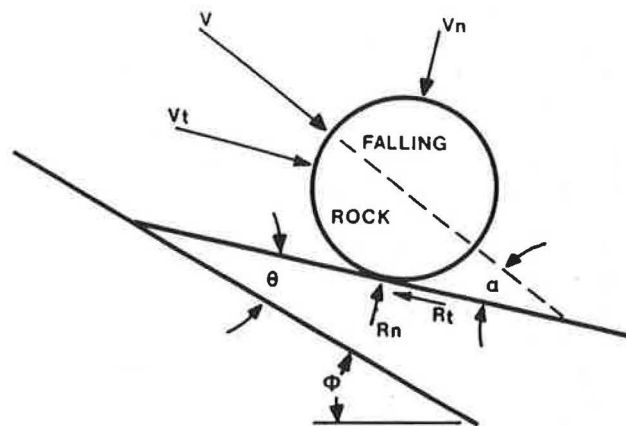


FIGURE 2 Impact angle (α) defined as a function of rock trajectory, slope angle (Φ), and slope variation (Θ). V_n , velocity normal to the slope; V_t , velocity tangential to the slope; R_t , coefficient of frictional resistance tangential to the slope; R_n , coefficient of restitution normal to the slope.

TABLE 2 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.

TABLE 3 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 sparse vegetation.
0.78 - 0.82	Brush covered soil slope.

and whether the rock is initially rolling over or sliding on the surface. A friction function is used to adjust 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 (2).

The velocity normal to the slope is another major influence on the loss of kinetic energy tangential to the slope. An increase in velocity normal to the surface results in a greater normal force during impact. A scaling factor is incorporated to adjust for the increased frictional resistances owing to an increase in the normal force. CRSP considers angular momentum by allowing rotational energy to be converted to tangential energy or by allowing tangential energy to be converted to rotational energy (1,2).

The normal coefficient of restitution (Rn) and a velocity-dependent scaling factor are used to determine a new normal velocity. A normal scaling factor adjusts for the decrease in normal coefficient of restitution as the impact velocity increases (2). This factor represents a transition from a more elastic rebound at low velocities to a much less elastic rebound caused by increased fracturing of the rock and cratering of the slope surface at higher impact velocities (2,9).

An iteration is used after each bounce to find the time elapsed until the next bounce. Elapsed time is calculated from the x , y velocities, gravitational acceleration, and the slope profile. The next bounce is calculated as before after a new

impact position is established. If the distance the rock travels between bounces is less than its radius, then the rock 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 (2).

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 effects of surface roughness and slope material coefficients decrease on steep slopes because the rock bounces less often.

As is 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 presented in Figure 3. The average rockfall equilibrium velocity from Figure 3 is the average velocity predicted by CRSP after the

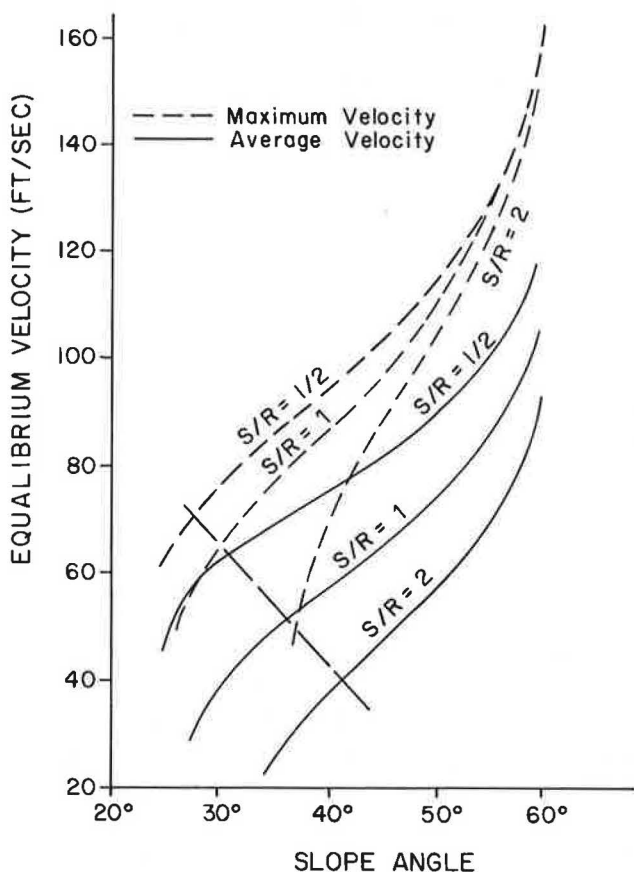


FIGURE 3 Maximum and average equilibrium velocity versus slope angle for uniform slopes.

