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Assessment of rockfall rollout risk along varying slope geometries using the Rocfall and CRSP software

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ASSESSMENT OF ROCKFALL ROLLOUT RISK ALONG VARYING SLOPE GEOMETRIES USING THE ROCFALL AND CRSP SOFTWARE

by

MARIAM S. AL E'BAYAT

A THESIS

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Approved by

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ABSTRACT

Most routes in mountainous areas suffer from rock falling, rolling and bouncing risk. There are many computer programs concerned with simulating the rockfall problem, and whereas they have the same purpose, they however differ in the input data that's needed to simulate the problem, and they also differ in the way of processing and kind of output.

This study used Rocfall® and the Colorado Rockfall Simulation Program (CRSP®) to simulate sixty-three models of varying slope geometry, where only the slope geometry is changed with the same material properties for both the slope and the rocks.

Both programs were fast and easy in the data input stage, whereas the "Barrier" feature of Rocfall added an advantage over the CRSP program in enhancing the solving of the rockfall problem. Also, "Data Collectors", "Results Animation" and "Graph Distribution" on the slope profile help display the analysis results in Rocfall.

Generally, the Rocfall and CRSP program results are not similar. The rock falls at a different angle in each program; CRSP is closest to the Physics theory, so that affects the results. Also, the rocks can be located just at (X=0) in CRSP that affects the allowed number of rocks falling along slope profile.

Despite of the differences between the Rocfall and CRSP programs, their results indicated the slopes with 90^0 slope angle is the ideal slope geometry for rockfall problem. For vertical slopes, no rocks passed the shoulder edge onto highway in both programs. CRSP results indicated that the percentage of rocks that reach the highway are increasing when the slope height increases.

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®CRSP is a registered trademark of Colorado Geological Survey (CGS).

ACKNOWLEDGEMENT

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1. INTRODUCTION

The degree of risk and hazard due to rockfall in mountain routes varies depending on the size of the rock cuts, the traffic volume and vehicle type. Rockfall (The term rockfall in this study refers to the free-falling rocks from the top of slope until they reach stability) directly affect vehicles or cause them to swerve off the road when rock sizes are large, while small sharp rock fragments may damage the tires and cause cars on the road crash. Rockfalls can cause injuries or death to drivers and passengers. As well, the economic and social impact of closed roads is considerable.

Free falling rocks are classified into four categories, based on their sizes; single block falls (involved volume ranging between 10^{-2} and $10^{2}m^{3}$), mass falls (10^{2}–$10^{5}m^{3}$); very large mass falls (10^{5}–$10^{7}m^{3}$) and mass displacement (more than $10^{7}m^{3}$) (Rochet, 1987). In this study, the first type (involved volume ranging between 10^{-2} and $10^{2}m^{3}$) of rockfalls were used, which are known as "fragmental rock falls" meaning there are no interaction among the falling blocks and each block falls freely.

The most frequent triggers of rockfalls are mainly related to the winter season, with phenomena such as rainfall, freeze-and-thaw cycles, snowmelt, channel runoff, and springs and seeps. Also, the site geological conditions like the effect of discontinuities rock, rock types and slope inclination affect the stability of rock slopes. In addition, rock decomposition, man-made activities and earthquakes can stimulate rockfall.

Usually, the rock cuts created to facilitate highway constriction were designed in a stable geometry under the site geological conditions. Despite that the rock cut is constructed in a stable geometry, rockfalls pose a problem on the transportation corridors because of climate, rock mass condition and slope geometry. Consequently, rock cut design is done to create stable slopes but also to minimize rockfalls and reduce sliding problems. Some of the design parameters include slope height, length, angle, and shoulder angle.

Accordingly, numerical modeling of rock slopes is used to simulate slopes and help to understand the varying strengths and limitations inherent in each slope design to get the perfect slope geometry. For this reason, there are many numerical applications available to simulate and solve rockfall problems. Furthermore, numerical modeling helps to solve the problem in easy way and a short time.

The purpose of the rockfall modeling programs is simulating the rockfall problems, however, modeling programs differ in the way they define the problem, how they process the parameters and how they display the results. This research used Rocfall (Rocscience 2013) and CRSP (Colorado Rockfall Simulation Program) to study how these programs simulate and analyze the down slope movement of falling rocks, and determine the ideal slope geometry that produce the minimum rollout risk of falling rocks.

1.1. OBJECTIVES OF THE STUDY

The objectives of the study are:

- To determine the differences and similarities between the Rockfall program and Colorado Rockfall Simulation Program (CRSP) in how each of these programs handles the simulation of the falling rocks. Rockfall, in this study, is defined as the free movement of loosened blocks of rocks along slopes under gravitational force only. This movement could be in a form of rolling, bouncing or free falling.

- To determining the ideal slope geometry that minimizes the rollout falling rock risks on highways using (i) slope angle (ii) slope height (iii) the inclination of the ditch parameters.

1.2. IMPORTANCE OF THE STUDY

This kind of studies help to improve rock cut design for road safety, particularly along mountain roads. People who live in mountainous areas, often have one access road to link them to the necessary services. Blocking of these roads by falling rocks, essentially might in some situations constitute life and death conditions, hence designing roads cuts with appropriate parameters is important to communities. This study will help engineers construct safer roads by providing the optimum slope parameters during the design process. Governments can also benefit from this study in cutting the cost of maintenance and other hidden costs such as the hospitalization cost of the driver and passengers, the repair of the vehicle, the legal costs, and compensation.

2. LITERATURE REVIEW

In this section are listed some previous studies that surveyed rockfall problems along transportation corridors. These discussed the causes and degree of risk on the humans and on traffic. Finally, some of the programs listed were used to simulate the slopes to determine where is the risk zone along the maintain roads and allow the engineers to examine suitable solutions then choose the ideal one for the problem quickly and easily.

2.1. CAUSES OF ROCKFALL AND DRIVED DAMAGES

Peila and Guardini, (2008) referred most of the rockfall causes to rainfall, the freeze-thaw process, snowmelt, channel run-off, differential erosion, springs and seepage and the physical stress exerted by the growth of tree roots in cracks, which eventually create fractures in the rocks and loosen the blocks on the slopes. Most landslides/rockfalls in India are associated with the monsoon season (June – September) compared to winter season (December - March). The main weather factor triggers rock fall is rain, where about 30% of rockfalls are initialed by rainfall, which is usually more intense during monsoon time. Because of the heavy rainfall on 18th August 1998 in Uttarakhand, landslides and rockfalls occurred and caused a disaster on the Malpa village, where 220 people killed and village destroyed completely. Also, the heavy rainfall of July 25th, 2013, triggered a huge size rockfalls (boulders were almost of the size of two trucks size). The disaster killed two people and blocked the highway for almost a week. (Ansari 2014).

Keefer (2002) showed that rockfalls are also triggered by earthquakes, which also drive the most disastrous types of landslides, soil slides and rock slides. Keefer's results were based on 40 worldwide studies of historical landslides triggered by earthquakes.

According to Word Bank data, developing and under-developing countries are suffering from natural disasters including, earthquakes, landslides, floods and rock-falls. Natural disasters have substantial economic impacts that estimated to be a minimum of $10 billion in 2008, and as well, the death toll estimated to be to take the life of 235,000 persons in the same year. (Kumar 2009).

2.2. ROCKFALL DAMAGE MITIGATION

Most of USA highways rock cut were designed by using Rock Hazard Rating system (RHR), The Missouri Rock Fall Hazard Rating system (MORFH RS) (Maerz et al. 2005) was prepared for Missouri highways after evaluation of about 300 rock cuts. MORFH is distinct from the others, because it considers both the risk and consequence of rockfall. MORFH includes 23 factors; 9 factors for risk, 10 factors for consequence, 3 adjustment factors (2 for risk and 1 for consequence), and one factor for an internally calculated value. The range of rating is from 0 to 100, where the 100-value rating indicates to maximum risk and consequence. However, other rock hazard rating systems focus on the risk of failure and disregard the consequence of failure or mix both risk and consequence into a single classification value such as New York's system (Hadjin, 2002), Oregon's RHR system (Pierson and Van Vickle, 1993), Tennessee (Bateman, 2002; Bellamy et al., 2003; Vandewater et al., 2005), Washington RHR System (Badger, 1992), and Colorado RHR System (Santi et al. 2009).

Maerz & Youssef (2009) studied the stability of limestone rock cut face (2km) located on Eastern Desert Highway in Saudi Arabia, where found the geologic, method of excavation and road design factors are affect the rock cut instability after simulated the rock cut by using the Missouri rock fall hazard rating system (MORFH RS) and the Colorado Rockfall Simulation program (CRSP). Because the highway faced a real risk from rocks that come by free falling, toppling, bouncing, rolling or sliding from the rock cut, the mesh draped over the rock cut face is the most suitable solution to mitigate the rockfall risk. Furthermore, rockfall posed a threat along the roads of Fayfa Mountain in the Kingdom of Saudi Arabia. Rock cuts were assessed by Maerz & Youssef (2014) based on Missouri Hazard Rating System (Maerz et al. 2005). After defining the higher risk rock cuts, several suitable solutions had been chosen such as, scaling of loose rock, reshaping the slope and increasing the ditch capacity (preferred solutions), that, in additional to other expensive solutions such as anchoring systems, anchored retaining walls, draped mesh, and sacrificial fences.

2.3. ROCK ROLLOUT MODELING PROGRAMS.

The Colorado Rockfall Simulation Program (CRSP) was developed by the Colorado Department of Transportation to aid in rockfall mitigation design. CRSP allows definition of the slope geometry and then predicts the flow of debris along the slope. Maerz & Youssef (2009) used CRSP to simulate the rock cuts after dividing the slope to 5 sections with differing geometry. Also, the Washington State Department of Transportation (WSDOT) used CRSP to developed rock cut design for mitigation of rockfall hazard (Thomas & Steve, 1992).

I’nan, (2011) used the Rockfall program to examined the risks of rockfall on a settlement near the intersection of the North Anatolian fault line (NAF) and East Anatolian fault line (EAF), Turkey. The settlement is located at the vicinity of an active earthquake and it is highly prone to catastrophic rockfalls.

The tourist cave and pathway site of Ajanta, India are jeopardized by rockfalls. This has encouraged the researchers Ansari and Singh (2013) to simulate the jointed basaltic rocks of the area using the Rockfall program. Discontinuities and rainfall represent major driving factors for rockfall in this region.

Moreover, STONE is a computer program that help to simulate the slopes and show the movement of free falling rock along the slope. Guzzetti, et. al., (2003) used the STONE program to estimate rock-fall runout in Yosemite National Park (Guzzetti, et. al., 2002). In additional, (Budetta, et. Al., 2004) used the Hoek’s rockfall program (Hoek, 1998) to analyze seven cross sections along section of the Sorrentine Road in Southern Italy.

Barla (2001), used UDEC (Universal Distinct Element Code, 1996) to describe the Brenva Glacier rock avalanche along the Mount Blanc, where fragments as well as ice and snow were rollover along the mountain side. Also, Sun (2004) studied the truck dumping along the slope, which it represents rockfall.

3. METHOD OF STUDY

This study assumes that all simulated slopes are considered to be of homogeneous material, and only the geometry varies among the slopes. Sixty-three slope designs were defined in this study by changing the geometrical parameters and these were simulated using the Rocfall and CRSP modeling software. Table 3.1 shows the variable geometry parameters for sixty slopes.

Table 3.1. Variable Geometry Parameters.

Slope Angle	Slope Height	Ditch Angle	Slope Angle	Slope Height	Ditch Angle
90	20	0	60	40	45
90	20	30	60	40	90
90	20	45	60	80	0
90	20	90	60	80	30
90	40	0	60	80	45
90	40	30	60	80	90
90	40	45	45	20	0
90	40	90	45	20	30
90	80	0	45	20	45
90	80	30	45	20	90
90	80	45	45	40	0
90	80	90	45	40	30
75	20	0	45	40	45
75	20	30	45	40	90
75	20	45	45	80	0
75	20	90	45	80	30
75	40	0	45	80	45
75	40	30	45	80	90
75	40	45	30	20	0
75	40	90	30	20	30
75	80	0	30	20	45
75	80	30	30	20	90
75	80	45	30	40	0

Table 3.1. Variable Geometry Parameters Cont.

Slope Angle	Slope Height	Ditch Angle	Slope Angle	Slope Height	Ditch Angle
75	80	90	30	40	30
60	20	0	30	40	45
60	20	30	30	40	90
60	20	45	30	80	0
60	20	90	30	80	30
60	40	0	30	80	45
60	40	30	30	80	90

3.1. PARAMETERS OF SLOPE GEOMETRY

The geometry and parameters of slope are illustrated in Figure 3.1 below.

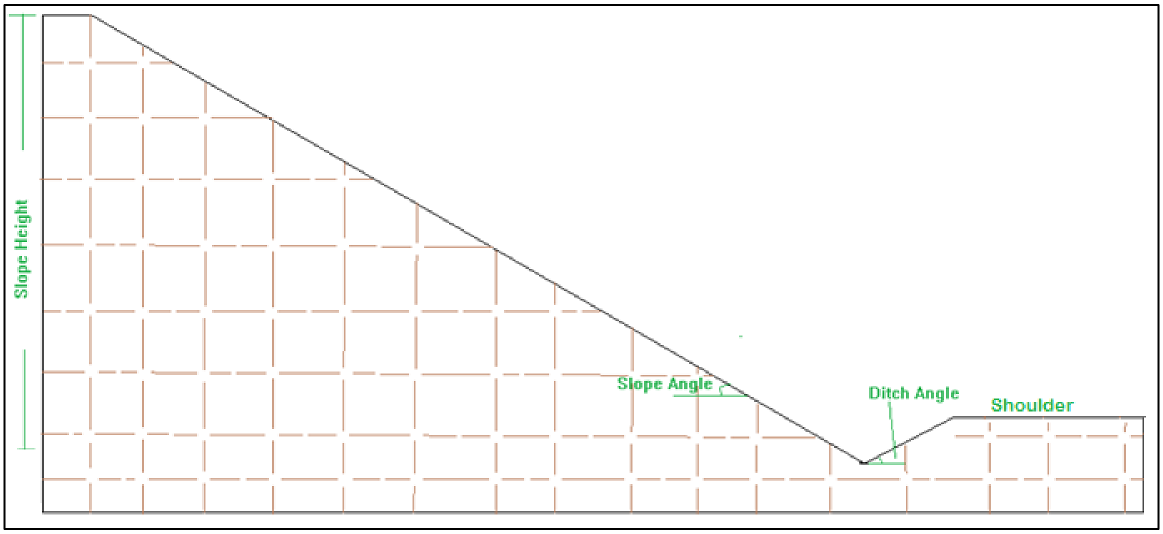


Figure 3.1 Slope Parameters

- The Slope Height represents the vertical distance of the slope measured from the highest point from which rockfall are expected to fall to the bottom of the slope.
- Slope Length represents the inclined length of the slope, measured from the beginning point where rockfall are expected to start moving to the toe of the slope.

- Slope Angle is the angle in degree of the slope face, and is expressed in degrees (e.g. 45^o) or as fraction a ratio (vertical/horizontal; e.g. 1/2) of slope.
- Ditch Size is the size of the area that is available to catch the falling rock and prevent it from reaching the road. Ditch effectiveness is dependent on ditch width, depth, and shape. In this research, ditch size was defined by the ditch angle, because ditch depth and shape could be derived from ditch angle, where the width of all slopes is constant equal to 1.75m.
- Road shoulders are a part of the road vehicles use in emergencies and serve as a support for base of road.

3.2. MODELING SOFTWARE

Two software packages were used in this study to model rock runout along the slope.

3.2.1. Rocfall Software. The Rocfall program, version 5.0, was utilized in modeling the rockfall problems and in simulating their profiles in two dimensions (2D). It was used also for the prediction of rockfall behavior on slopes after defining the geometry and parameters of the slope and the quantity, shape, parameters, and position of the rock falling.

3.2.2. CRSP Software. The Colorado Rockfall Simulation Program (CRSP), version 4.0, 2000, was utilized in modeling the slopes and in simulating their profiles in two dimensions (2D). It was used also in modeling the slope material, slope irregularities, ditch shape and the rock size and quantity.

4. PROGRAMMING AND CODING

4.1. PROBLEM STATEMENT

This study seeks to define slope geometries that prevent loose rocks from reaching the roadway. A lot of slope geometries are needed to find the ideal one which will minimize falling rock from reaching to the road. The path and final resting position of a falling block is highly dependent on size, shape, location and the properties of the surface on which it bounces. Usually, highways have shoulders on the both sides (right and left). A highway shoulder as defined by AASHTO is “the portion of roadways contiguous with the traveled way for accommodation of stopped vehicles for emergency use, and for lateral support of base and sub base courses”. There are no specific design criteria provided in AASHTO Guide, but shoulders usually range between three to four meters in width. Consequently, this study assumes the shoulders have a width of three meters, so in each model the amount of rock-fall that final resting on shoulder as well as roadway is taken into consideration.

The Rocfall and CRSP programs used to examine each slope geometry shown in table 1. Each model was run in both programs to estimate the percentage of rocks that passing two critical points:

- The edge of ditch.
- The edge of highway shoulder, with 3m width.

In additional to the slope geometries that listed in table 1, three geometries were used which had several sections of different inclination angles. Thus, their geometries are used to examine the rock falling, rollout and bouncing along a gradual slope face.

4.2. ROCFALL SOFTWARE

4.2.1. Overview. The Rocfall program is a one of many geomechanics software programs that created by Rocscience company since 1996. The program was developed by group of rock engineers at University of Toronto, Canada. Geological, civil, and mining engineers utilize Rocfall in their fields. Also, the program simulates the problems in two-dimensions and three-dimensions. It is easy to use, define parameters, and analyze the results.

Rocfall is a statistical analysis program utilized in simulating rock-falling along slope. The program calculates the energy, velocity and bounce height of rocks at the location of endpoints of their paths. Also, the program can describe the condition of the rocks anywhere along its path by giving graphs for energy, velocity and bounce height of rocks along the slope profile.

Rocfall allow users to define slope geometry, rock properties and barriers. Users can easily define and change the slope profile and parameters, and rock quantity and parameters which this allowed results to be compared. Also, Rocfall lets users use a barrier either the predefined barriers, or creating new barriers, where the energy information and the impact on a barrier can help users to determine the required capacity, size and location of barriers.

Rocfall displays the results in a clear graphs and histograms can be exported to an Excel file that helps users in their analysis and reports. Also, rock paths can be filtered, where each path selected can be displayed alone on the screen. Furthermore, when any barrier has been selected only the paths that had the highest velocity impact on the barrier will display on the screen.

4.2.2. General Features. The main purpose of Rocfall is simulating the rockfall problems. Rocfall provides analysis of the energy, velocity and height bounce of rockfall and determines the impact on mountain roads.

Rocfall let users use barriers, shown as a line segment standing vertically on anywhere along slope surface. Barriers are used to stop falling rocks or absorb a part of their energy during they travel along the slope. Rocfall defines eight Macafferri barriers that can be used by users or users can define a new barrier with special properties and height as it suits the slope.

The Data Collector is a vertical line segment used to pinpoint the location on the slope and collect data about rocks that pass the segment while moving down the slope. The Data Collector can be created anywhere on the slope and does not affect the rocks that pass through it, but it records the kinetic energy, velocity, vertical location, and horizontal location of all rocks that pass through when they fall down the slope.

The rock type library comes with the rigid body mechanic analyses, where it is used to define the rocks. In Rocfall, the density, mass, quantity and shape of rock can be defined. The slope profile can be built by using a number of segments, where users can assign material properties to each segment.

There are many more features in the Rocfall program, some of these are listed below:

- Slope Roughness. In the rigid body formulation, Slope Roughness is defined by spacing and amplitude. The mean Slope Roughness is equal to the slope segment angle in the lumped mass analysis.

- Sliding Rocks. Rocks can continuously slide after they lose the necessary kinetic energy to bounce or roll.
- The Crest Loss. Used when simulating rockfalls on a slope that is wearing away at the crest.
- Animate Results. This feature allows to display the rock moving down the slope in slow motion.
- Rock Starting Location. The initial location of falling rocks in Rocfall is called a seeder. There are two types of seeders: point seeders (all rocks fall from a single starting location) and line seeders (rock fall form a set of starting locations).

4.3. COLORADO ROCKFALL SIMULATION PROGRAM SOFTWARE

4.3.1. Overview. The Colorado Rockfall Simulation Program (CRSP) is a two - dimensional numerical program utilizing for modeling and solving rockfall rollout problems. The original CRSP version 1.0 was created in 1988 by Timothy J. Pfeiffer. It was developed for CDOT (Colorado Department of Transportation) to estimate the probable bounce height and velocity of rockfall events was needed to design rockfall fences and alternative catchment ditches in Glenwood Canyon, Colorado.

CRSP provides for rockfalls modeling in two-dimension. The slope geometry and rockfall size should be in 2D, which this make the modeling easier. However, 2D modeling in CRSP causes some problems in the rotation and interaction between slope face and non-spherical rock. Therefore, a cylindrical shaped rock has two behaviors during it rollout based on velocity; (i) a cylindrical shaped rock will roll end-over-end at high speeds, (ii) rocks will tumble and roll along the long axis at slower speeds. This may affect the results and give incorrect consequences, for this reason cylinder shape is not used in CRSP-2D.

However, CRSP-3D simulates the rockfall problems in three-dimensions. CRSP-3D is more accurate in simulating the interaction between the rock and slope geometry than the previous versions of CRSP. Indeed, CRSP-3D uses the Discrete Element Method (DEM) for dynamic model simulation using the equations of motion, so it helps to model several rockfall paths on a section of slope, and has the capability to model the rotational movement of non-spherical rocks (Andrew, Hume, Bartingale, Rock, & Zhang. 2012).

4.3.2. General Features. The main purpose for CRSP software is simulating the rock falling, rollout and bouncing. The program is still undergoing improvement, in progression and development from version 1.0 to provide versions that could to simulate rockfall in 3D. The CRSP results help in the design of rockfall fences, rockfall attenuators, catch ditches, catch berms and other rockfall protection structures.

CRSP displays the slope profile and rocks 2D. Indeed, CRSP divides the slope geometry into cells based on the changing in the slope inclination and properties such as roughness and hardness. Furthermore, rocks can build in a several shapes such as spherical, cylindrical and discoidal.

In additional to the slope geometry, slope and rock properties can be defined in CRSP. The surface roughness and hardness coefficient defined for each cell, where the tangent and normal coefficient represented the hardness coefficient of slope surface. For the loose rock, their density can be chosen.