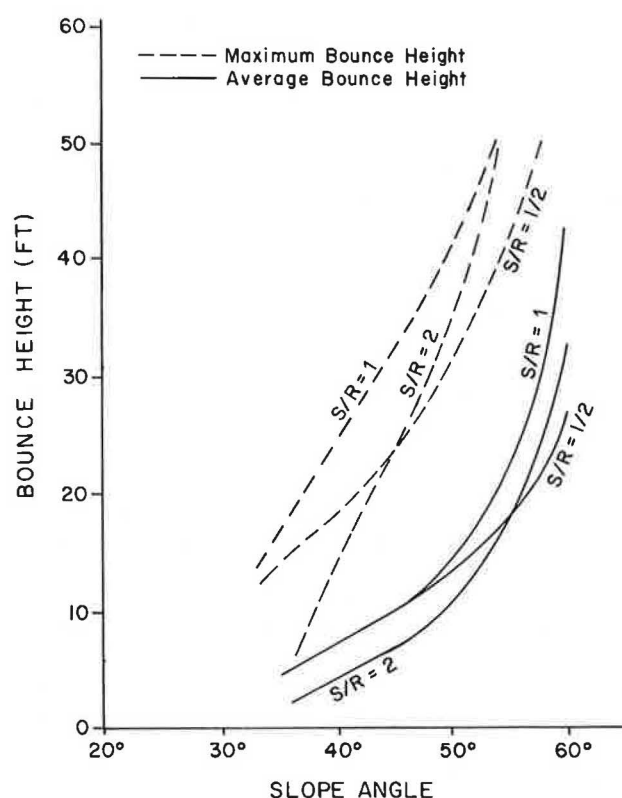


FIGURE 4 Maximum and average equilibrium bounce heights versus slope angle.

equilibrium condition is reached. The maximum equilibrium velocity predicted is the velocity of the fastest rock.

Bounce height will also tend to reach an equilibrium height on long slopes. The relationship between slope angle and bounce height is presented in Figure 4.

Also important in determining rockfall behavior is surface roughness. The ratio of the surface roughness to rock size (S/R) is used to determine the maximum variation in the slope. Therefore, the effect of surface roughness may be studied by investigating the effect of S/R (defined in Figure 1). Figures 3 and 4 indicate that 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 degrees. However, on shallower slopes the decrease in velocity with increasing S/R ratio results in a decrease in bounce height.

Material coefficients affect rockfall behavior by controlling the amount of energy absorbed during impact. Higher coefficient values correspond to less energy loss during impact. The effect of material coefficients on bounce height and velocity depends on the number of impacts or bounces. On steep slopes, where rocks hit 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 (1).

To summarize, several factors act to reduce the effect of slope material on rockfall behavior. First, the effect of slope angle and surface roughness is so much greater than the effect of material properties that the angle and roughness obscure the effects of variations in material coefficients. Second, the coefficients are modified by scaling factors and the friction function, which tend to further obscure the results of changes in coefficients. Third, and most important, is that the velocity normal to the slope at impact depends on the impact angle, which is determined by the slope angle, rock radius, and surface roughness. For those reasons the effect of variations in material coefficients depends largely on the slope configuration.

Figures 3 and 4 provide a basis for developing a conceptual understanding of the relationships between the input parameters and may also be used to make estimates of probable rockfall bounce heights and velocities for uniform slopes. However, cases with variable slope angles are too complex for estimates by using those graphs.

Figures 3 and 4 are limited to slopes between 30 and 60 degrees. The energy lost during the bounce will always be less than the energy gained between bounces on slopes greater than about 60 degrees, and the velocity will decrease until the rock comes to rest on slopes of less than about 30 degrees. Figure 3 was developed for hard, rocky slopes. The equilibrium velocity for soil slopes of less than about 40 degrees will be about 15 percent less than that predicted by the graph. The effect of surface material will be negligible on slopes steeper than 50 degrees.