The Discrete Element Method used in CRSP-3D to simulate the interaction between slope and fall rock. Using DEM in CRSP-3D makes it owns in many features such as:

- Modeling the rock-slope interactions forms like impact, rolling, sliding, launching, sliding, and damping during the rock falling along the slope face.
- The hardness coefficient is a numerical input value represented the slope hardness.
- The slope roughness coefficient could be defining in CRSP-3D depending on lateral variations normal to the slope instead of using both lateral variations and the size of the falling rock as in CRSP-2D.

5. METHODOLOGY

5.1. THE ROCFALL MODEL

In this section, one of the models is used to show the methodology of modeling. The slope geometry is 20m heights, with a 30^0 slope angle, and 20^0 ditch angle. Also, 100 spherical rocks with 1m diameter falling from the top of slope are used.

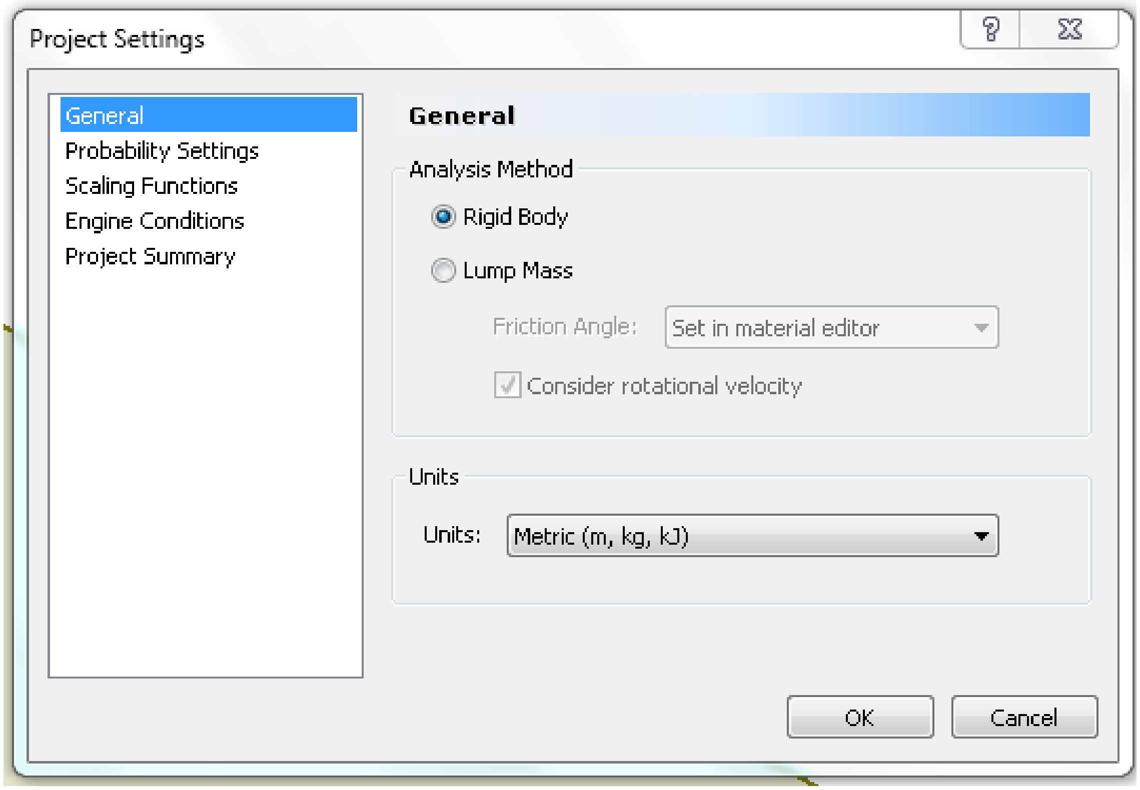
5.1.1. Design Mode. The first screen appears when Rocfall program is opened is a title screen (Figure 5.1), then a new blank document opened to begin creating a model immediately.

Figure 5.1. Rocfall title screen.

The analysis method, either rigid body or lump mass, can be chosen in the beginning from Project Settings window (Figure 5.2). Where:

- Lump Mass analysis method: Users could not change in the rockfall parameters in this method, so all rocks are assumed to be very small point mass with no physical size.
- Rigid Body analysis method. In this method users, can be defined the rock parameters such as shape, size, density and mass.

The units of measuring also can be selected from this window.



Analysis Method

● Rigid Body

○ Lump Mass

Friction Angle: Set in material editor

☑ Consider rotational velocity

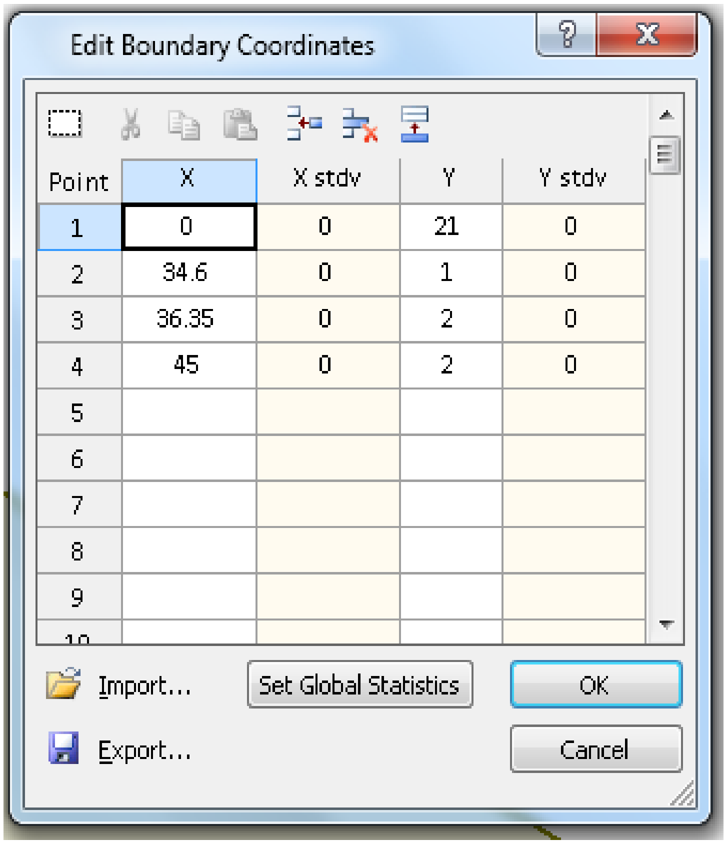
Units

Units: Metric (m, kg, kJ)

Figure 5.2. Project Settings.

In Rockfall program, the slope can be built in two ways:

- Drawn the slope manually on the screen, or
- Input vertex coordinates in the Edit Boundary Coordinates window (Figure 5.3). The first vertex represents the top of slope. The standard deviation is used for probabilistic variation of the slope, so standard deviation for all vertices was set to zero.



Point	X	X stdv	Y	Y stdv
1	0	0	21	0
2	34.6	0	1	0
3	36.35	0	2	0
4	45	0	2	0
5				
6				
7				
8				
9				

Figure 5.3. Edit Boundary Coordinate.

The rock dropping location can be assigned by the seeder window (Figure 5.4). The location is identified using the cursor on the screen or by entering the coordinates in the prompt line. The seeder placed on the top of slope.

Then, the seeder properties such as seeder name, number of rocks, rock type, initial horizontal (0.3m/s) and vertical velocity(-0.3m/s) for all slopes except in the vertical slopes is (0m/s), rotational velocity and rotation can be input in the Seeder Properties window. Figure 5.5 illustrates the value that used in this study.

From Rock Type window, the name, color, mass and density of rocks can be selected. The value used shown in Figure 5.6.

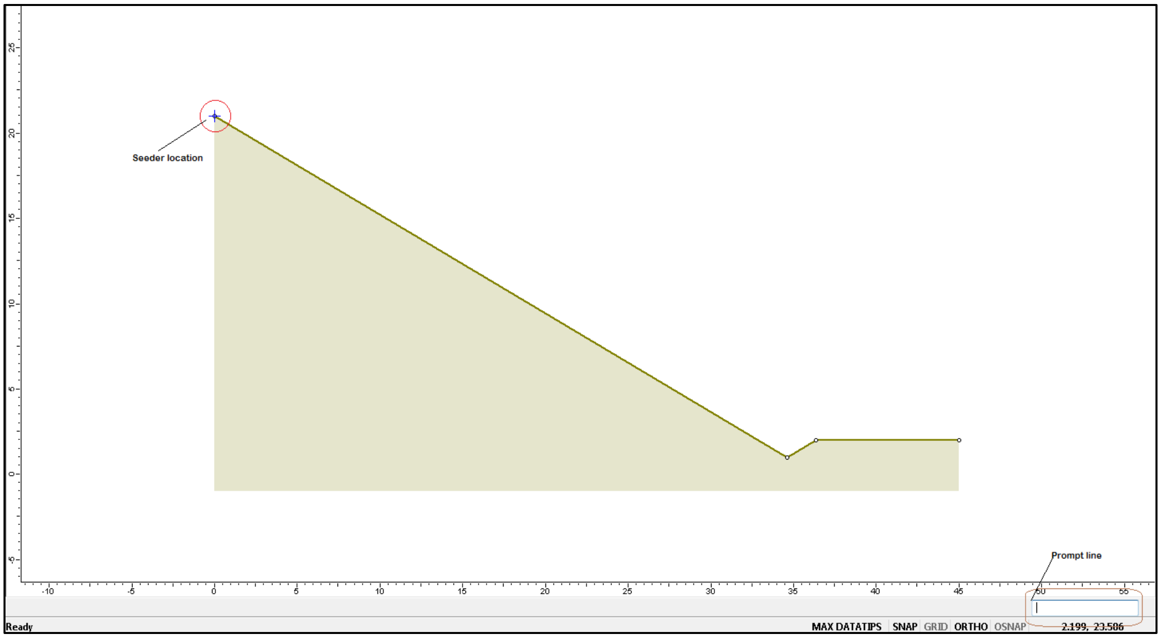
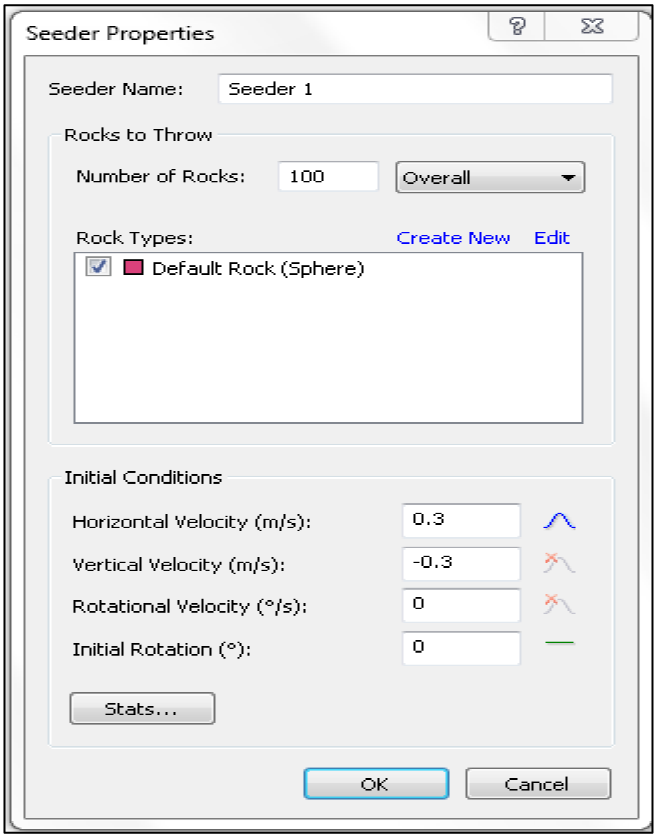


Figure 5.4. Seeder location and Prompt line.



Seeder Name: Seeder 1

Rocks to Throw

Number of Rocks: 100 Overall

Rock Types:

☑ 🟥 Default Rock (Sphere)

Initial Conditions

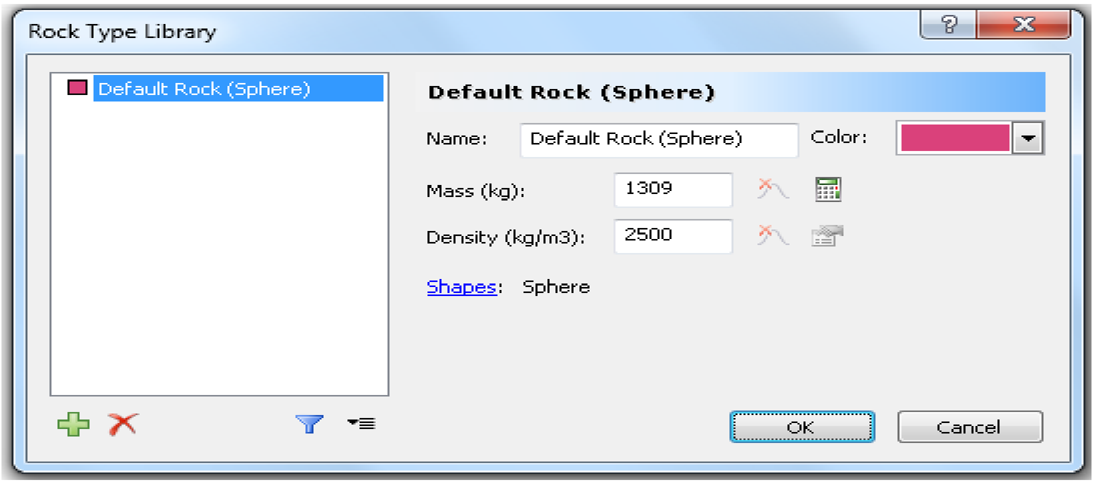
Horizontal Velocity (m/s): 0.3

Vertical Velocity (m/s): -0.3

Rotational Velocity (°/s): 0

Initial Rotation (°): 0

Figure 5.5. Seeder Properties, the initial horizontal (0.3m/s) and the initial vertical velocity (-0.3m/s) for all slopes except in the vertical slopes is (0m/s).

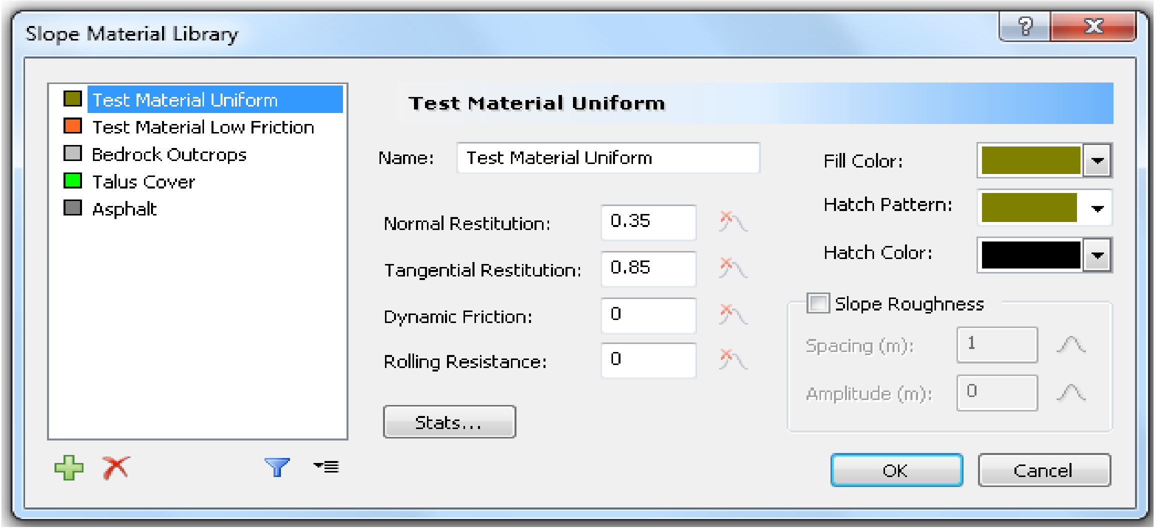


Default Rock (Sphere)

Name: Default Rock (Sphere)
Color: 🟥
Mass (kg): 1309
Density (kg/m3): 2500
Shapes: Sphere

Figure 5.6. Rock Type Library

In the Slope Material Library window (Figure 5.7), the material parameters such as rock name, color, normal restitution, tangential restitution, dynamic friction and rolling resistance for each vertex can be defined.



Test Material Uniform

Name: Test Material Uniform
Normal Restitution: 0.35
Tangential Restitution: 0.85
Dynamic Friction: 0
Rolling Resistance: 0
Fill Color:
Hatch Pattern:
Hatch Color: ■
☐ Slope Roughness
Spacing (m): 1
Amplitude (m): 0

Figure 5.7. Slope Material Library.

5.1.2. Results Mode. The model is run after all design options are selected Results from the main toolbar then the rock paths are shown on the slope. Figure 5.8.

Animate Path is a useful feature in Rocfall, where it displays the rock path that selected and the rock as a circle moving along slope surface. Figure 5.9 shows the Animate Result window with a several locations of rocks during it moves down the slope.

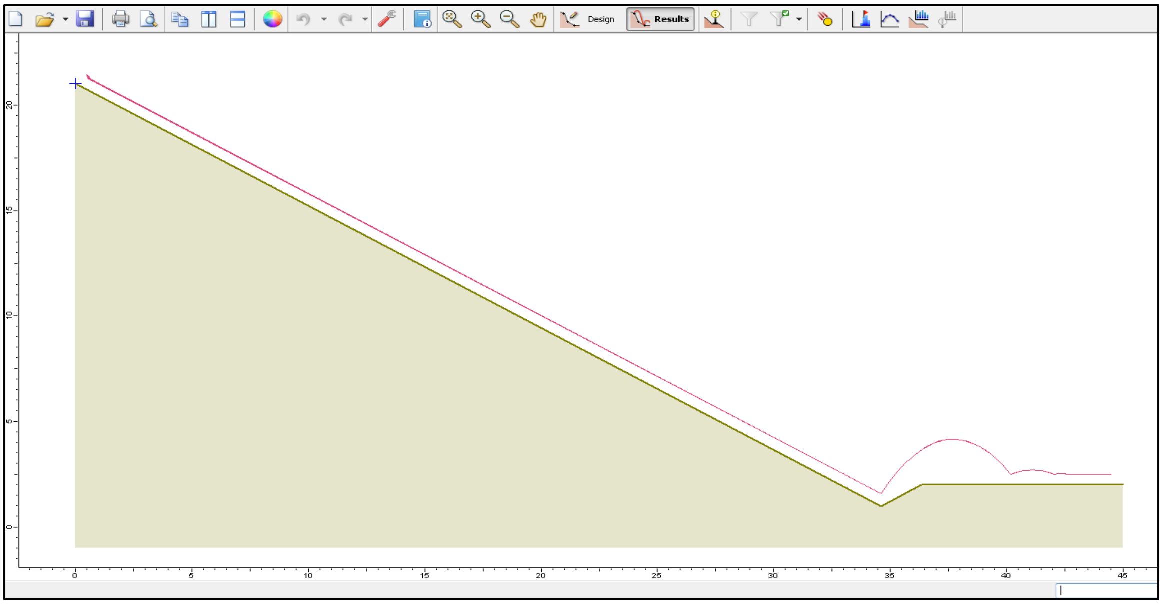
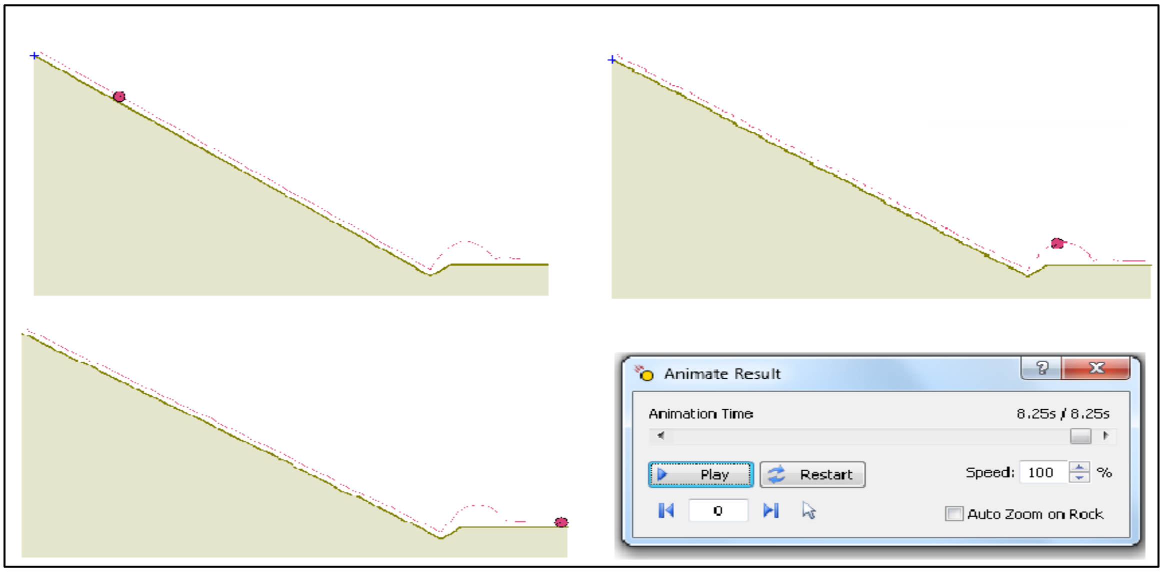


Figure 5.8. Results of 100 rock falls.



Animation Time 8.25s / 8.25s

Speed: 100 %

☐ Auto Zoom on Rock

Figure 5.9. Animate Result.

5.1.3. Analysis Graph

5.1.3.1. Graph endpoints. The location where rocks come to rest graphed in a histogram, so it easy to analyze where the most rocks come to rest. When hovering the cursor over the bars, the bar information such as x-location, number of rocks is displayed. The rock endpoint histogram is built over the slope profile (Figure 5.10) to illustrate the location of the endpoint on the slope surface in a clear and simple way.

5.1.3.2. Graph data on slope. From Graph Data on the Slope window (Figure 5.11) can be selected the graph of data needed to display on the slope, where the widow has many options like kinetic energy (total, translational, and rotational), velocity (translational, and rotational) and bounce height.Figure 5.12 shows the graph of bounce height on the slope, where it can exported to execl file.