Figure 3 gives the average and maximum equilibrium velocities. The rockfall may not reach the equilibrium condition for slopes shorter than 300 to 500 ft. In this case the average and maximum velocities may be obtained by multiplying the velocity from Figure 3 by the distance factor obtained for the slope length and angle in Figure 5. Similarly, the bounce height values obtained from the graph in Figure 4 may be corrected for slope length by multiplying by the distance factor obtained from Figure 5. Those products are an estimate of the velocities and bounce heights that would be predicted by CRSP for uniform slopes (*I*).

CRSP FIELD TESTING

Rocks were rolled down a 300-ft-high hillside near Rifle, Colorado, to test rockfall fence designs and to collect data on rockfalls for verification and calibration of CRSP. The test hillside consisted of thin desert soil with rocky ledges (Figure 6). The 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. Figure 7 presents the slope profile of the test site.

The time for each rock to travel through two zones of the hillside, the number of bounces in each zone, and the bounce height at the analysis point were collected from viewing videotapes of the rockfalls. Those data were compared with data generated by CRSP. The program required modification to present the travel time data (*I*). Material coefficients were chosen according to the guidelines presented in Tables 2 and 3.

Figure 8 presents a graphical representation for the simulation at the West Rifle test site. Dots that represent the position of the simulation rock every tenth of a second occur in characteristic parabolic arcs above the slope profile. This visual aid can be helpful to determine the most likely locations for and types of mitigative measures that can be taken.

Figure 9 presents the distribution of simulated rock velocities and bounce heights produced for the analysis point near the base of the slope and maximum bounce heights and velocities along the slope profile. Those results provide estimates of parameters required for the location and design of fences, ditches, or other types of structures at the selected analysis point.

Table 4 compares the field tests with CRSP results. Because CRSP attempts to represent worst-case situations, only data from the fastest 50 percent of the rocks rolled were used in the comparison. The comparison in Table 4 indicates that CRSP was able to provide reasonable predictions of rockfall behavior.

CRSP Application in Glenwood Canyon

CRSP has been used extensively to aid in the design of rockfall mitigation for I-70 in scenic Glenwood Canyon where aesthetic values were an important concern. The steep canyon slopes above the road lead to frequent rockfalls in the 15-mile-long canyon. Rockfalls may originate both high on the steep

canyon slopes and from rock cuts and natural cliffs near the roadway. Rockfall hazards from high on the canyon slopes may be reduced by using catch fences designed with the aid of CRSP. Rockfall hazards associated with rock slopes closer to the highway may require other mitigative measures such as benches or ditches.

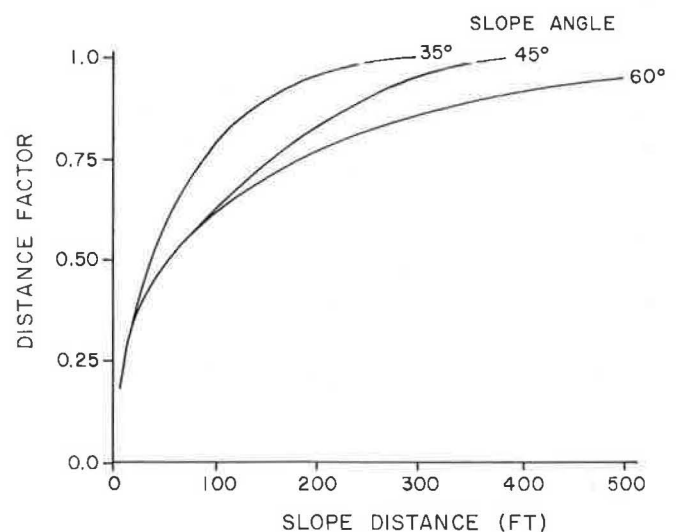


FIGURE 5 Distance factor indicating the proportion of the equilibrium velocity achieved versus horizontal slope distance.



FIGURE 6 Slope used for CRSP testing near Rifle, Colo.