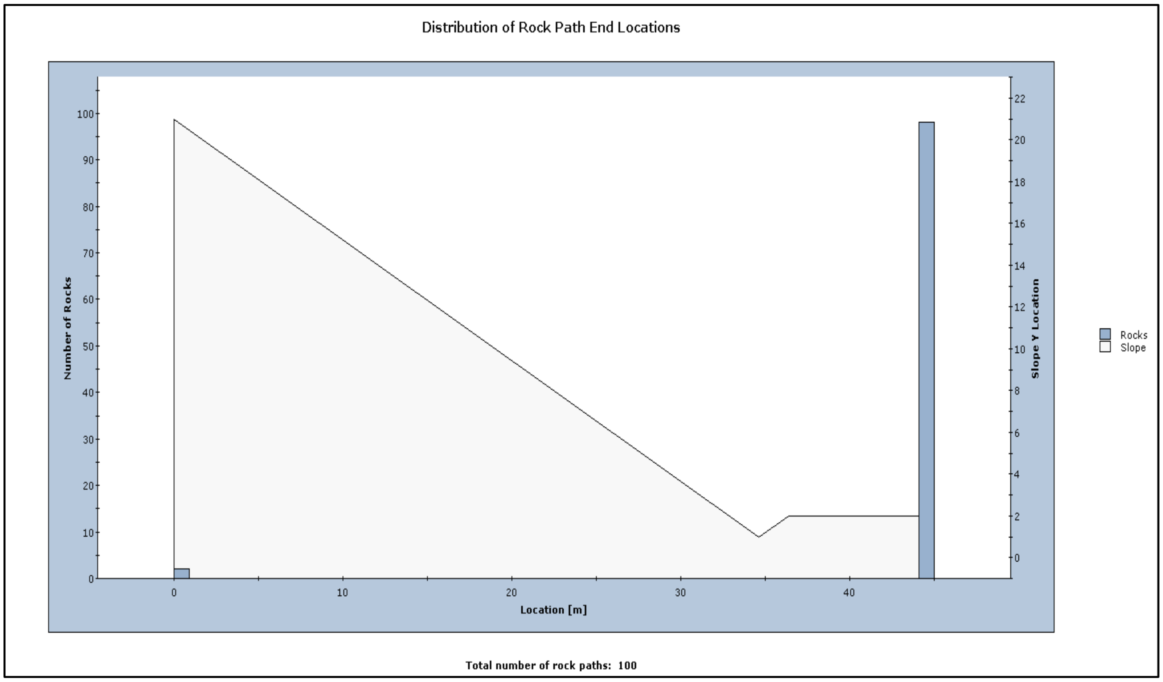
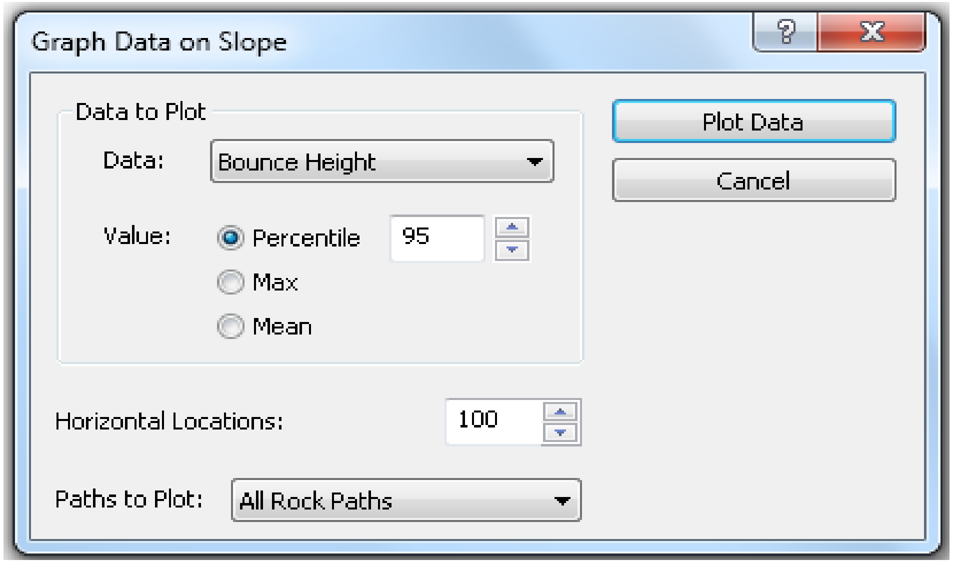


Figure 5.10. Rock endpoint histogram over the slope profile.



Data to Plot

Data: Bounce Height

Value: ● Percentile 95

○ Max

○ Mean

Horizontal Locations: 100

Paths to Plot: All Rock Paths

Figure 5.11. Graph Data on the Slope.

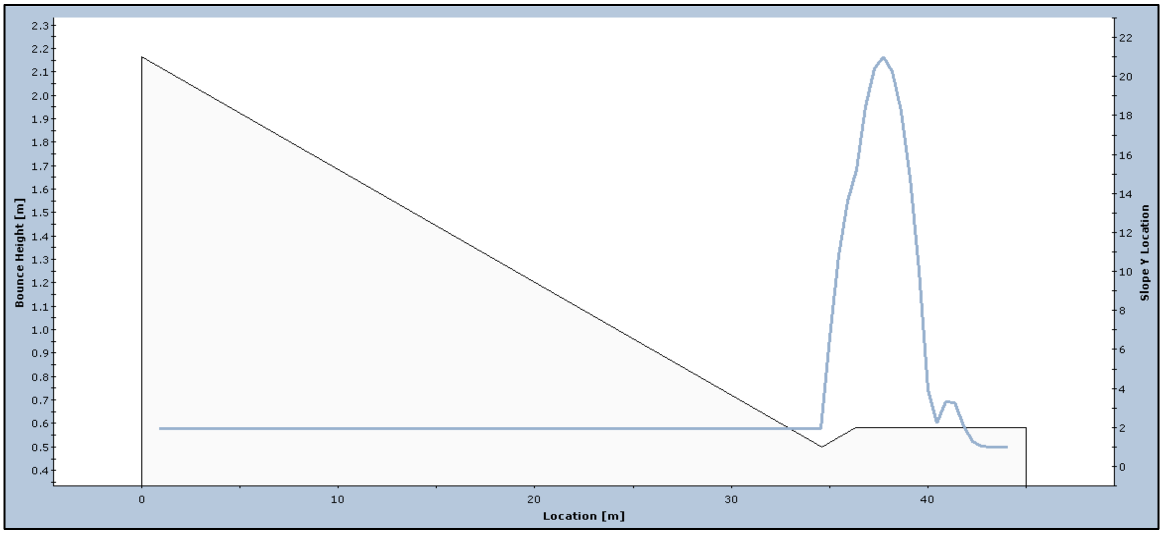
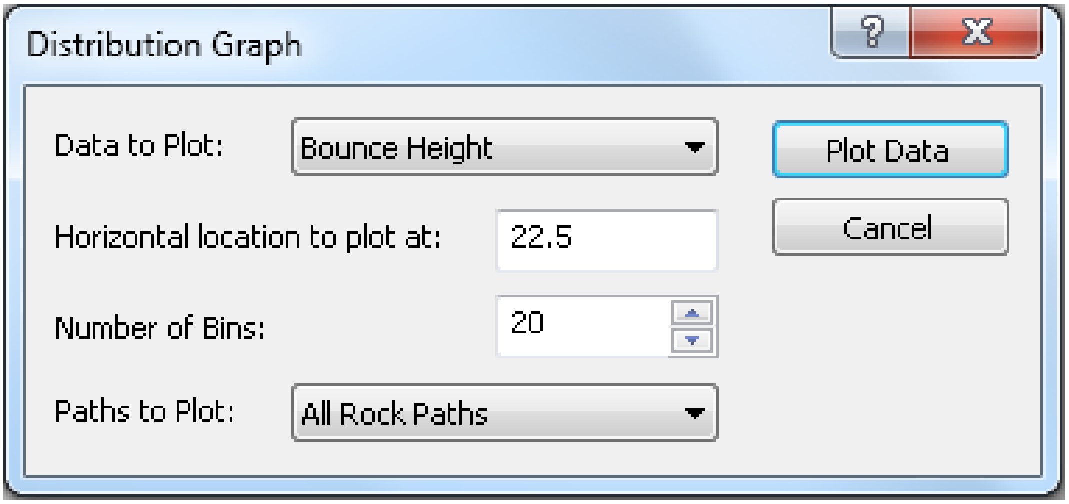


Figure 5.12. Bounce Height Graph on the Slope.

5.1.3.3. Graph distribution. From the Distribution Graph window (Figure 5.13) can be selected the graph of data required to display on the slope, where there are many options like kinetic energy (total, translational, and rotational), velocity (translational, and rotational) and Bounce Height.



Data to Plot: Bounce Height

Horizontal location to plot at: 22.5

Number of Bins: 20

Paths to Plot: All Rock Paths

Figure 5.13. Distribution Graph Window.

In the Distribution Graph, the histogram update with the distribution results that correspond to the indicator locations. Figure 5.14 shown the Distribution Graph of translational velocity at selected X-location. Also, this chart can be exported to an excel file.

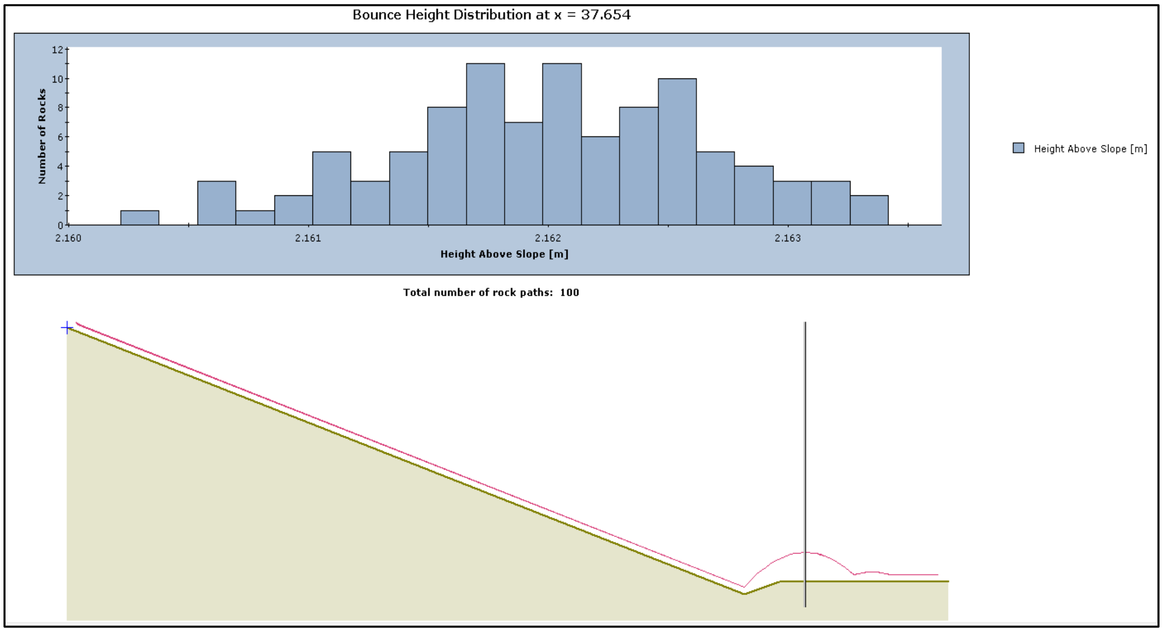
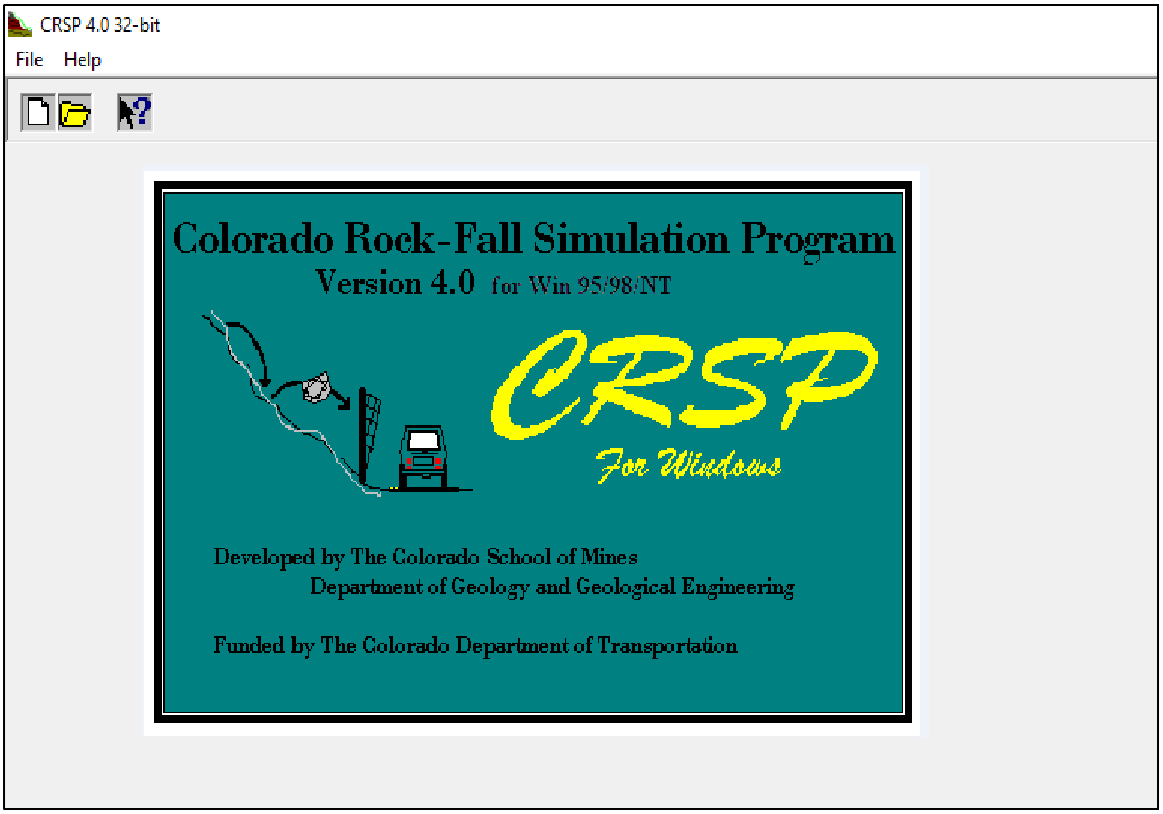


Figure 5.14. Distribution Graph of Bounce Height at selected X-location.

5.2. CRSP MODEL

This section shows the CRSP modeling procedure. The slope geometry that is used has 20m heights, 30^0 slope angle, and 20^0 ditch angle. Also, 100 spherical blocks represented the loose rocks with a 1m diameter.

5.2.1. Model Design. The first screen appears when CRSP program opened is a title screen (Figure 5.15), then the acknowledgment screen (Figure 5.16) appears for a few seconds followed by a disclaimer screen (Figure 5.17). In each figure, there is a main menu and toolbar, which has three options; new input file, open and help.



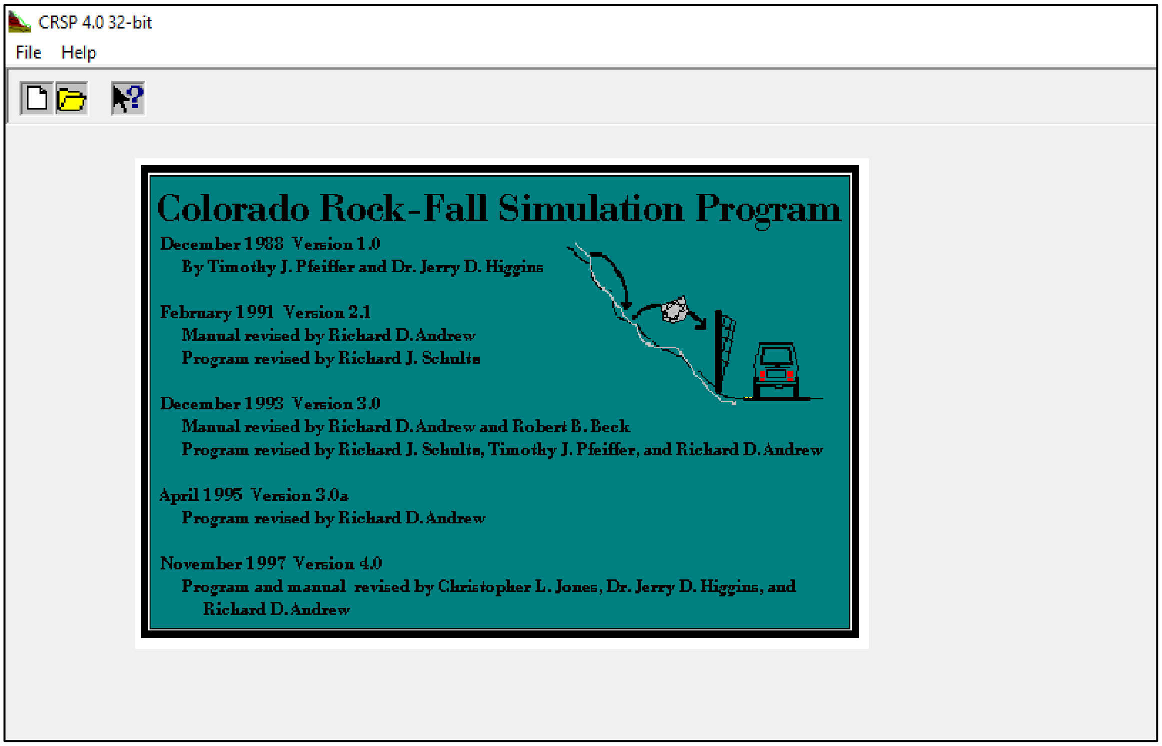
Colorado Rock-Fall Simulation Program

Version 4.0 for Win 95/98/NT

Developed by The Colorado School of Mines
Department of Geology and Geological Engineering

Funded by The Colorado Department of Transportation

Figure 5.15. CRSP Title Screen.



Colorado Rock-Fall Simulation Program

December 1988 Version 1.0
By Timothy J. Pfeiffer and Dr. Jerry D. Higgins

February 1991 Version 2.1
Manual revised by Richard D. Andrew
Program revised by Richard J. Schultz

December 1993 Version 3.0
Manual revised by Richard D. Andrew and Robert B. Beck
Program revised by Richard J. Schultz, Timothy J. Pfeiffer, and Richard D. Andrew

April 1995 Version 3.0a
Program revised by Richard D. Andrew

November 1997 Version 4.0
Program and manual revised by Christopher L. Jones, Dr. Jerry D. Higgins, and Richard D. Andrew

Figure 5.16. CRSP Acknowledgement Screen.

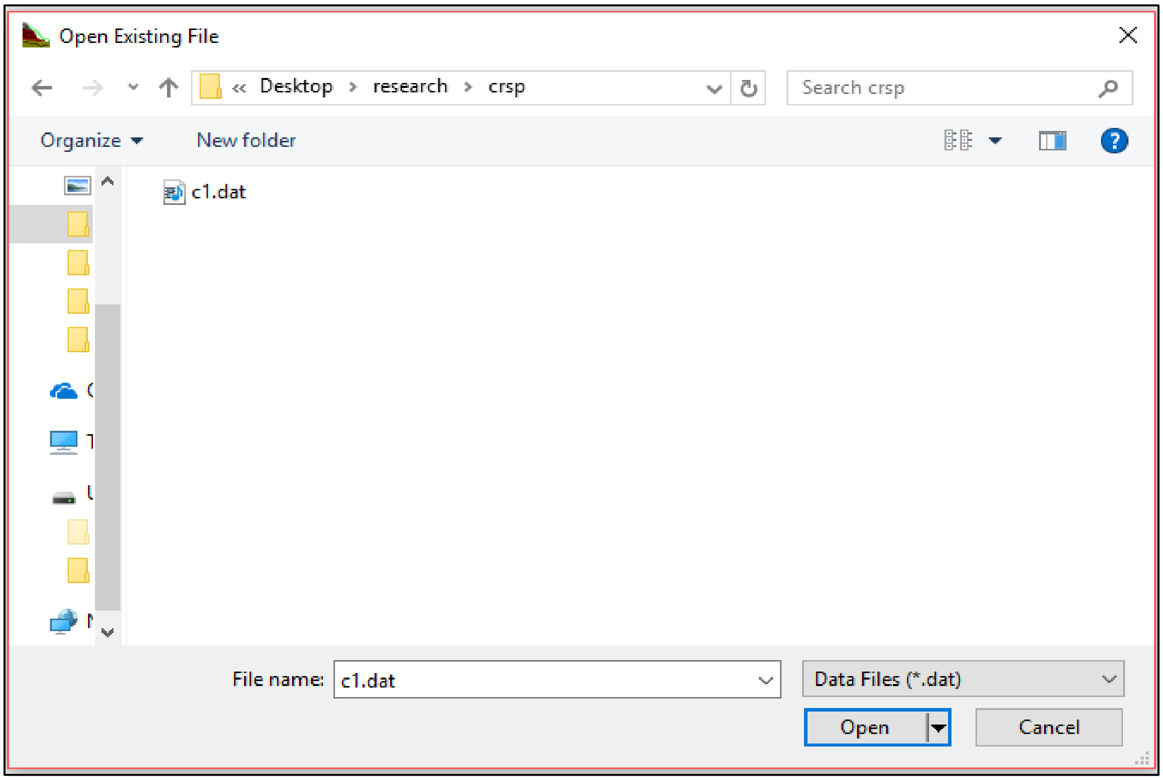
Colorado Rock-Fall Simulation Program

Disclaimer:

This program has been tested and is believed to be a reliable engineering tool. No responsibility is assumed by the authors, the Colorado School of Mines, the Colorado Department of Transportation, or any employees of the above for any errors, mistakes or misrepresentations that may occur from any use of this program.

Figure 5.17. CRSP Disclaimer Screen.

CRSP allow users to input data in an input data file such as Data files (*.dat), CRSP files (*.csp), Bimaps (*.bmp) …etc. the input data file can be called from File – Open then the Open Existing File box (Figure 5.18) appear, then the file can choose.