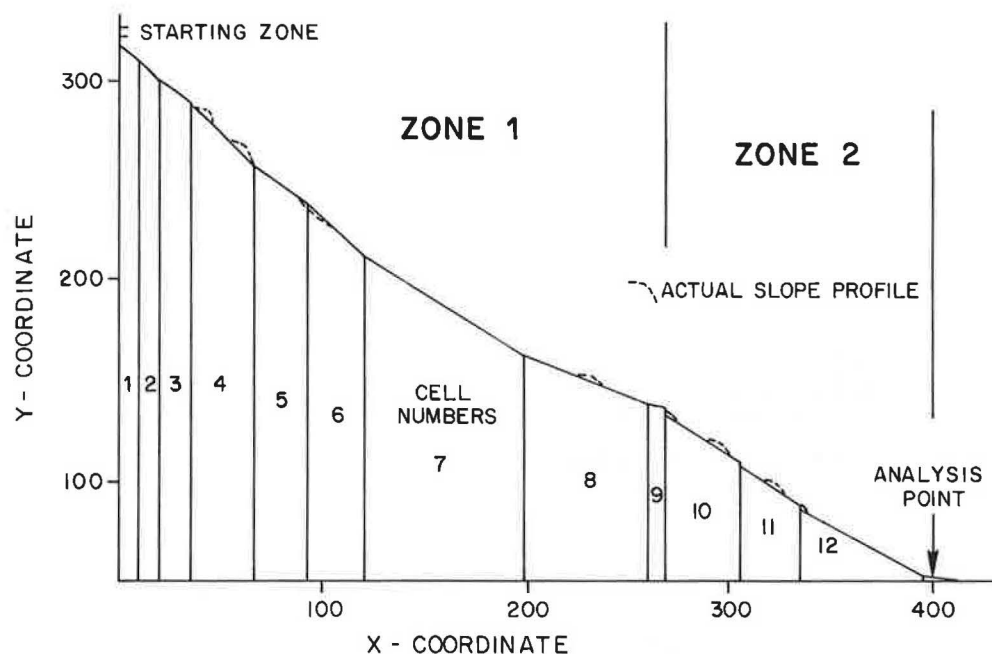


FIGURE 7 Slope profile of West Rifle test site.

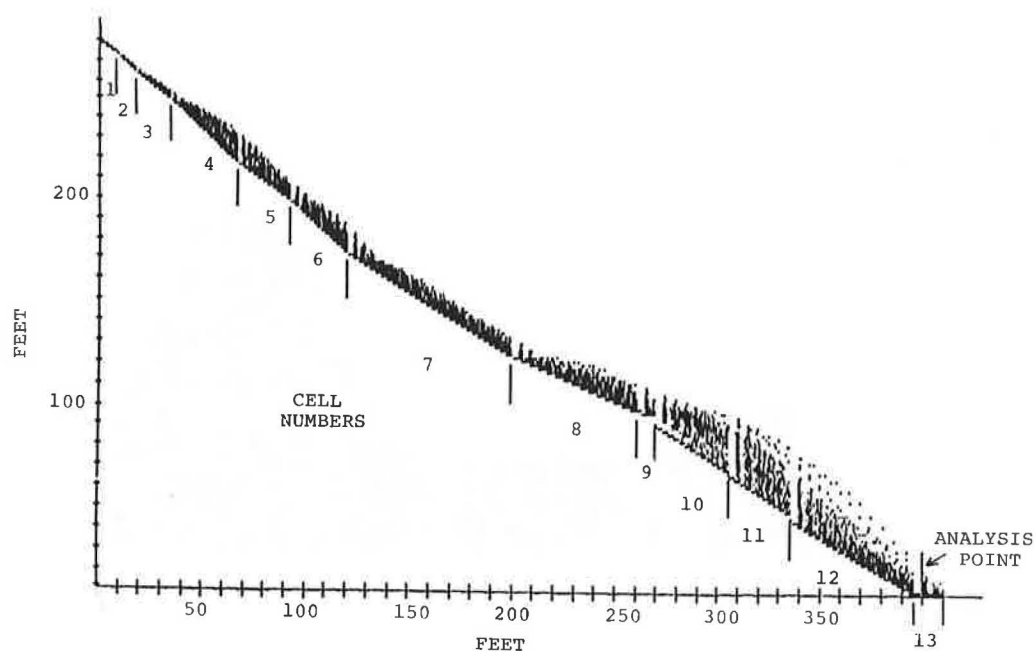


FIGURE 8 CRSP graphical representation of rockfalls at the West Rifle test site.