File name: c1.dat

Data Files (*.dat)

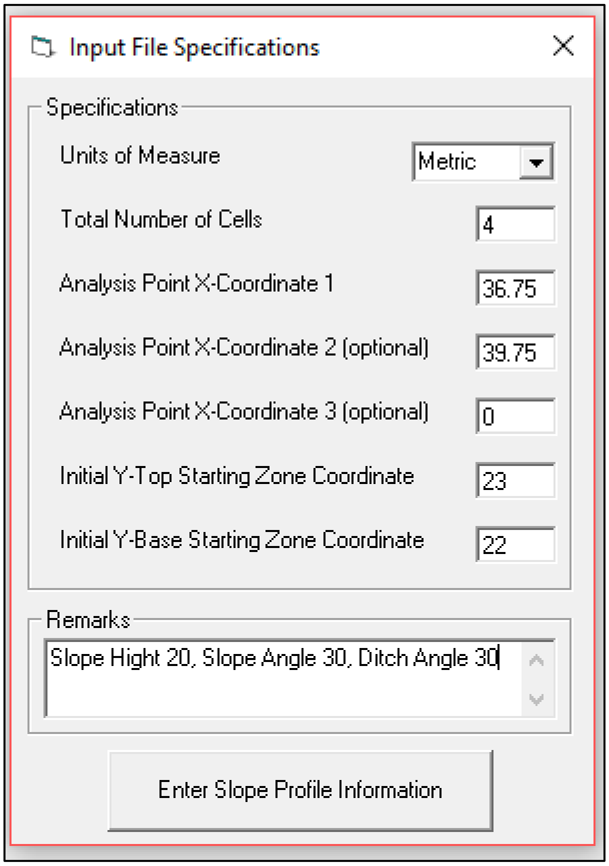
Figure 5.18. CRSP Open Existing File box.

Also, data can be entered directly in the Input File Specifications (Figure 5.19) that appears after selecting the New Input File from the File menu. It's like the CRSP Input File Preview – Part A Window that appear when opened an existing file. The following information required to fill in the Input File Specifications window:

- Units of Measure. Either U.S or metric units can be used.
- Total Number of Cells.
- Analysis Point X-Coordinate 1

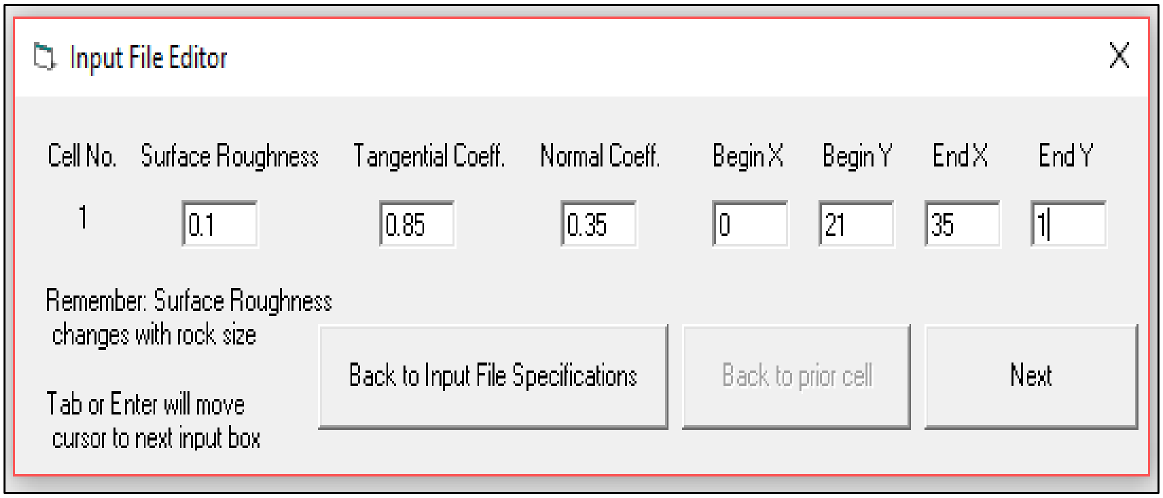
- Analysis Point X-Coordinate 2
- Analysis Point X-Coordinate 3
- Initial Y-Top Starting Zone Coordinate
- Initial Y-Base Starting Zone Coordinate
- Remarks

Once the Enter Slope Profile Information button is selected the Input File Editor window (Figure 5.20) appears. It is required to enter data for the first cell such as Surface Roughness, Tangential Coefficient, Normal Coefficient, Begin X, Begin Y, End X and End Y. The same window appears after Next is selected for each cell.



Units of Measure: Metric
Total Number of Cells: 4
Analysis Point X-Coordinate 1: 36.75
Analysis Point X-Coordinate 2 (optional): 39.75
Analysis Point X-Coordinate 3 (optional): 0
Initial Y-Top Starting Zone Coordinate: 23
Initial Y-Base Starting Zone Coordinate: 22
Remarks: Slope Hight 20, Slope Angle 30, Ditch Angle 30

Figure 5.19. Input File Specifications Window.

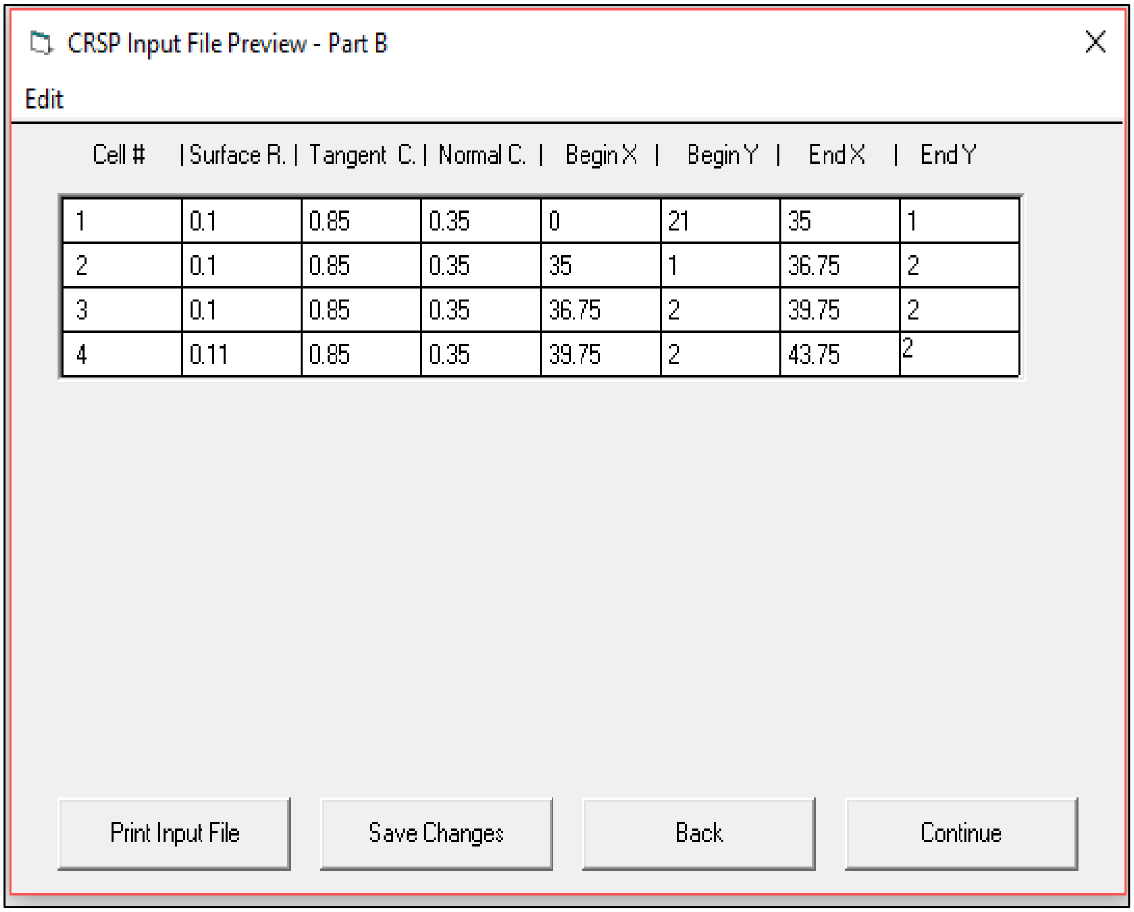


Cell No.	Surface Roughness	Tangential Coeff.	Normal Coeff.	Begin X	Begin Y	End X	End Y
1	0.1	0.85	0.35	0	21	35	1

Remember: Surface Roughness changes with rock size

Tab or Enter will move cursor to next input box

Figure 5.20. Input File Editor Window.

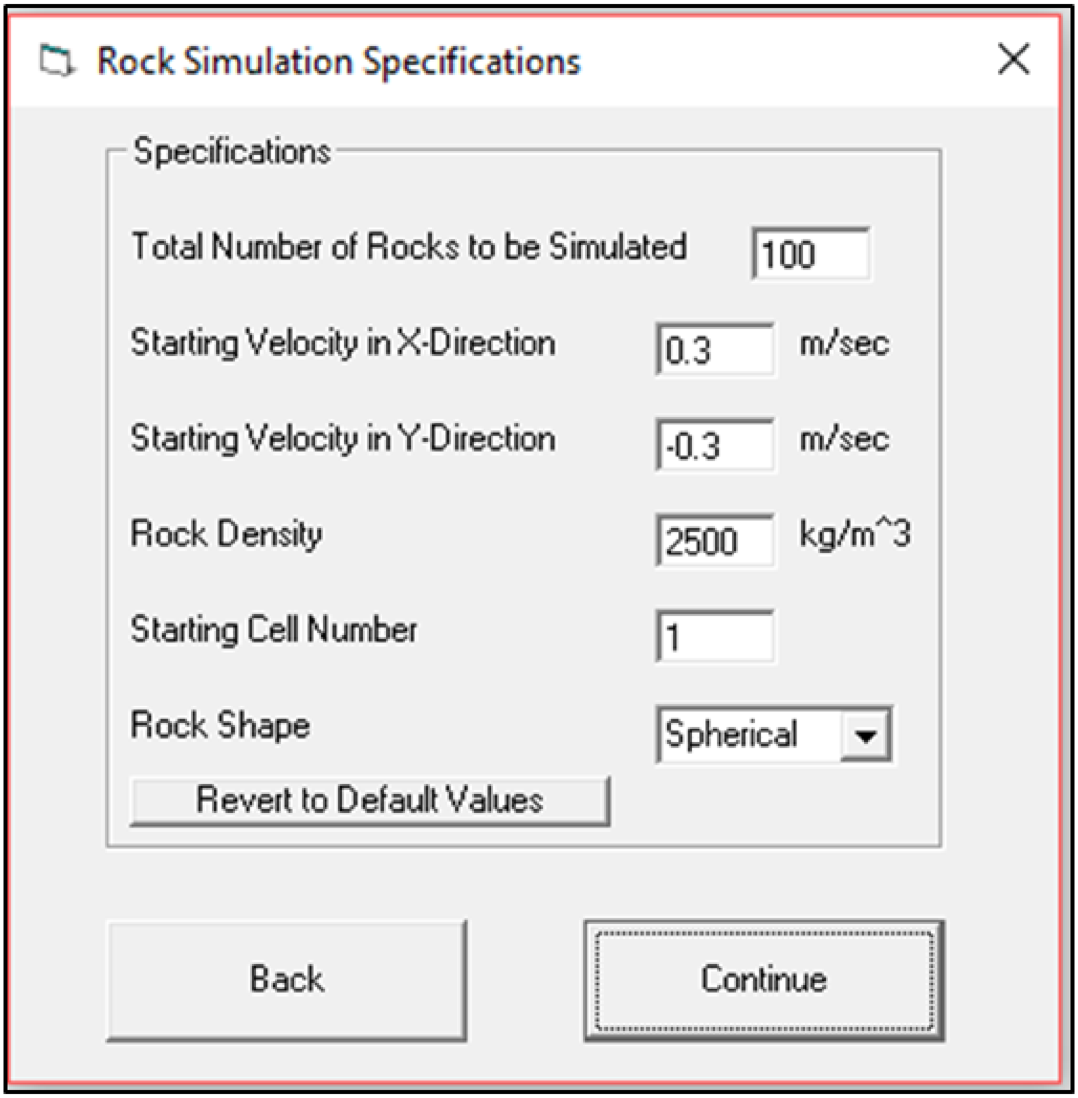


Cell #	Surface R.	Tangent C.	Normal C.	Begin X	Begin Y	End X	End Y
1	0.1	0.85	0.35	0	21	35	1
2	0.1	0.85	0.35	35	1	36.75	2
3	0.1	0.85	0.35	36.75	2	39.75	2
4	0.11	0.85	0.35	39.75	2	43.75	2

Figure 5.21.CRSP Input File Preview – Part B Window.

Figure 5.21 show the CRSP Input File Preview – Part B window which it shows the cells with their information. This window appears if an existing input file is selected.

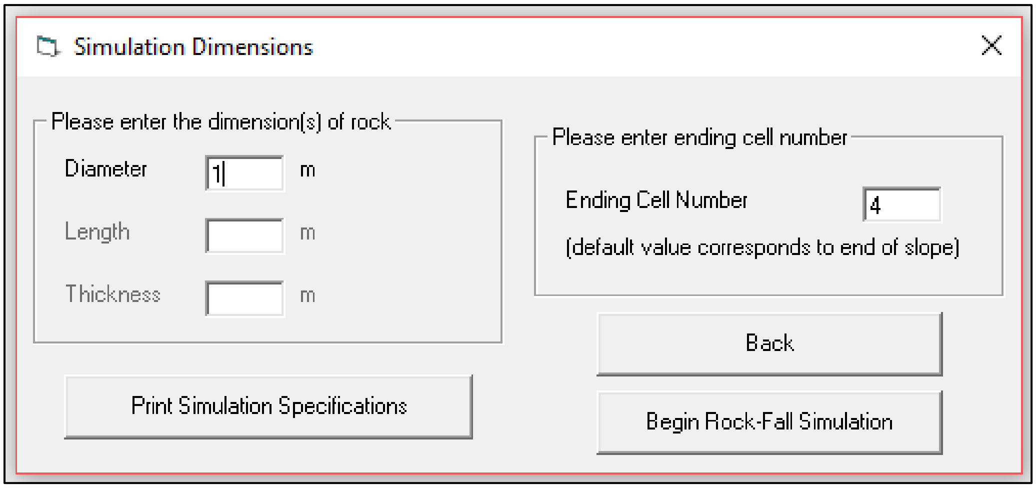
Then the Rock Simulation Specifications window (Figure 5.22) is shown. From this window the number, shape and density of rock fall can be selected, the X and Y velocity also can be defined.



Total Number of Rocks to be Simulated: 100
Starting Velocity in X-Direction: 0.3 m/sec
Starting Velocity in Y-Direction: -0.3 m/sec
Rock Density: 2500 kg/m^3
Starting Cell Number: 1
Rock Shape: Spherical

Figure 5.22. Rock Simulation Specifications window. The initial velocity in Y direction is (-0.3m/s) for all slopes except in the vertical slopes is 0m/s.

Finally, the Simulation Dimensions window (Figure 5.23) is the last input window. The required data for dimensions is based on the rock shape, where spherical is shown here. Also, the ending cell number of the slope needs to be entered in this window. After that, the Begin Rock-Fall Simulation button is selected to trigger the rock to fall, roll and bounce.



Diameter 1 m

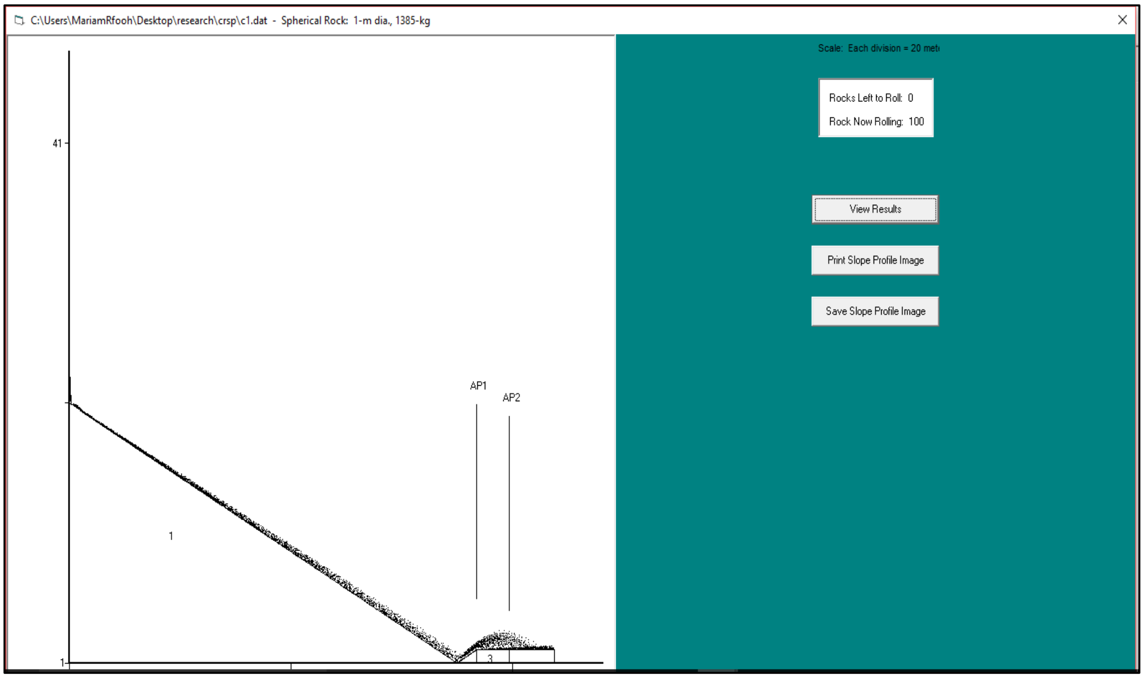
Ending Cell Number 4

(default value corresponds to end of slope)

Figure 5.23.Simulation Dimensions Window.

5.2.2. Running Model. Figure 5.24 shows the slope profile and path of the falling, rolling, and bouncing rocks along the slope face. The profile plotted in X and Y coordinates with plot scale is 20m per division. Above the plot of the slope profile, the location of analysis points shown based on the X-coordinate. The analysis points are used as critical points to estimate the percent of rock that pass it. Also, the shape, dimensions and mass of rock shown on the top of the screen. The number of rocks left to roll and rocks now rolling are shown to the right of the slope profile.

Falling rocks still appear along the slope face where CRSP record the position of rocks every 10 seconds. Consequently, CRSP helps the users to determine the position of highest bouncing.



C:\Users\MariamRfooh\Desktop\research\crsp\c1.dat - Spherical Rock: 1-m dia., 1385-kg

Scale: Each division = 20 meti

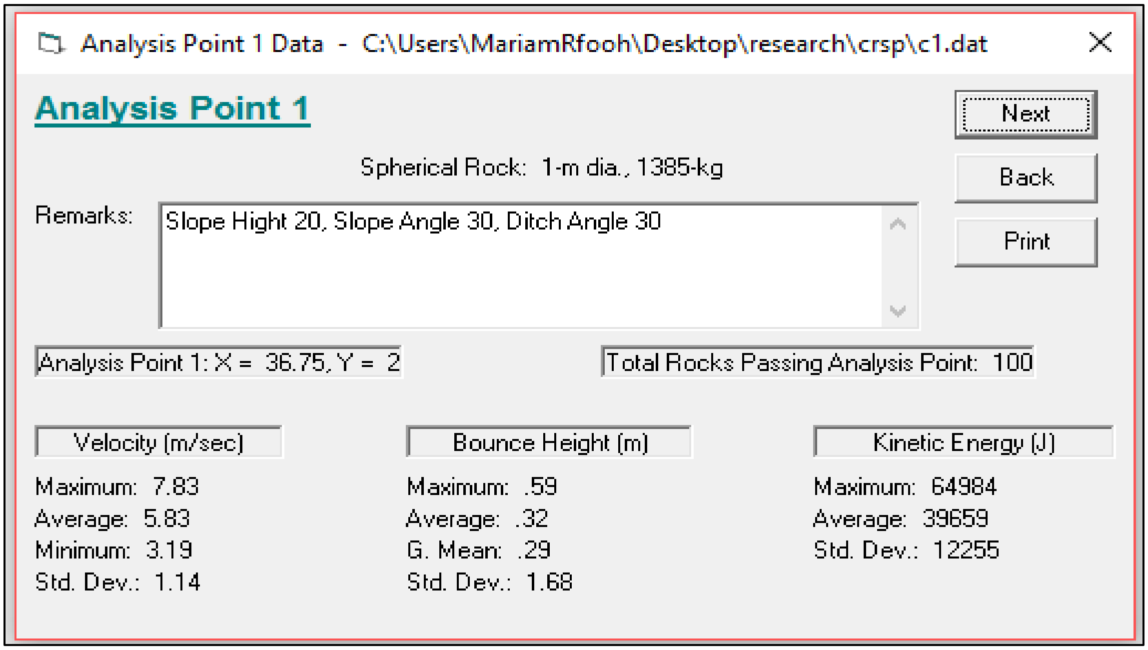
Rocks Left to Roll: 0
Rock Now Rolling: 100

Figure 5.24. CRSP Slope Profile Window, location of analysis point 1 (AP1) and analysis point 2 (AP2).

5.2.3. Analysis Graphs and Data. The Analysis Point 1 Data window (Figure 5.25) is shown after the View Results button is selected from slope profile window. This window illustrates analysis point location, rock information, remarks (used as a title for the model), total rocks passing analysis point, velocity, bouncing height and kinetic energy. Additionally, every analysis point showed its results in an individual window.

Analysis Point Bounce Height Distribution histogram (Figure 5.26) is shown for each analysis point, but it does not appear for analysis points that had no rocks passing.

Figure 5.27 show the Analysis Point Velocity Distribution histogram, where it shown for each analysis point.



Analysis Point 1 Data - C:\Users\MariamRfooh\Desktop\research\crsp\c1.dat

Analysis Point 1

Spherical Rock: 1-m dia., 1385-kg

Remarks: Slope Hight 20, Slope Angle 30, Ditch Angle 30

Analysis Point 1: X = 36.75, Y = 2

Total Rocks Passing Analysis Point: 100

Velocity (m/sec)	Bounce Height (m)	Kinetic Energy (J)
Maximum: 7.83	Maximum: .59	Maximum: 64984
Average: 5.83	Average: .32	Average: 39659
Minimum: 3.19	G. Mean: .29	Std. Dev.: 12255
Std. Dev.: 1.14	Std. Dev.: 1.68	

Figure 5.25.Analysis Point 1 Data Window.