The concern for aesthetics was the driving force behind the design philosophy to minimize disturbance to natural slopes and to construct rock cuts to look natural. Therefore, rock cuts were constructed with irregular cut faces and minimal planted ditches or benches. However, those construction methods could result in a greater rockfall hazard than that associated with traditional rock slope design considerations that call for even, presplit slopes and large ditches. Few prac-

tical methods were available to assess the rockfall hazard associated with irregular slopes before the development of CRSP.

CRSP use allows compromises between the landscape architect's aesthetic concerns and concerns for rockfall safety. Safe rock cuts could be designed and constructed while still incorporating planted benches and the irregular shape needed to have the appearance of a natural rock slope. The "ski

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

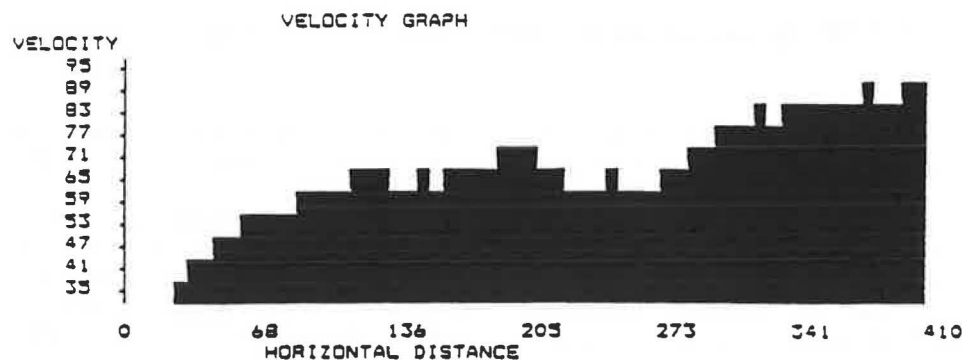
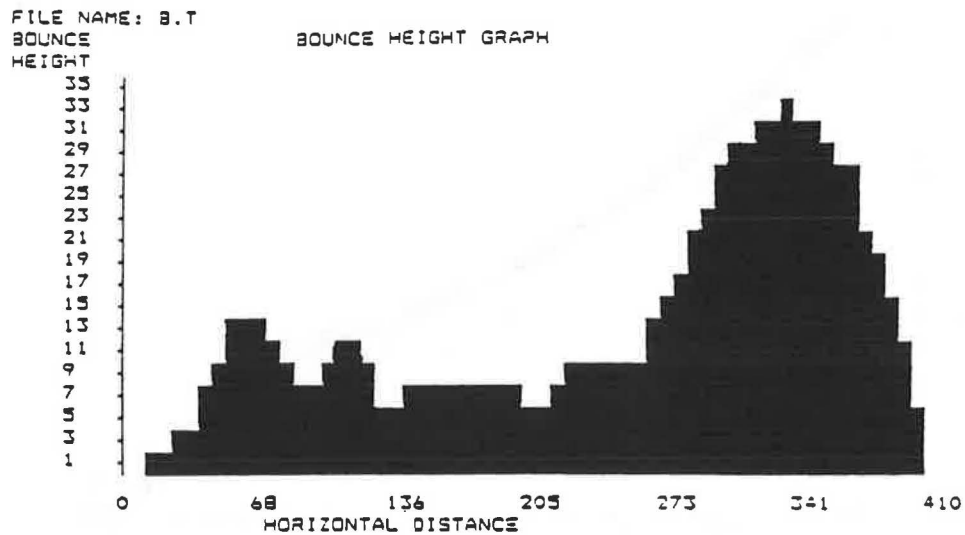
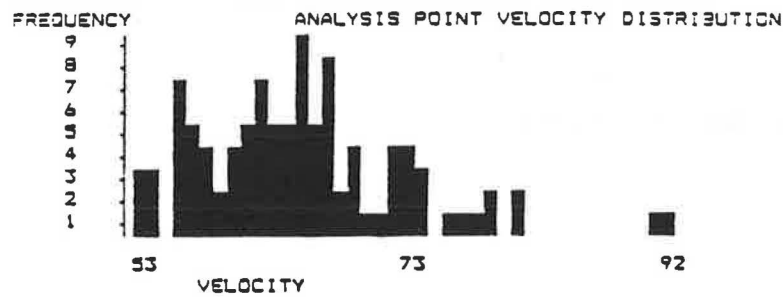
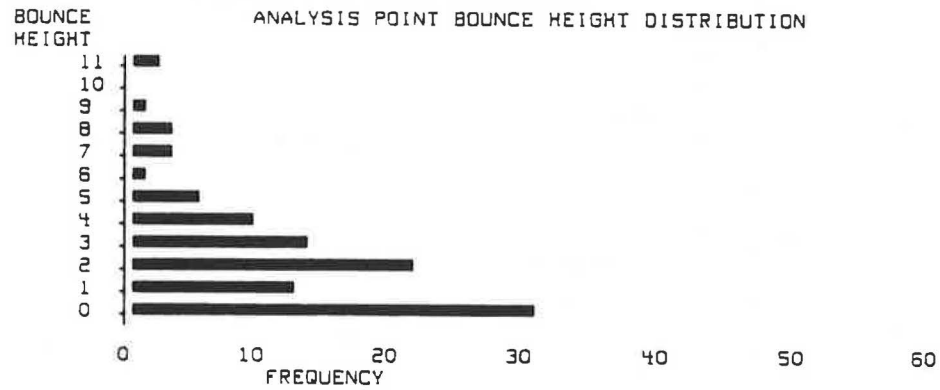