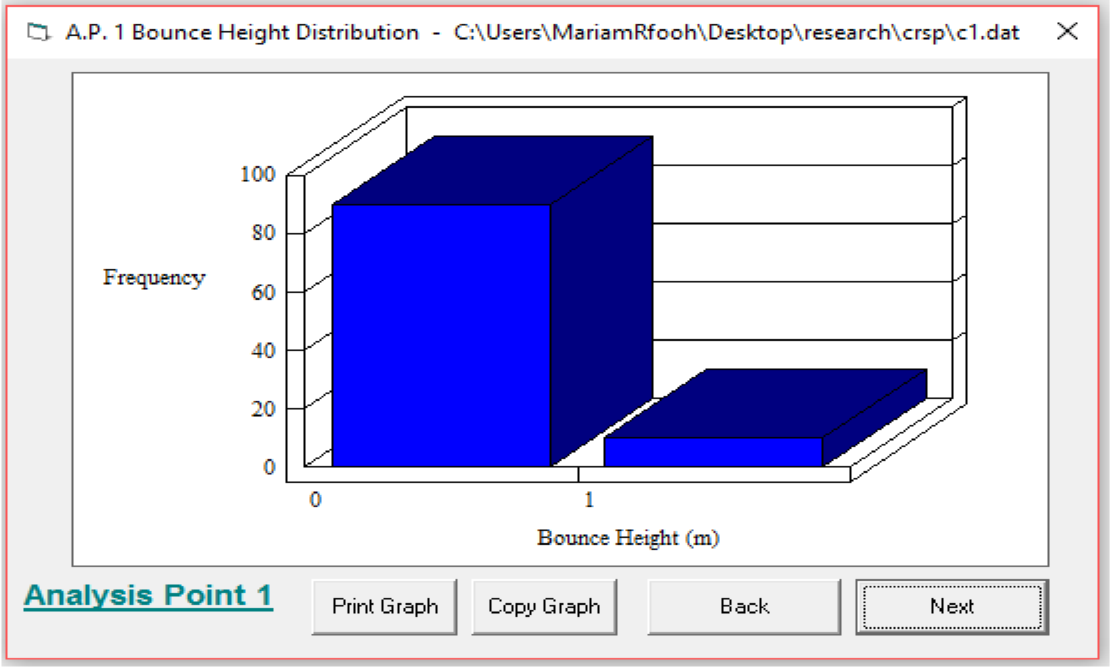


Figure 5.26.Analysis Point Bounce Height Distribution.

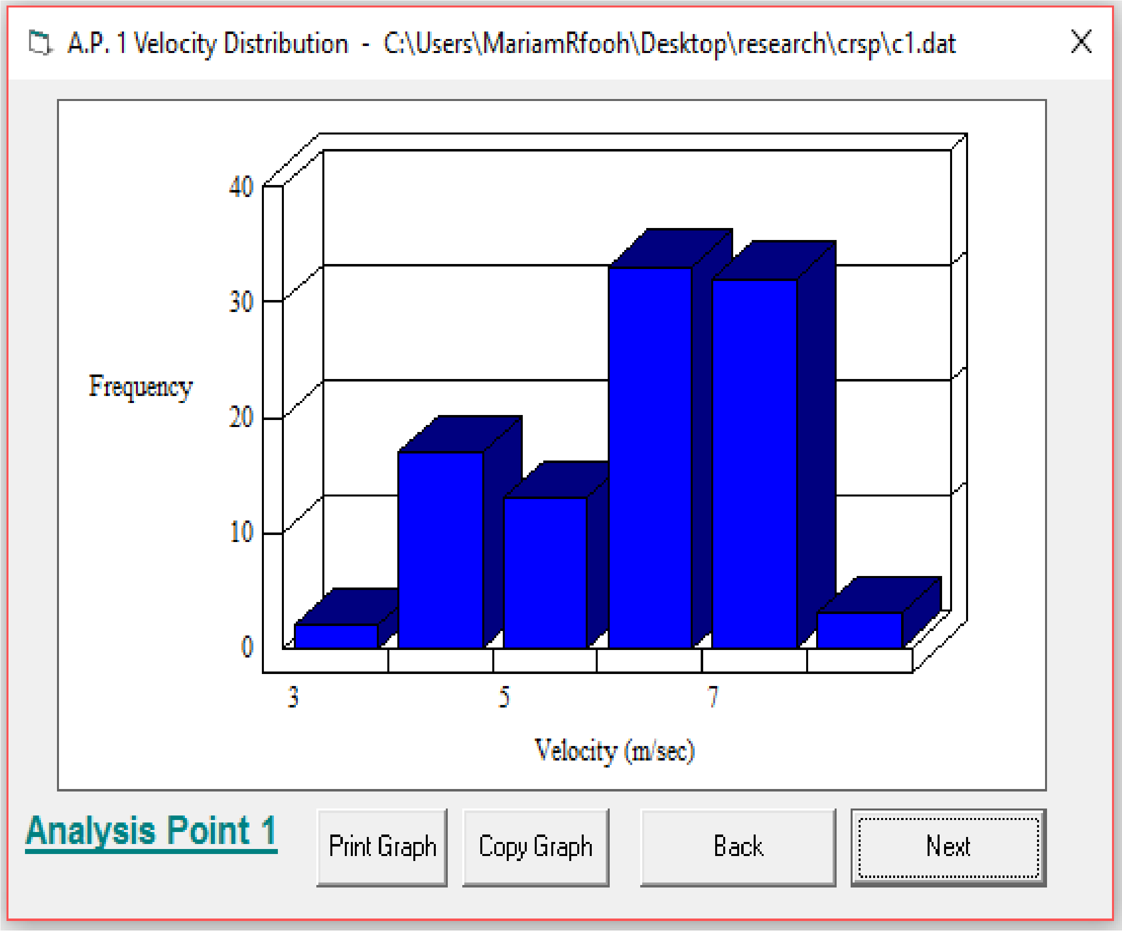


Figure 5.27.Analysis Point Velocity Distribution.

The Bounce Height Graph window (Figure 5.28) and the Velocity Graph window (Figure 5.29) are shown. These graphs are not related to any analysis points, so they illustrate where the position of the maximum bounce height and maximum velocity of rocks during it falling along the slope.

CRSP lets users analyze the rocks rolling in each cell. Figure 5.30 show the Data Collected at End of Each Cell; this helps to study each cell as an individual part of slope and make the required treatment for the cell that has a risk.

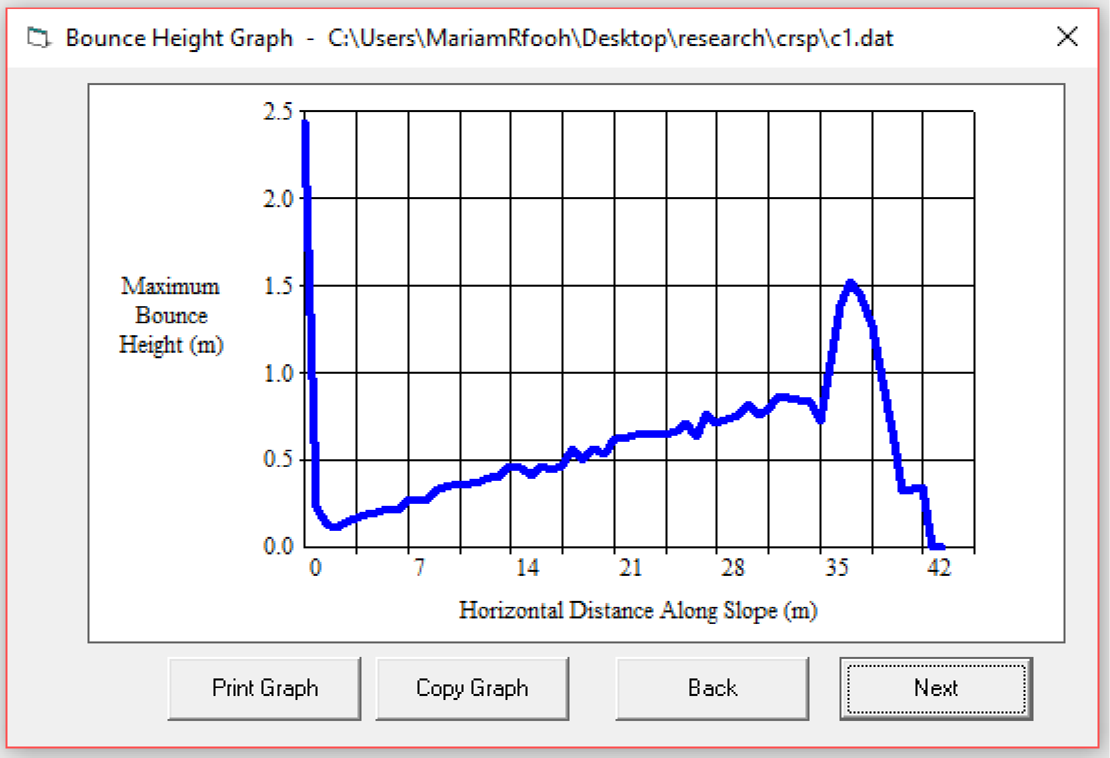


Figure 5.28.Bounce Height Graph Window.

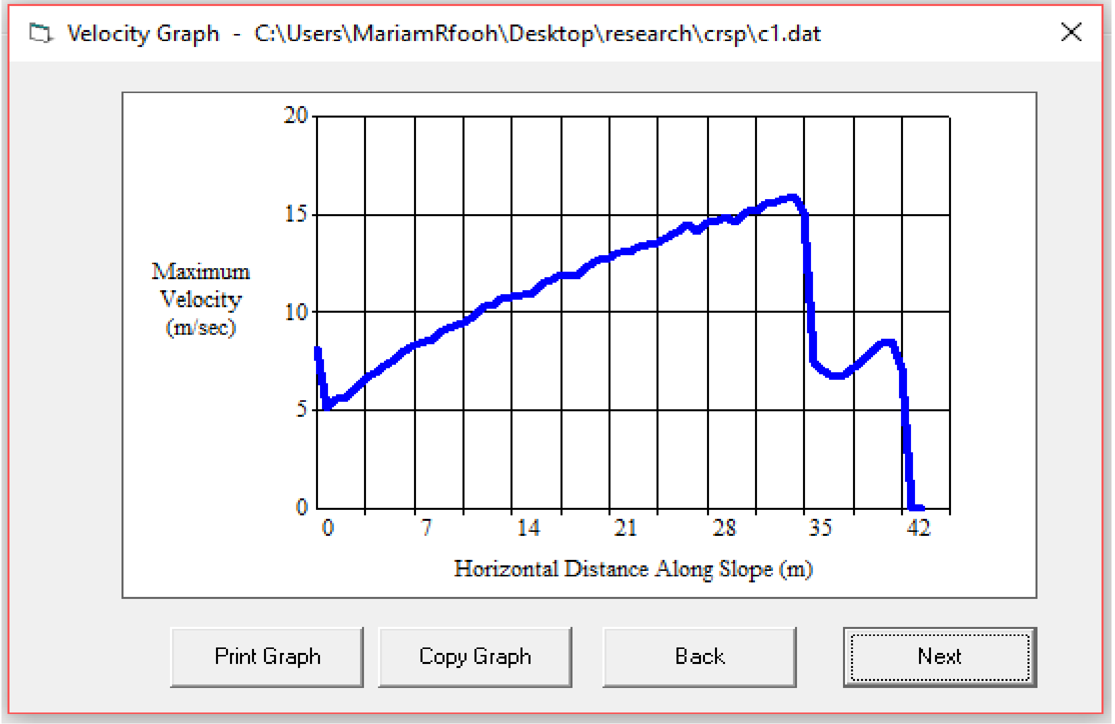
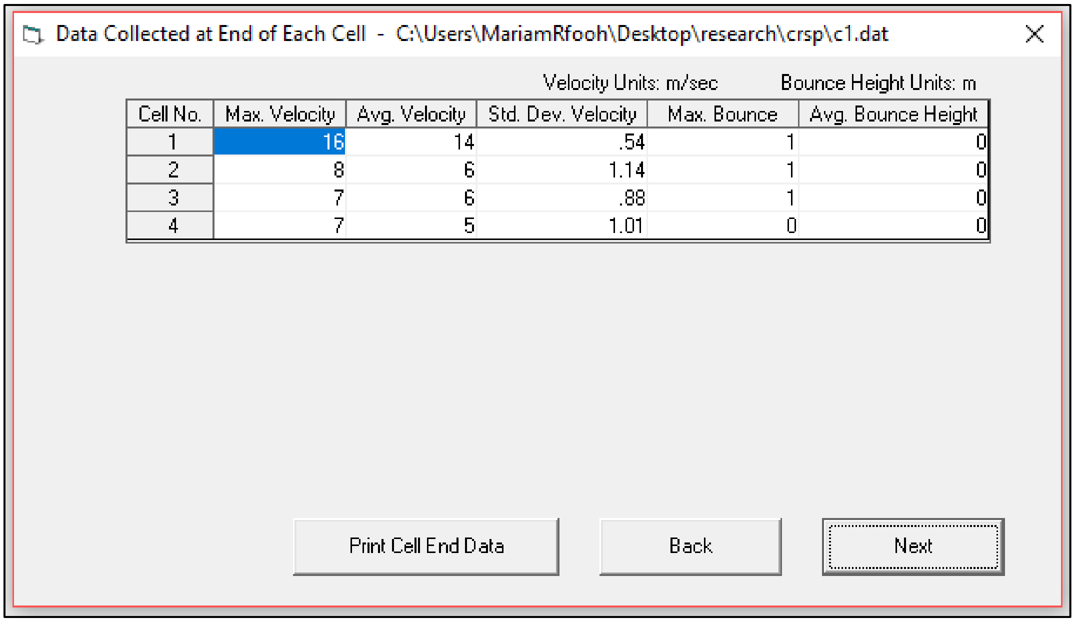


Figure 5.29.Velocity Graph Window.



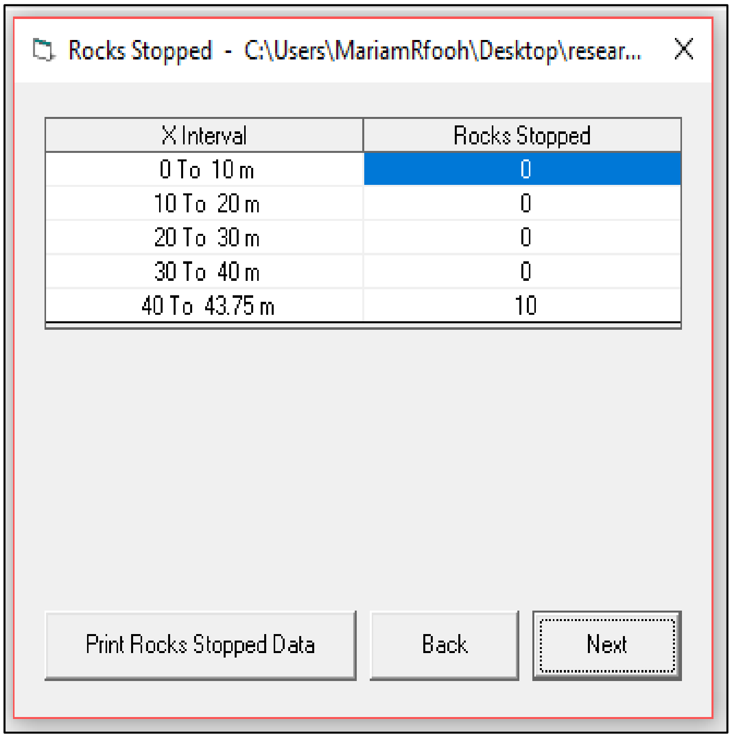
Data Collected at End of Each Cell - C:\Users\MariamRfooh\Desktop\research\crsp\c1.dat

Velocity Units: m/sec Bounce Height Units: m

Cell No.	Max. Velocity	Avg. Velocity	Std. Dev. Velocity	Max. Bounce	Avg. Bounce Height
1	16	14	.54	1	0
2	8	6	1.14	1	0
3	7	6	.88	1	0
4	7	5	1.01	0	0

Figure 5.30. Data Collected at End of Each Cell.

Finally, the Rocks Stopped window (Figure 5.31) displays the number of rocks that stopped in each interval of slope (the intervals based on X-axis).



Rocks Stopped - C:\Users\MariamRfooh\Desktop\resear...

X Interval	Rocks Stopped
0 To 10 m	0
10 To 20 m	0
20 To 30 m	0
30 To 40 m	0
40 To 43.75 m	10

Figure 5.31.Rocks Stopped Window.

5.3. SLOPE PARAMETERS

The slope geometry was variable in each model as shown in Table 3.1, but the properties of the material were constant. Both programs that were used required a special parameter values for the slope and rock material. Table 5.1 show the slope material and rock parameters which it used.

Table 5.1. Summarized of rock and slope material parameters.

Rocks Parameters	Slope Materials Parameters		
Density (kg/m^3)	Surface Roughness	Tangential Coefficient of restitution	Normal Coefficient of restitution
2500	0.1	0.85	0.35

6. ANALYSIS RESULTS

6.1. ROCFALL RESULTS

The Rocfall program was used to run the sixty-three-variety model to collect data for rocks moving down the slope and location of their rest. After running the model, the output of the program are graphs of Endpoints, Kinetic Energy (Total, Translational, and Rotational), Velocity (Translational, and Rotational) and Bounce Height. This study is concerned with only the endpoints.

The percentage of rocks that pass the edge of ditch and road shoulder are collected from the endpoint histogram for each model. After that the data is plotted in charts (% of rocks passing the edge of ditch and/or road shoulder vs slope height) for each slope angle.

Rocfall results for slope angle 90^0 show the probability of rock passing the ditch edge increase when height increase slope. Consequently, the percentage of the rocks passed the edge ditch varying in range (0 – 100) % as shown in Figure 6.1. However, all rocks that passed the ditch edge rested on the shoulder of road as Figure 6.2 shown.

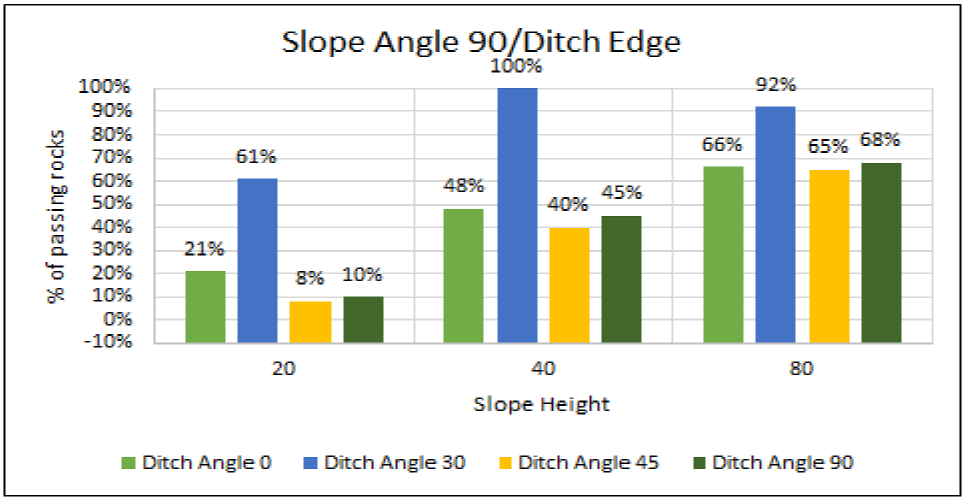


Figure 6.1. Percentage of rocks passing the ditch edge in slopes with 90^0 (Rocfall).

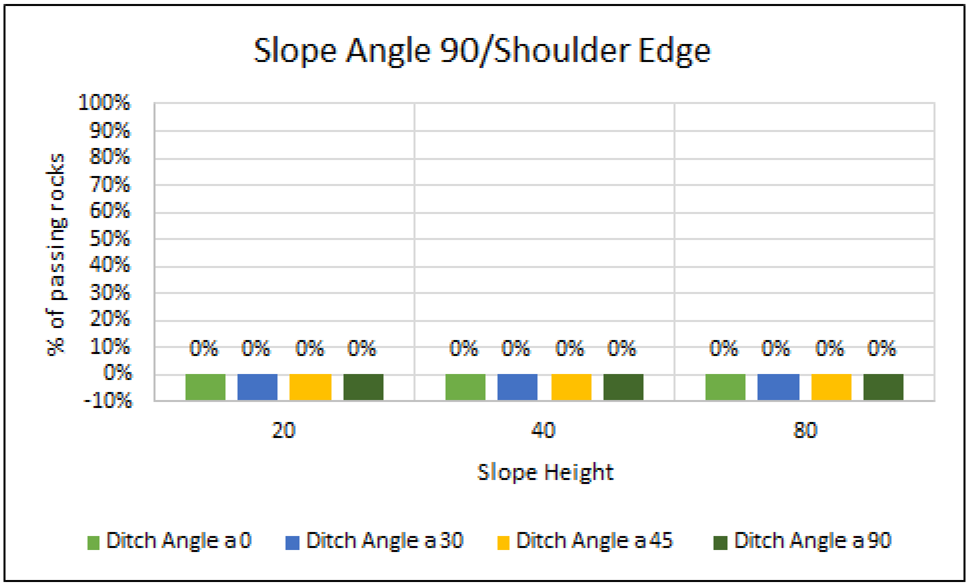


Figure 6.2. Percentage of rocks passing the shoulder edge in slopes with 90^0 (Rocfall).

For the slopes with 75^0 slope angle, 98% of rocks reached the road in all slopes with ditches 0^0 and 90^0, however, some of rocks rested on the slope face and others on the ditches at 30^0 and 45^0 except the slope with height 80m and ditch angle 45^0 where 98% of rocks passing ditch and rested on the shoulder as Figure 6.3 illustrates.

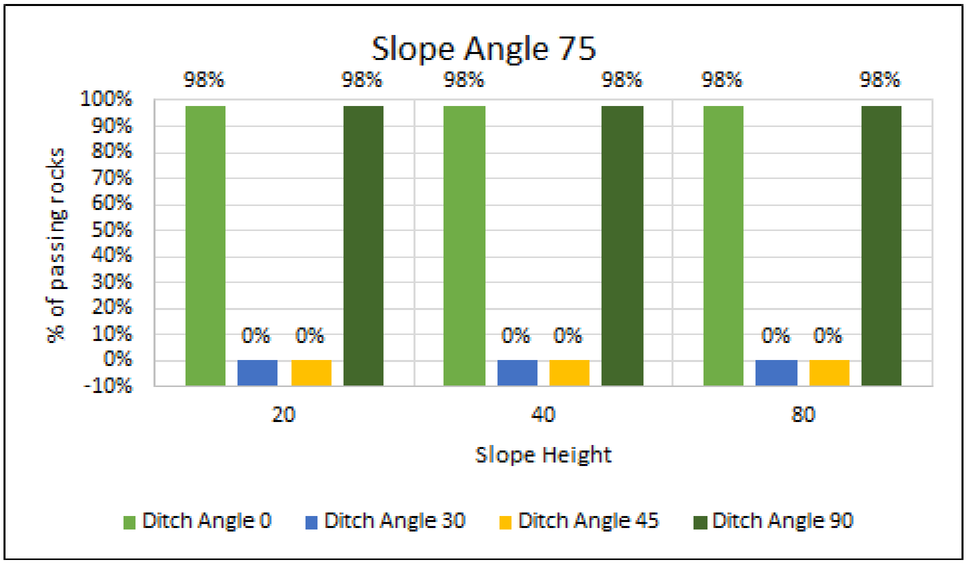


Figure 6.3. Percentage of rocks passing the ditch and shoulder edge in slopes with 75^0 (Rocfall).

In the slopes with 60^0 slope angle, no rocks passed the ditch edges with ditch of angles 30^0, 45^0, and 90^0 except the slope with 80m height and 90^0 ditch angle where 98% of rocks passing the ditch edge as well as in slopes with 0^0 ditch angle (Figure 6.4). Moreover, all rocks that passing the ditch reached the road without stopping on the shoulder.

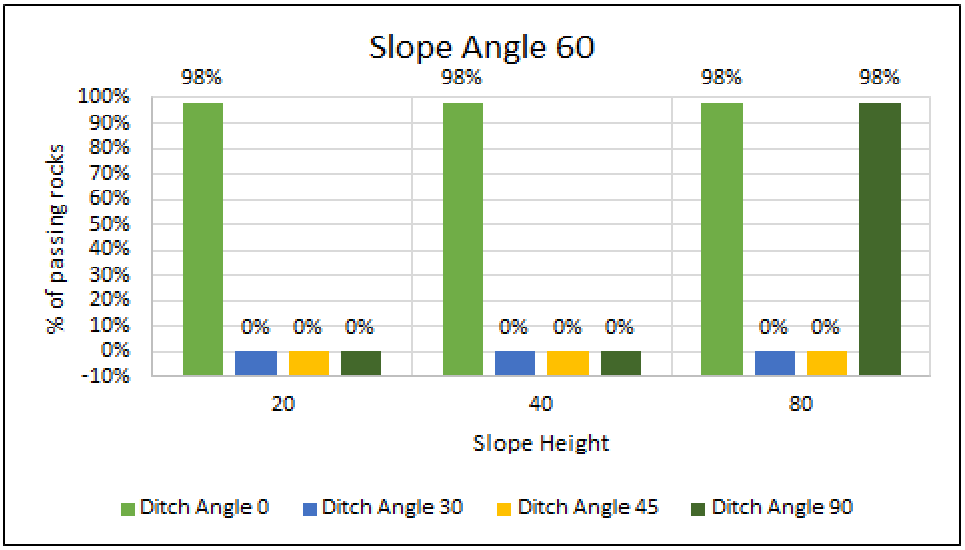


Figure 6.4. Percentage of rocks passing the ditch and shoulder edge in slopes with 60^0 (Rocfall).

For slopes with 30^0 and 45^0 slope angles, 98% of rocks passed the ditch and still rolled and bounced to reach the road in slopes with ditch angles 0^0, 30^0, while no rocks passed the ditch in slopes with ditch angles 45^0, 90^0 as Figure 6.5 illustrates.

In additional, a special slope was used which has three sections with width 2m and height 10m. In this slope geometry, as shown in Figure 6.6 most of rocks stabilized on the upper section at height 20m from the highway level and the rest stabilized in the ditch.

Figure 6.7 shows the slope profile and endpoints histogram for a slope which has two sections, the incline of the upper one is 60^0 and 30^0 for the lower one. In this slope geometry, all falling-rocks reached the highway. The same results in a slope of similar geometry (Figure 6.8) but with its lower section steeper (60^0) than upper section (30^0).

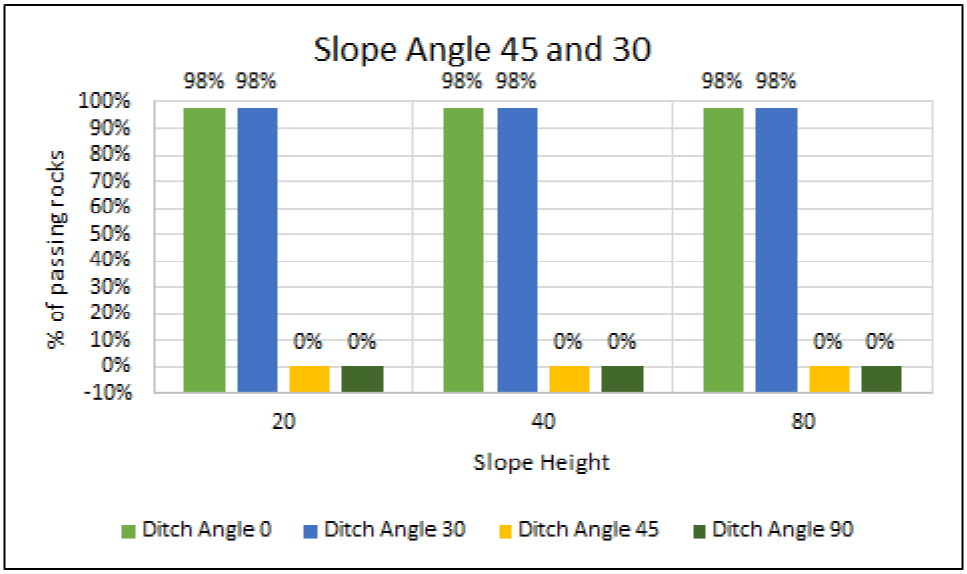


Figure 6.5. Percentage of rocks passing the ditch and shoulder edge in slopes with 30^0 and 45^0 (Rocfall).

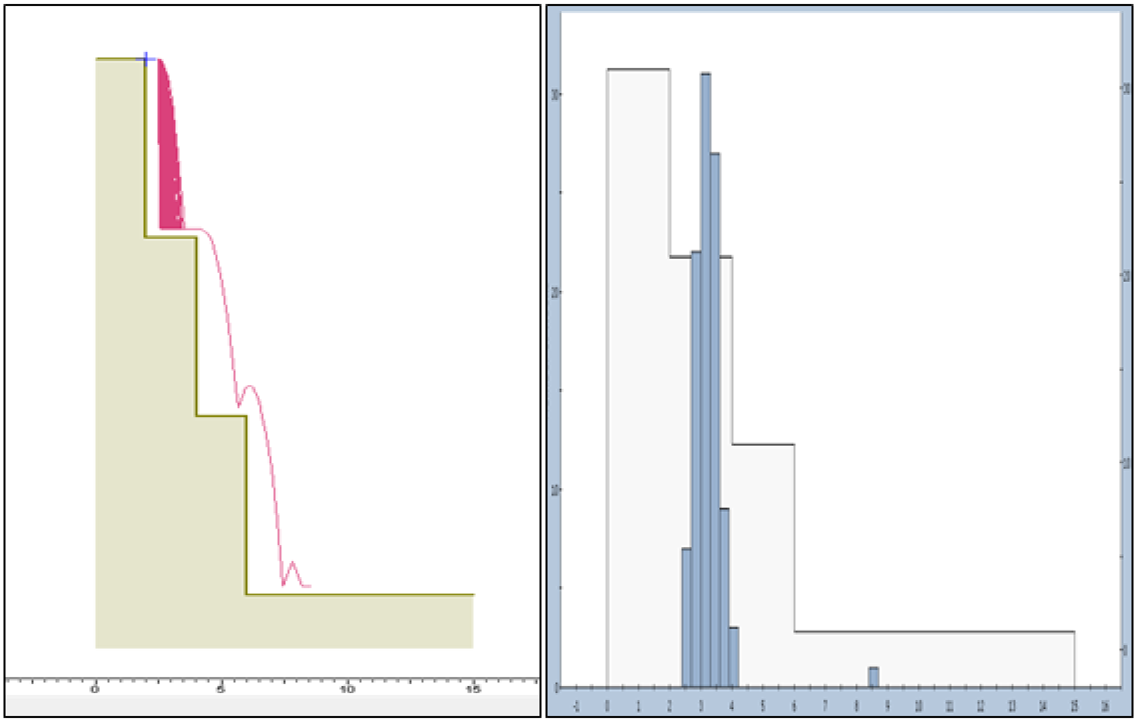


Figure 6.6. Rock and endpoints paths along slope with three sections (Rocfall).

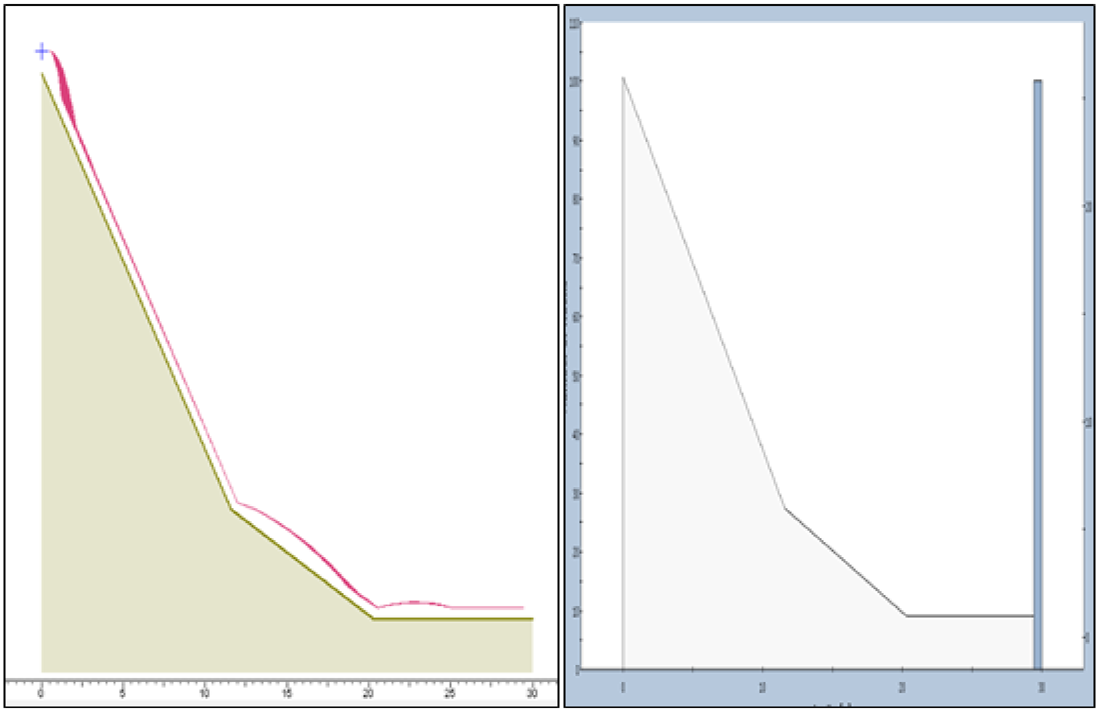


Figure 6.7. Rocks and endpoints paths along slope face with two sections, upper one steeper than lower section (Rocfall).

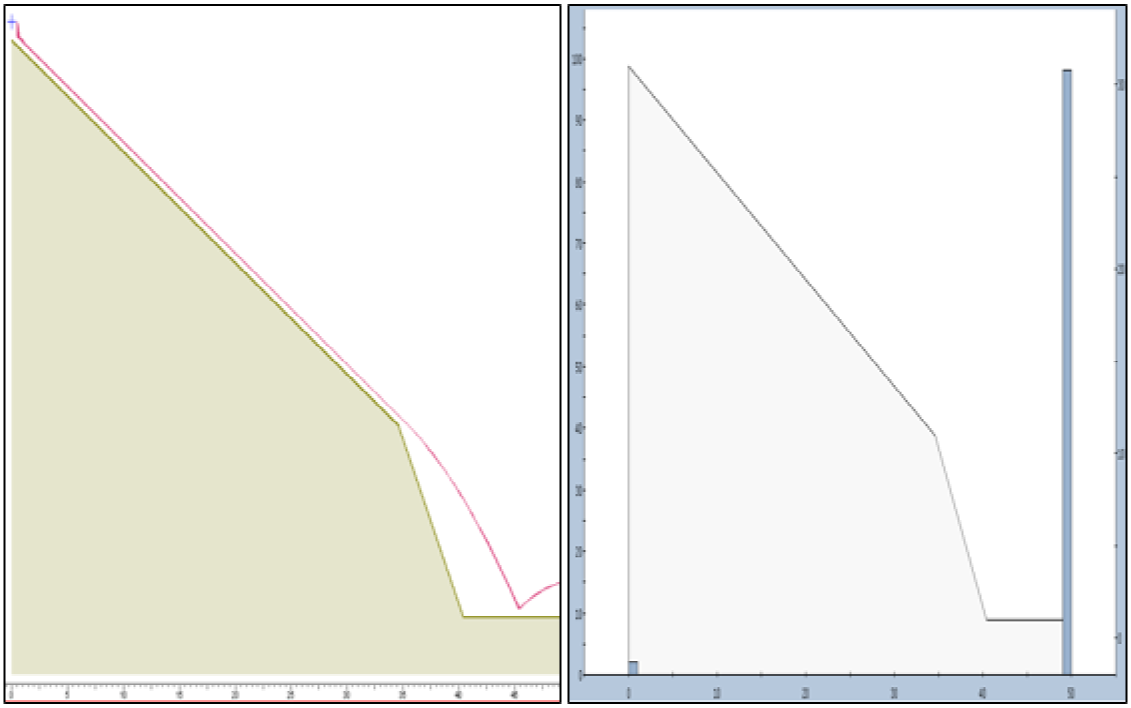


Figure 6.8. Rocks and endpoints paths along slope face with two sections, lower one steeper than upper section (Rocfall).

6.2. CRSP RESULTS

In this thesis, 63 models of slope geometry were used. These models were run by the CRSP program to study their effectiveness in problem of falling, rolling, and bouncing rock. CRSP display the results in more detail, first display the slope with all rocks position along the slope face every ten second, then displaying tables and charts illustrating the percentage of rocks that passing the analysis points, the kinetic energy, the maximum bouncing height, and the maximum velocity.

The data that collected after models had run by CRSP was plotted in several charts to illustrate the results. Consequently, the percentage of rocks passing edge of ditch and/or road shoulder is varies from zero (no any rock passing the safety limit and reaches the road) to 100% (all rocks reach to the road).

In all slopes geometries with slope angle 90^0, all rocks were collected in the ditch zone. One hundred spherical rocks were set to fall from 20, 40, and 80m were retained in a ditch with a width less than 1.75m, despite any differences in the ditch inclination toward the slope. Thus, no rock passed the shoulder and reached the road. Figure 6.9 shows no rock passing the shoulder for 0^0, 30^0, 45^0, and 90^0 ditch edge in slopes with 90^0.

For the slopes with 75^0 slope angle, the percentage of the rocks passing the edge ditch and shoulder edge varied in range (0 – 100) %. For the all ditch angles, the percentage of passing rocks increase with the slope height. All of rocks that passed ditch edge reached to the road except for the 0^0 ditch angle where there were less than four pieces of rock stabilized on the shoulder. Figure 6.10 illustrates the percentage of rocks passing the ditch edge in slopes with 75^0.

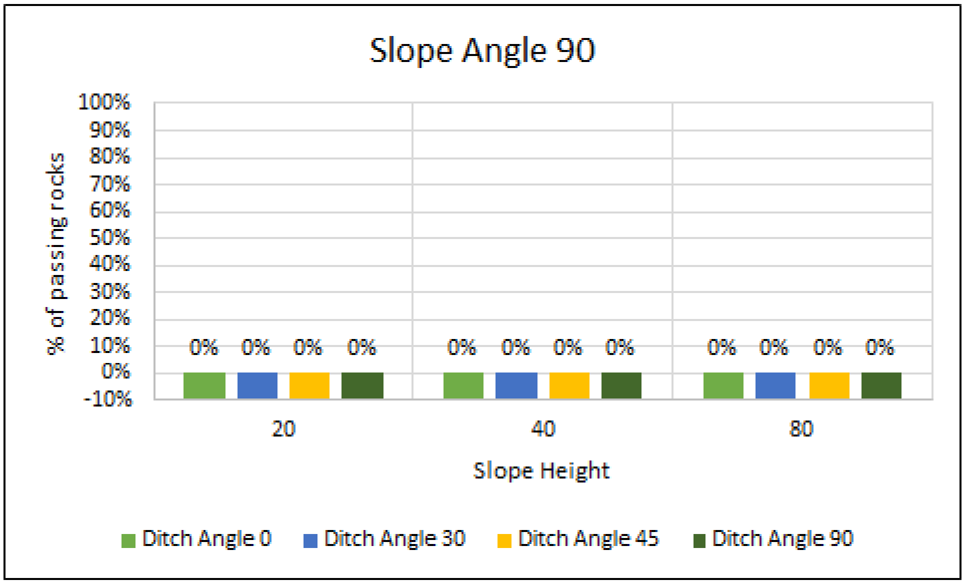


Figure 6.9. Percentage of rocks passing the ditch and shoulder edge in slopes with 90^0(CRSP).

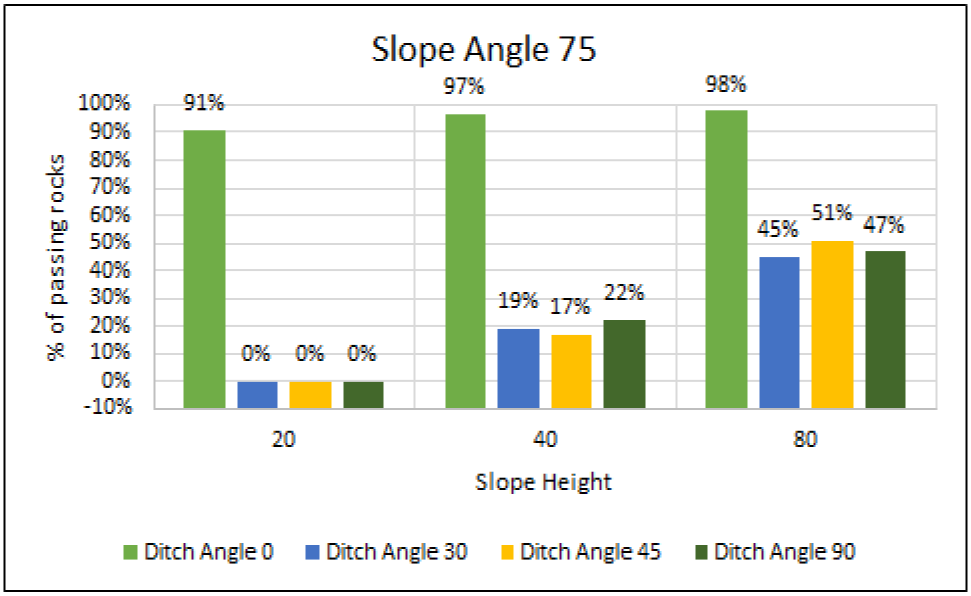


Figure 6.10. Percentage of rocks passing the ditch and shoulder edge in slopes with 75^0 (CRSP).

Figure 6.11 shows the percentage of rocks passing the ditch edge in slopes with 60^0. Also, the percentage of the rocks passing the edge ditch and shoulder edge vary in range from 0 to 100% (just in slopes with 0^0 ditch angle). For slopes with 30^0, 45^0, and 90^0

ditch angle, all rocks that passed ditch angle reached to the highway and its percentage less than 40%. In general, the percentage of passing rocks increase with the slope height.

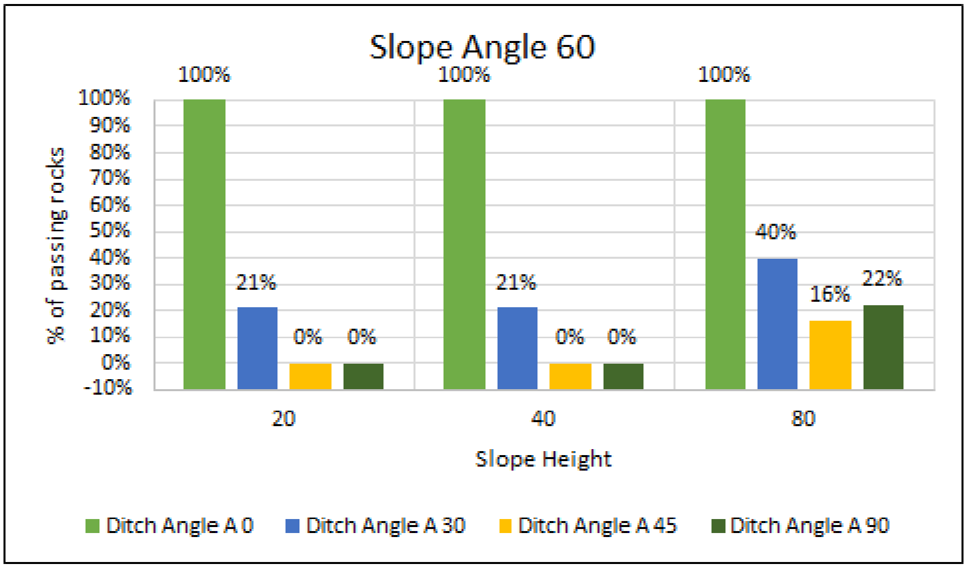


Figure 6.11. Percentage of rocks passing the ditch and shoulder edge in slopes with 60^0 (CRSP).

In the slopes with 45^0, all of rocks that passed ditch edge reached to the highway except a few pieces of rock that stabilized on the shoulder. The percentage of rocks that reached the highway increased with slope height and decreased with ditch angle e.g. less than eight rocks reached highway with 90^0 ditch angle as shown in Figure 6.12.

The road shoulders and ditches with angles 0^0 and 30^0 could not prevent the rocks falling from the top of slopes with 30^0 to reach to the highway. However, the ditch with incline 90^0 caught most of falling-rocks, but most of falling-rocks reached the highway in slopes with ditch angle of 45^0. Figure 6.13 shows the percentage of rocks passing the ditch edge in slopes with 30^0.