FIGURE 9 CRSP output of the distribution of rockfall simulations by (a) bounce height and velocity for the analysis point and (b) maximum bounce heights and velocities along the slope profile at the West Rifle test site.

TABLE 4 COMPARISON OF FIELD DATA FROM THE WEST RIFLE TEST SITE WITH DATA GENERATED BY CRSP

	ZONE 1		ZONE 2		ANALYSIS POINT
	TIME	# OF	TIME	# OF	BOUNCE
	SEC.	BOUNCES	SEC.	BOUNCES	HEIGHT (FT)
FIELD DATA					
SAMPLE SIZE	(23)	(21)	(19)	(18)	(17)
AVERAGE	8.72	12.6	2.58	2.0	2.52
RANGE	7.8-9.8	10-16	2.2-2.9	1-4	0-11
STANDARD DEVIATION	0.61	1.43	0.23	0.88	3.36
CRSP DATA					
AVERAGE	8.4	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	0.95	1.85	0.38	0.64	2.43

jump" effect of proposed bench locations and size was modeled, allowing adjustment of location and size to reduce the likelihood of launching rocks into the roadway.

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 useful visual aid to convince landscape architects that design changes were needed to reduce rockfall hazard.

At some locations, CRSP would indicate that rockfalls could present a hazard to the roadway, but wider ditches or reshaping of the slope did not present a practical solution. CRSP was used to evaluate alternative methods of rockfall mitigation located above the roadway in those cases.

CONCLUSIONS

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

Even though determining input values and using the output data requires judgment, the computer analysis adds objectiv-

ity to an otherwise largely subjective investigation of rockfall hazard. Because this computer program provides a site-specific analysis of rockfall, the program may help identify areas where roadside ditches can be narrowed or where alternate rockfall mitigation measures should be considered. Rockfall simulation may also note 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.

The CRSP method of rockfall analysis has been in use on the Glenwood Canyon project and at the Rifle, Colorado, test site. Also, it has been tested by using field data from the technical literature and data provided by practitioners. However, CRSP is still in the field-testing and development stages. The program will need industry-wide use in a variety of situations to ensure the validity of the program output and to identify any limitations of the program.

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The contents of this paper reflect the views of the authors and do not necessarily reflect the official views or policies of CDH or FHWA.

CRSP is available from the Research Section, Colorado Department of Highways, 4201 East Arkansas Avenue, Denver, Colo. 80222, (303) 757-9506.

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