Also, a different geometry was used which it has three sections with width 2m and height 10m (Figure 6.14). In this slope geometry, all falling-rocks stabilized on the upper section at height 20m from the highway.

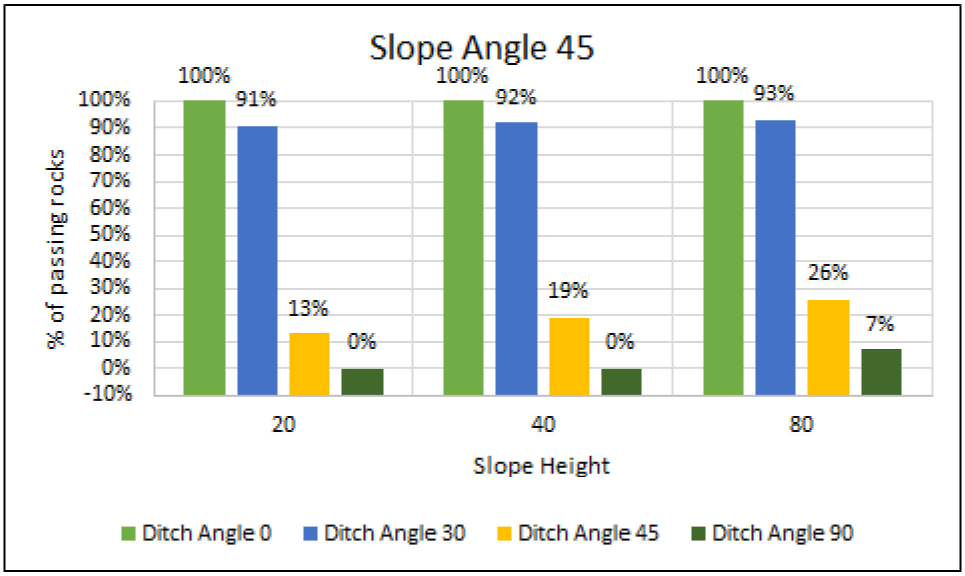


Figure 6.12.Percentage of rocks passing the ditch and shoulder edge in slopes with 45^0 (CRSP).

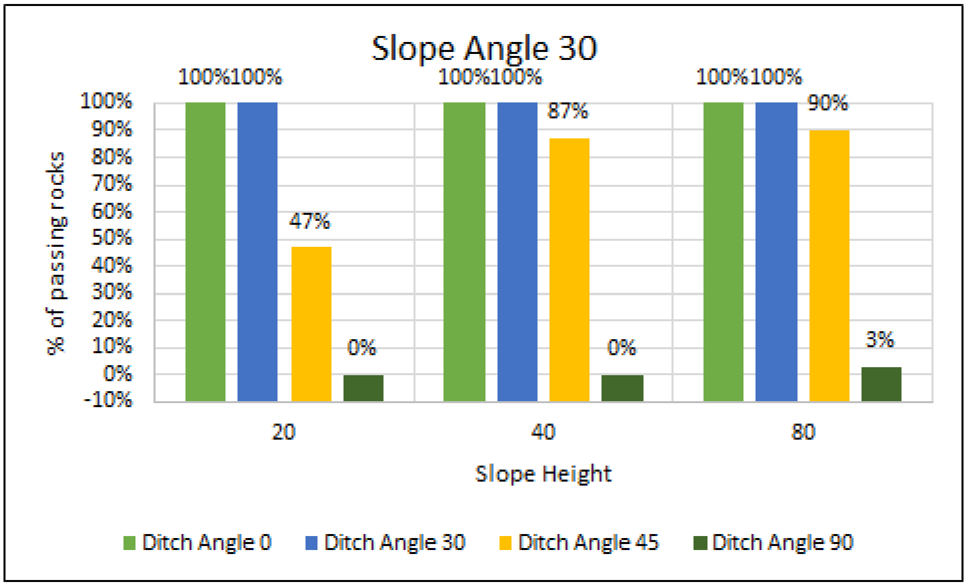


Figure 6.13. Percentage of rocks passing the ditch and shoulder edge in slopes with 30^0 (CRSP).

Figure 6.15 shows the slope has two sections, the incline of upper one is 60^0 and 30^0 for lower one. In this slope geometry, all falling-rocks reached to highway level. Also, the same results on the slope in a similar geometry (Figure 6.16) but with its lower section steeper (60^0) than upper section (30^0).

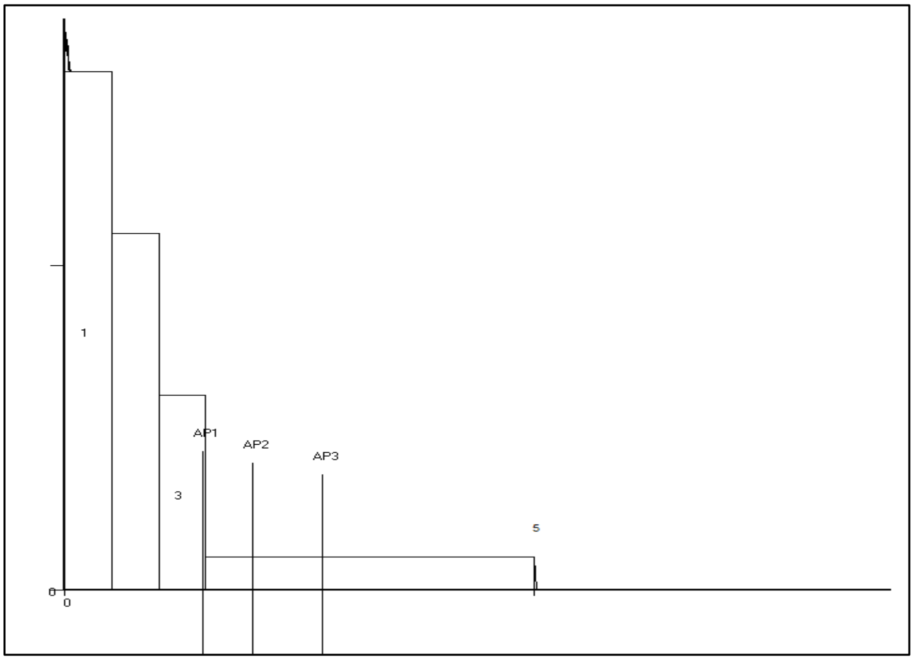


Figure 6.14. Rocks along slope with three flat sections.

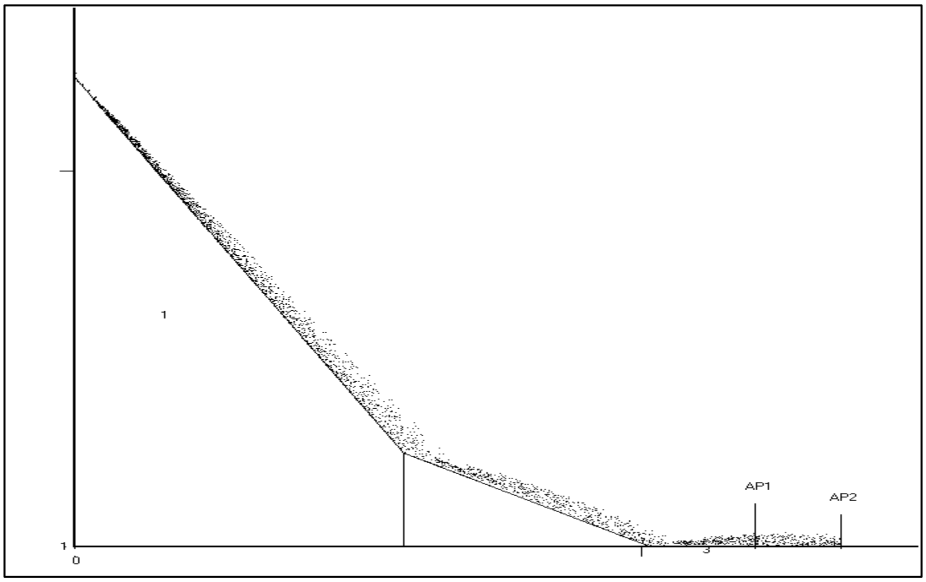


Figure 6.15. Rocks along slope face with two sections, upper one steeper than lower section.

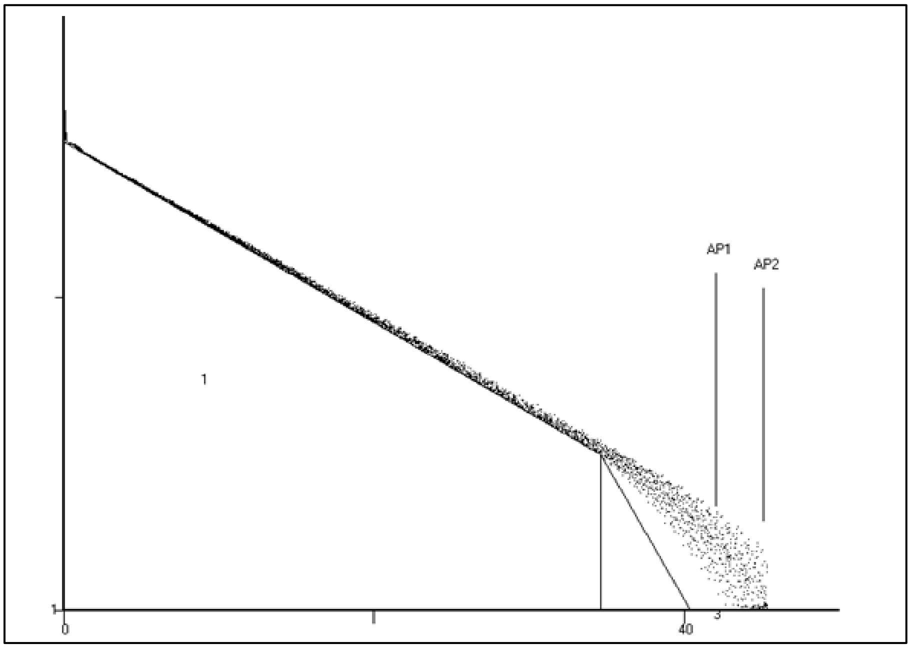


Figure 6.16. Rocks along slope face with two sections, lower one steeper than upper section.

7. COMPARISON DISCUSSION AND CONCLUSIONS

7.1. COMPARISON

The Rocfall and CRSP programs were used to run the models of different slopes geometries. The trait in common between the programs is simulating the rockfall, but they differ in the way of input and output data. This section discusses the similarities and differences between the programs.

For defining and modify the slope in Rocfall first the slope geometry is defined, then the material properties for each section, while the material properties for each section is defined with it geometry in the same step in CRSP program. Modifying on the geometry and parameters of slope and rock parameters and location easier in Rocfall than CRSP.

Roughness can be defined in both program, slope parameter affect to most affect rockfall is roughness with the exception of vertical slopes. When the rock is dropped on rough surface, it rebounds several times with higher than on a smooth surface. Figure 48 shows how the changing in roughness value from 0.1 to 0.6 for the slope with three flat sections had affect the rock paths. Thus, the endpoints distribution for a slope with (0.1) roughness value (see Figure 6.6) changed, Figure 7.1 shows the rock paths on slope with (0.6) roughness value, the endpoints distribution also changed when roughness value change (Figure 7.2).

The Animate Paths feature in Rocfall helps understand the rock path during move down the slope, because the animate path displays the rock travel along slope surface in a clear way. The CRSP program does not have this feature, but shows all the rock paths every ten seconds on the same screen.

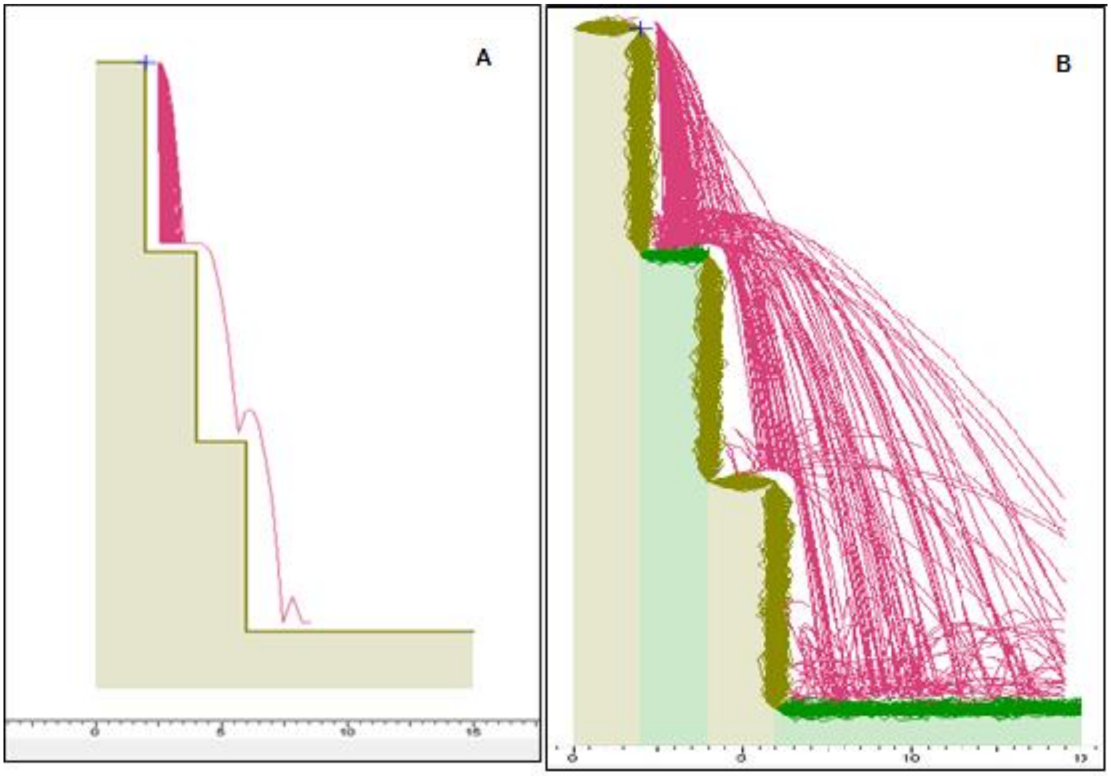


Figure 7.1. Roughness affect on rockfall. A. Rock paths on slope with 0.1 roughness. B. Rocks paths on slope with 0.6 roughness (Rocfall program).

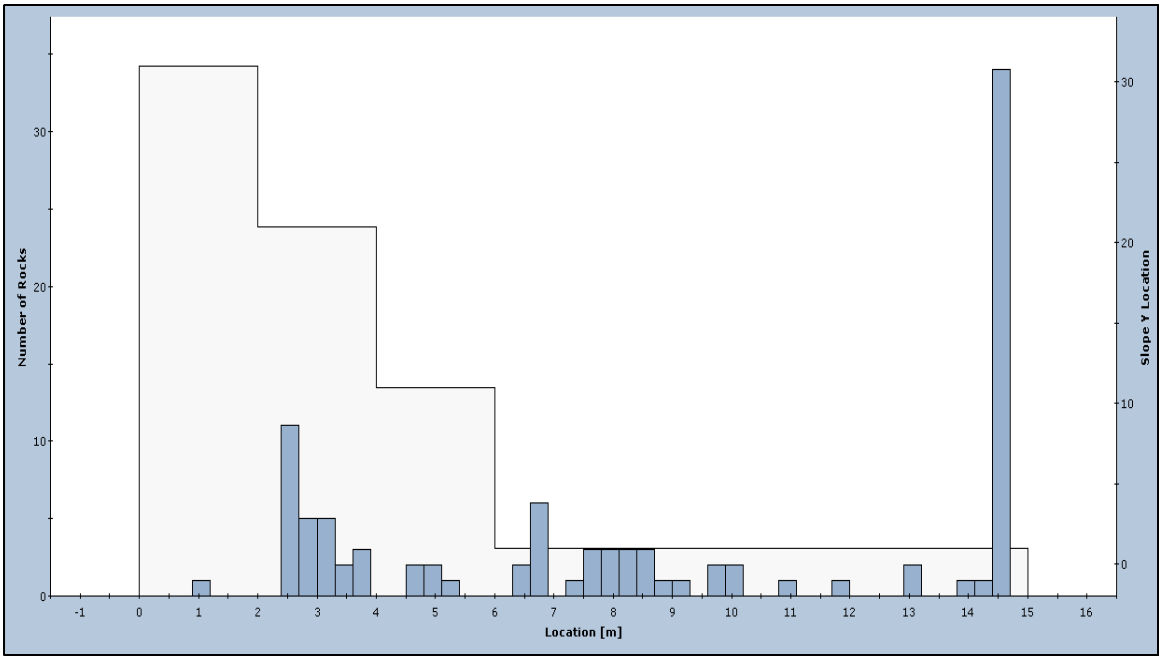


Figure 7.2. Endpoints distribution for a three-flat section slope with roughness (0.6).

The Barriers feature available in the Rocfall which it assists users to assess their effectiveness on the rockfall. Barriers are used as a solution for rockfall problem by forcing rock to stop or decrease its velocity and kinetic energy at the barrier location. A barrier features is not available in the CRSP.

The Rocfall program has a Data Collectors feature which is used to collect the information about rocks that passing it. The CRSP program also has this feature, known as point analysis, but the users could not specify more than three points in the analysis whereas in Rocfall where there is no restriction on the number of data collectors.

Results in the Rocfall program come with more detail than CRSP program. The results in the Rocfall display as graphs for easy interpretation, such as distribution graph of Kinetic Energy (Total, Translational, and Rotational), Velocity (Translational, and Rotational) and Bounce Height, updated for each point on the slope when hovering the cursor over the graph.

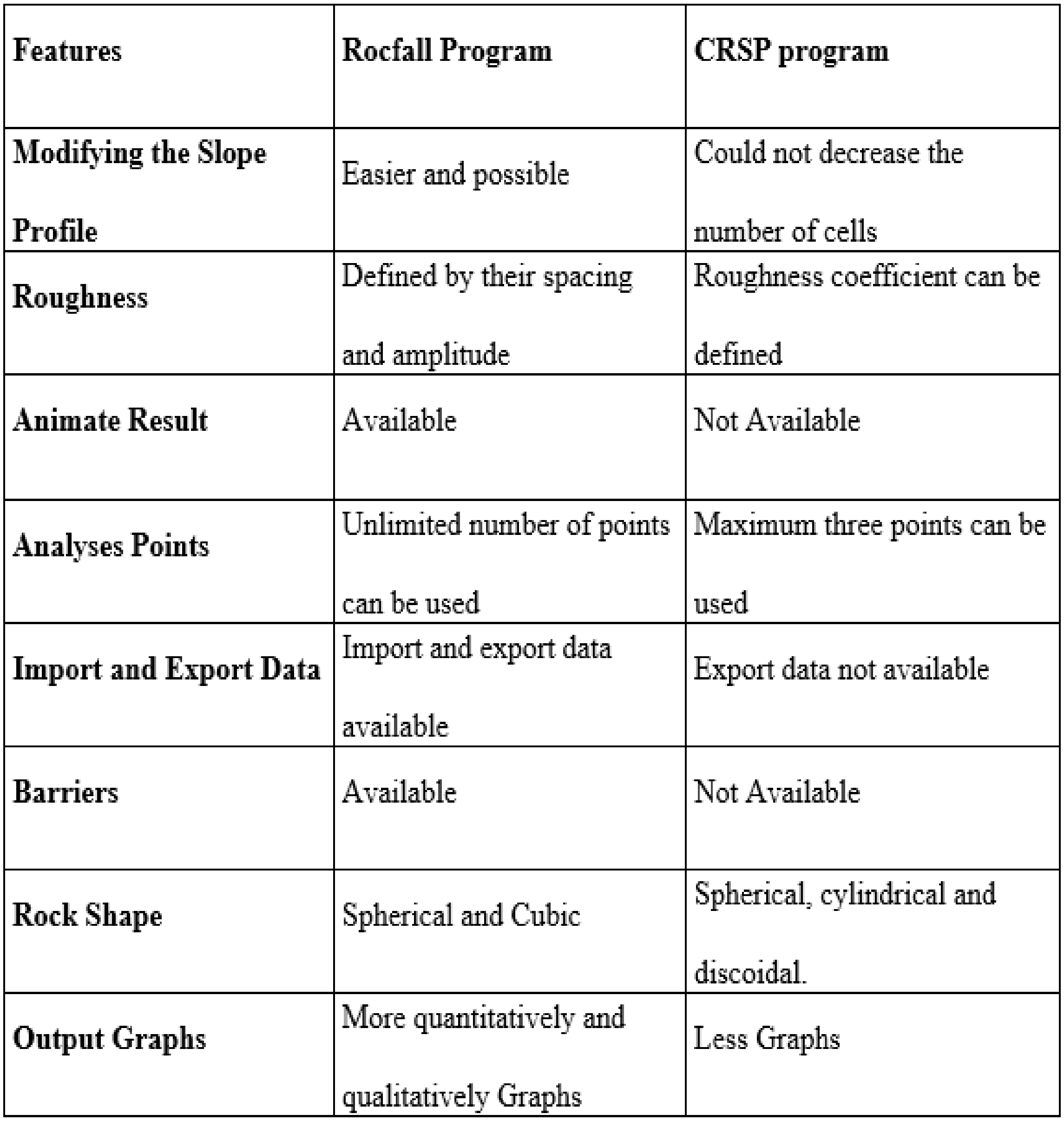
This study focused on the number of rocks passing the two critical points (ditch and shoulder edge) with respect to where the fallen rocks finally stabilized. The number of rocks that rested on each slope section are displayed in the CRSP program as a table form and as histogram chart in the Rocfall program.

7.2. DISCUSSION

Although the Rocfall and CRSP programs simulate the rockfall problem, each program has a certain approach in inputting the data, processing the data, and displaying the results. However, the programs are identical in some features that are necessary in simulating the rockfall issue. This section discusses some similarities and differences, and some graphics of outputs and results for both programs. Furthermore, there is a compare between the slopes geometries effectiveness on rockfall problems.

7.2.1. Similarities and Differences. Table 7.1 illustrates some available features on Rocfall and/or CRSP programs.

Table 7.1. Similarities and differences between Rocfall and CRSP programs.



Features	**Rocfall Program**	**CRSP program**
Modifying the Slope Profile	Easier and possible	Could not decrease the number of cells
Roughness	Defined by their spacing and amplitude	Roughness coefficient can be defined
Animate Result	Available	Not Available
Analyses Points	Unlimited number of points can be used	Maximum three points can be used
Import and Export Data	Import and export data available	Export data not available
Barriers	Available	Not Available
Rock Shape	Spherical and Cubic	Spherical, cylindrical and discoidal.
Output Graphs	More quantitatively and qualitatively Graphs	Less Graphs

7.2.2. Output Graphs. After the both programs, had run the same models, they displayed the results in a little bit differences. Figure 7.3 shows the slope profile after 100 pieces of rocks moved down the slope, where the CRSP shows the position of rock every 10 second but the Rocfall shows the paths of rocks along slope that make the interpretation easier especially if the Animate Result feature used.

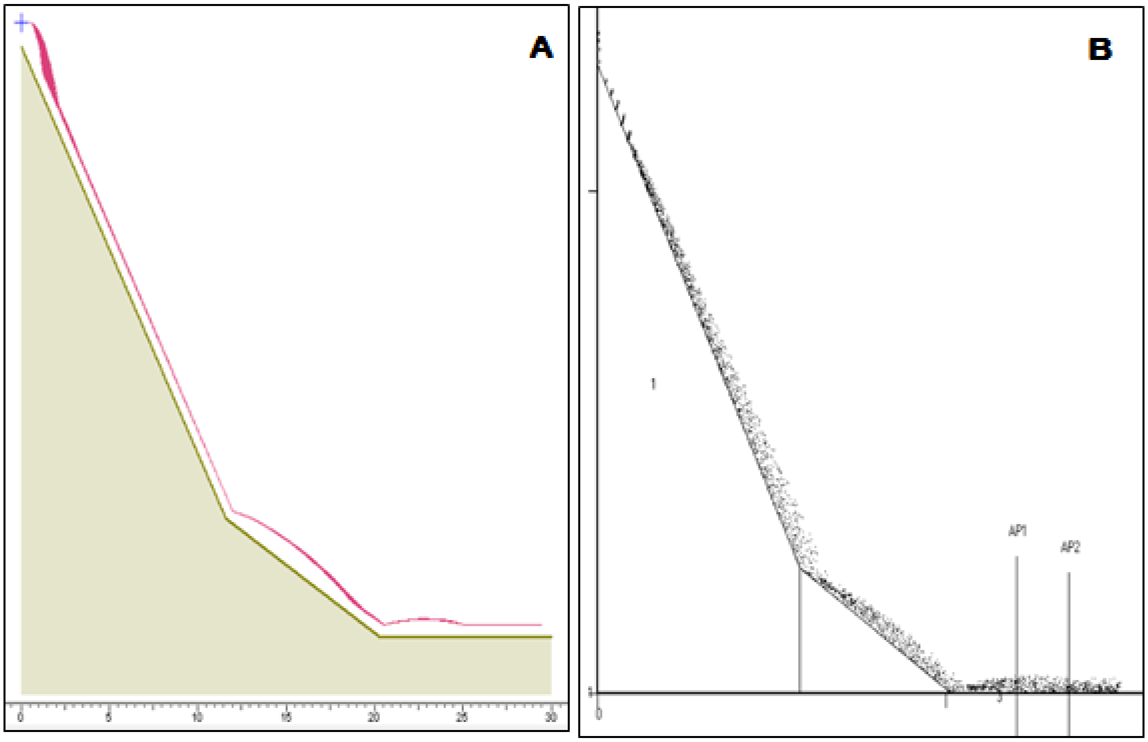


Figure 7.3. Slope profile after 100 rock moving down the slope; A. Rocfall B. CRSP.

Moreover, the results that came from both programs for the models with slope angle 90^0 (cliff) are difference. The rock hits the ground about 2.75m away from the base of slope (cliff) in Rocfall program and about 0.7m in the CRSP program (Figure 7.4), despite the initial velocity that used is the same (0.3m/s) in both programs. Consequently, this difference affects the results of slopes with 90^0 slope angle.

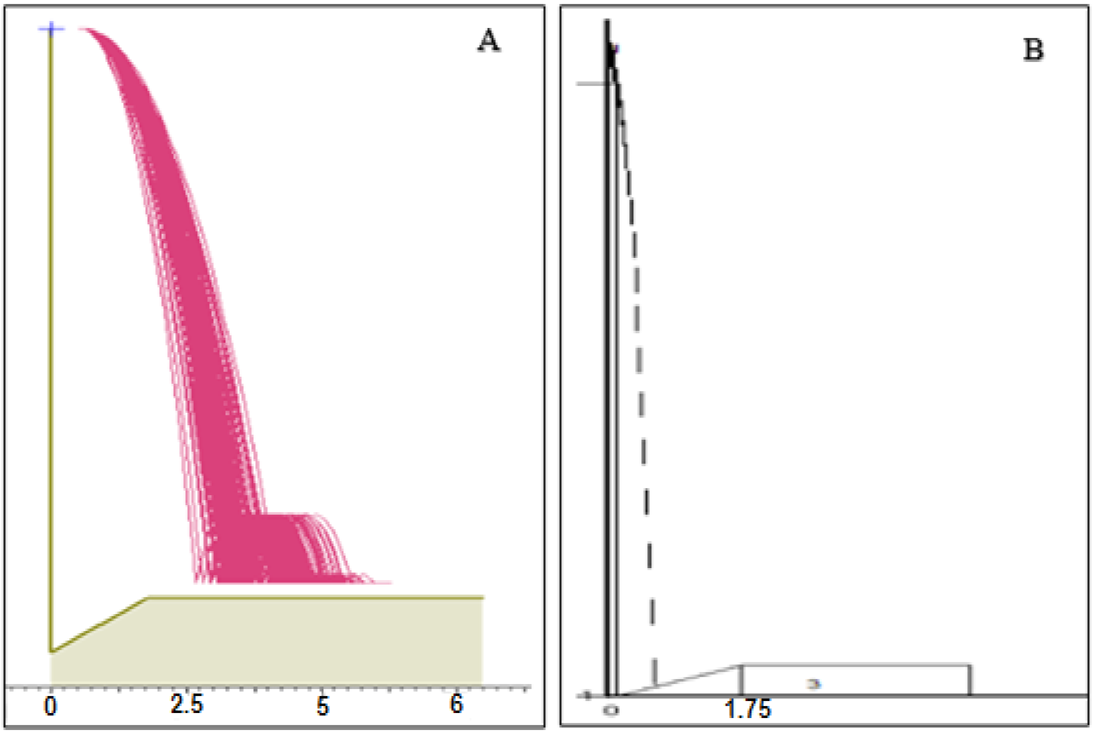


Figure 7.4. The way of rocks falling from a top of slope A. The rock hit the ground at 2.6m in the Rocfall B. The rock hit the ground at 0.7m in the CRSP.

Physically:

A manual calculation was made to verify the real horizontal distance where the rock hit the ground, when it dropped down from a slope (cliff) as shown in Figure 7.5.

First: the time (t) its need to hit a ground is:

$$\Delta y = V_{0y}\, t + 0.5\, a_y\, t^2$$

$$-20 = (0)\,(t) + (0.5)\,(-9.81)\,(t^2) = 2.02 \text{ sec}$$

Second: horizontal displacement

$$\Delta x = V_{0x}\, t + 0.5\, a_x\, t^2$$

$$\Delta x = (0.3\text{m/s})\,(2.02) + (0.5)\,(0)\,(2.02^2)$$

$$\Delta x = 0.6 \text{ m.}$$

The rock hit the ground at 0.7m from the base of the slope in CRSP program, but in the Rocfall program hit the ground at 2.60m from the base of the slope. Consequently, the CRSP results in the vertical slopes more realistic than the Rocfall results.

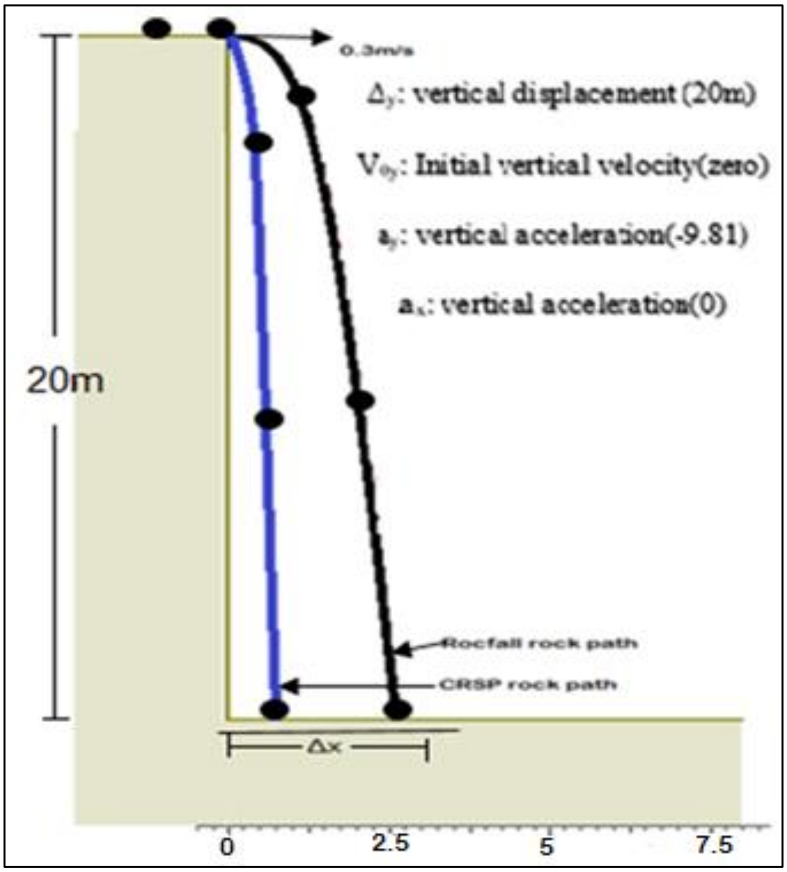


Figure 7.5. Physical interpretation of rock-falling.

Also, the rock starting location can be dropped from any point on the slope on the Rocfall, while the CRSP lets users to define the rocks location at points with X = 0 and y equal or higher than slope height, so that’s affect the result in some models such as the slope with three flat sections (Figure 7.6).

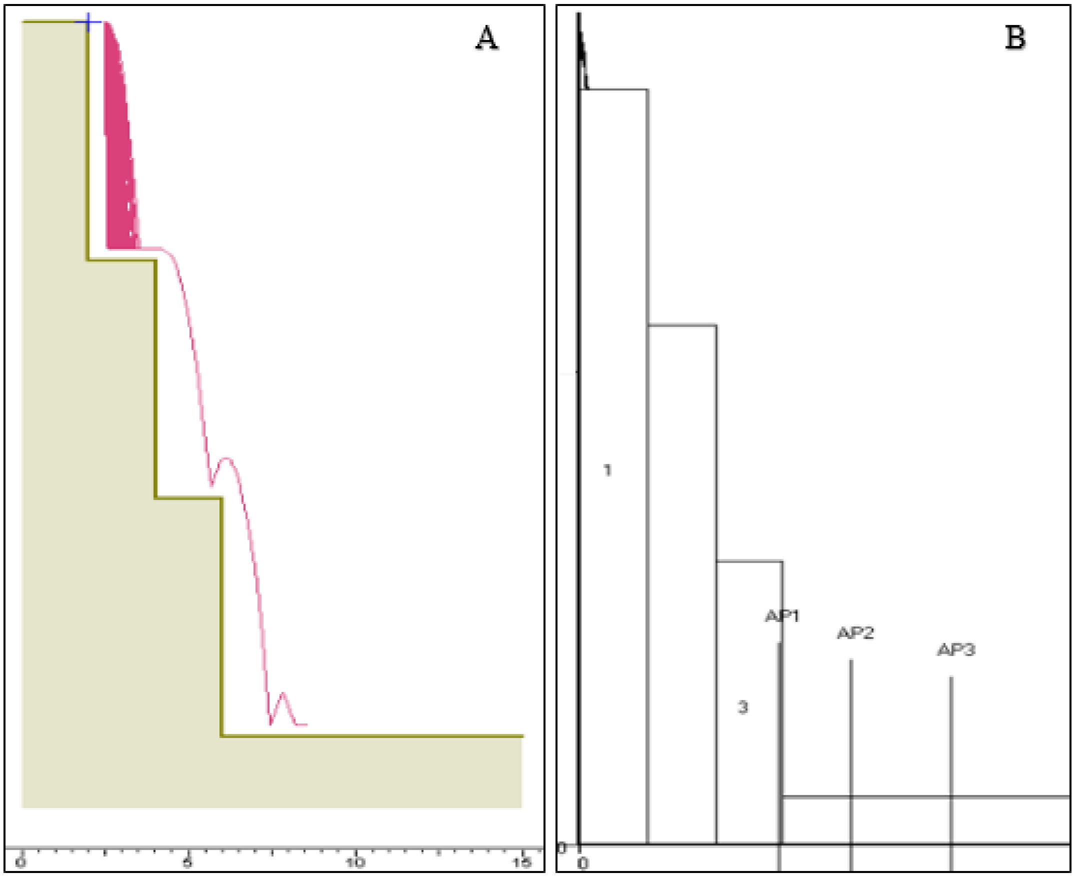


Figure 7.6. The location of rocks on the slope affect results A. Rocfall B. CRSP.

7.2.3. Results Charts. The results of run out the models by the Rocfall and CRSP programs are plotted in charts and in these charts, appear some differences between programs results in most of slopes. Figure 7.7 shows the widest difference appears in the percentage of rocks that passed the ditch edge in slopes with 90^0 slope angle, because of the reason which illustrated in Figure 7.5. However, both programs give the same results for the percentage of rocks that passed the shoulder edge in same slopes, where on rocks passing. Also, the percentage of rocks that passed shoulder and reach the road in slopes with 45^0 slope angle are convergent in both programs as shown in Figure 7.8.

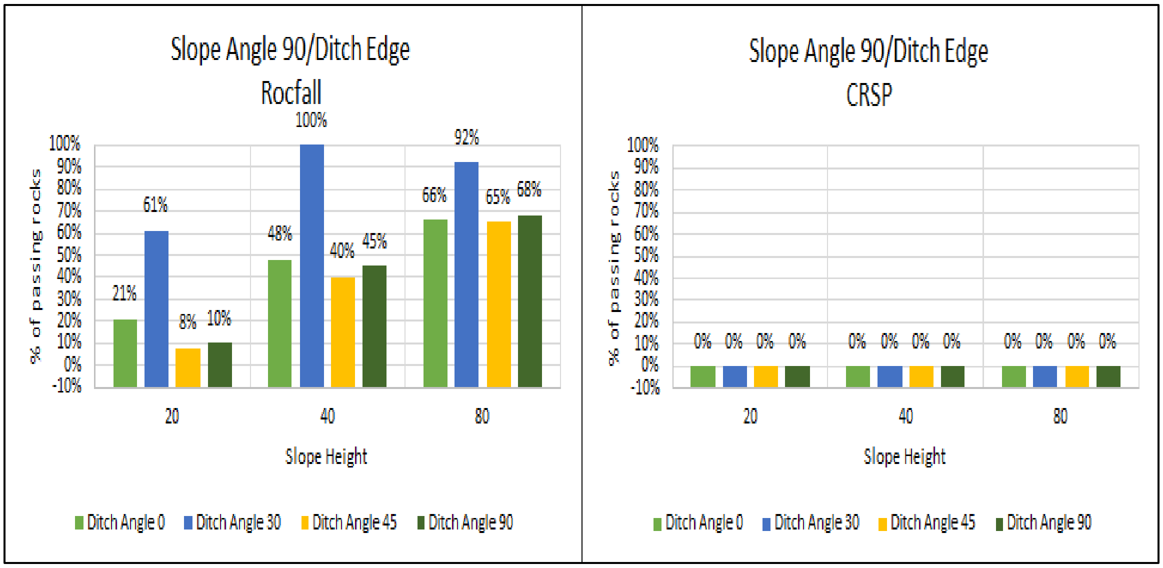


Figure 7.7.Comparison between the Rocfall and CRSP results in slopes with slope angle 90^0.

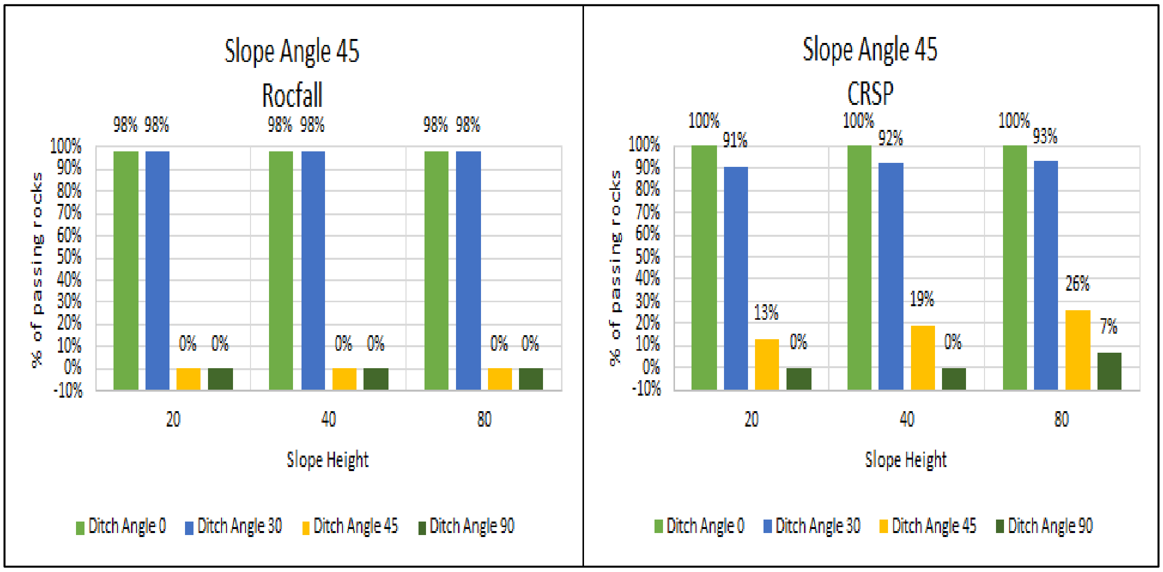


Figure 7.8.Comparison between the Rocfall and CRSP results in slopes with slope angle 45^0.

7.2.4. Comparison of the Results of Slopes Geometries. Slope geometry affects the percentage of rocks that reach the road; the geometry parameters that were changed in this research to study their affect the rockfall problem were slope height, slope angle and ditch angle.

The CRSP results clearly show that the probability of rock reaching the road is increases when slope height increase and vice versa. However, the Rocfall results did not show any relationship between slope height and percentage of rocks that reached the road.

The slopes with 90^0 slope angle are the ideal slope geometry for rockfall problem, where the both programs results indicate that is no rocks reached the road. Otherwise, the 30^0 slopes angle recorded the highest percentage of rocks that passed the ditch and shoulder edge in all slope height and ditch angles, most clear in CRSP results as shown in Figure 7.9.

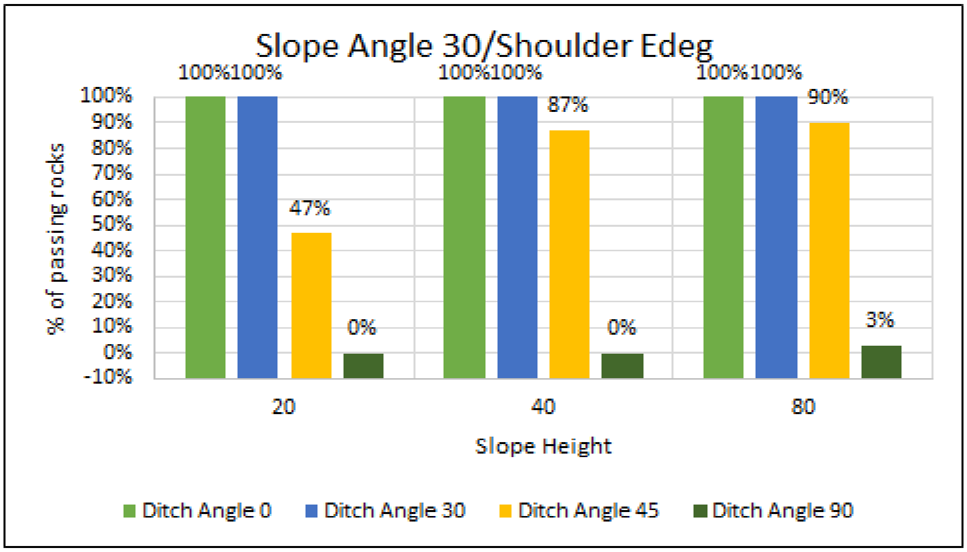


Figure 7.9. Percentage of rocks passing shoulder edge in slopes with 30^0-slope angle (CRSP results).

The ditch helps to catch the rock and prevent it from reaching the road. The degree of the ditch inclination affects the falling-rocks, so both programs results indicate the 0^0 is worst ditch angle in all slopes. However, the programs results are dissimilar in the suitable ditch angle (catch most falling rocks), where the 30^0-ditch angle is the ideal ditch relative to the Rocfall results and 90^0-ditch angle is the perfect ditch according the CRSP results.

7.3. CONCLUSIONS

A number of conclusions were obtained from this study on the comparison of the Rocfall and CRSP programs in the manner they handle rockfall data and the obtained results for the slope geometries.

The study found that defining and modifying the slope and rocks parameters are easier and faster in the Rocfall program, and that the output in Rocfall program is clearer and easier to interpret than the CRSP output. Another advantage of the Rocfall program is that it gives information about rocks at any point on the slope surface, and its barriers features provides extra help in finding solutions for rockfall data and determining the optimum location to place barriers along the slope.

On the other hand, CRSP program provides a more realistic and correct results in simulating a rockfalling at from a near vertical slope, where the rock will travel a longer vertical distance to the ground compared to the shorter vertical distance it travels when it falls along an inclined slope. Both Rocfall and CRSP provide varying results in most of the situations for slope angles falling between 90^0 and 30^0.

The study also concluded that the geometry of a slope with a 90^0 slope angle is the ideal geometry for rockfall problems, regardless of the slope height or ditch angle, and that the geometry of slopes with a 30^0 slope angle is the worst geometry for rockfall problems. For a ditch of 0^0 angle, Rocfall show that rocks will rest on the shoulder area, while CRSP show that rocks will be confined to the ditch area at a falling angle of 90^0. For a zero-slope ditch, most of the rocks will reach the road provided that the slope angle is less than 90^0.

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