HHS Public Access
Author manuscript
*Min Metall Explor*. Author manuscript; available in PMC 2024 July 22.

Published in final edited form as:
*Min Metall Explor*. 2023 ; 40(4): 1101–1112. doi:10.1007/s42461-023-00776-4.

# UTILIZATION OF STATISTICAL ANALYSIS TO IDENTIFY INFLUENTIAL SLOPE PARAMETERS ASSOCIATED WITH ROCKFALL AT OPEN PIT MINES

**Josef Bourgeois**,
CDC/NIOSH/SMRD, Spokane, WA

**Sean Warren**,
CDC/NIOSH/SMRD, Spokane, WA

**Jorge Armstrong**
Kinross, Elko, NV

## Abstract

The application of statistical analysis software programs has proven useful for the investigation of rockfall runout distance along a designed slope. Rockfall modeling programs are continually being upgraded with more sophisticated analysis tools, such as the use of the rigid body versus lump mass models. Engineers at mine sites utilizing the software may have varied experience related to these models, their associated input parameters, and how to interpret the generated results. To address this concern, researchers at the Spokane Mining Research Division (SMRD) of the U.S. National Institute for Occupational Safety and Health (NIOSH) investigated the influence of slope height, slope angle, slope material, and rock size for both rigid body and lump mass models in a 2-D statistical analysis program. Based on a literature search and industry input, specific ranges common to that of an open pit mining environment were chosen for each of the input parameters to determine 90% rock runout distance as well as their sensitivity to change. Data collected from this numerical analysis and simulation will be compared to empirical rockfall data gathered through the duration of the Highwall Safety project conducted by NIOSH from 2022–2026.

## Introduction

In open pit mines, rockfall can occur due to slope degradation and can be made more severe through inadequate implementation of slope design. The dynamics of these events are largely a function of the mechanical properties of the detached rock, location of the detachment, the rock mass, and downslope profile [1]. Rockfall potential is one of the most significant geotechnical hazards to the open pit mining workforce [2] and is typically

Disclaimer
The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH.

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

addressed by catch benches as required by the Mine Safety and Health Administration (MSHA). The Modified Ritchie Criterion (MRC) is an industry-accepted standard in North and South America for initial rockfall catch bench design [3] and is presented in Equation 1 [4].

$$W = 0.2H + 4.5 \tag{1}$$

Where: W = minimum catch bench width (m)

H = bench height (m)

While the MRC only considers bench height in calculating minimum catch bench width, individual mine studies [5, 6, 7] show that rockfall hazard and catch bench performance are a function of multiple variables, including bench face angle, rock size/shape (geology), operational practices (e.g. blasting), and bench berms. Williams et al. state that, although efforts to understand rockfall behavior in relation to bench design have been completed, each individual mine site possesses its own specific set of constraints and conditions, thus requiring custom investigation [8]. Statistical analysis programs, such as RocFall [9] can be used to assist with assessment of slopes at risk for rockfall events.

## Use of RocFall in the Mining Industry

A typical workflow of a rockfall trajectory study that may incorporate the use of statistical analysis programs, such as RocFall, was developed by Dorren et al. [10] and can be divided into six phases including: (1) preparation phase, (2) definition of the release scenarios, (3) rockfall simulation, (4) plausibility check/validation of the simulated results, (5) fixation of the model results, and (6) transformation into rockfall process maps. Mine sites have utilized this workflow in some form or another to gain a better understanding of rockfall behavior with respect to their specific bench design.

Through the years, RocFall has continually been upgraded with more sophisticated analysis tools, such as the use of the lump mass versus rigid body models. With the lump mass model approach, each rock is modeled as a very small spherical particle and the rocks are not considered to have any size, only mass. With the rigid body approach, the shape of the rocks is accounted for by selecting from a wide variety of pre-defined smooth or polygonal shapes in the program’s rock type library, and the mass of the rock determines the actual size of the rock shape. Additional details on the differences between the aforementioned modeling methods can be found on Rocscience’s website [11].

With regards to mine sites utilizing the program, a literature search shows that users either apply the lump mass approach [5, 12, 13, 14, 15] or the rigid body approach [8, 16] but rarely use both. Additionally, field experience and extensive use of RocFall in both mining and civil applications has helped identify key variables, additional to bench height, that affect the runout distance of rocks along a designed catch bench slope [14, 16, 17, 18, 19] ; however, there is less clarity on how results can differ between the available RocFall models. This prompted researchers at the Spokane Mining Research Division (SMRD) of the U.S.

National Institute for Occupational Safety and Health (NIOSH) to reach out to industry partners, conduct an analysis of 90% rock runout distance according to changes in slope height, slope angle, slope material, and rock size for both lump mass and rigid body models, and compare/contrast the results with the MRC bench design criterion according to each designed test. This research is part of the NIOSH Highwall Safety project which started in October of 2021.

### NIOSH Highwall Safety Project

In October of 2021, the Geomechanics Team at NIOSH SMRD started the Highwall Safety project, which will run for 5 years. This project is a continuation of a pilot project conducted by Warren et al. [20] where one of the main goals is to quantify the performance of available criterion for rockfall catchment bench design in a variety of bench configurations and optimize said criterion based on field calibration. As shown in Equation 1, the MRC only considers bench height in determining catch bench width; however, field testing and statistical analysis programs show that additional variables related to geology and operational practices play a role in rockfall runout distance and necessary catch bench width.

Therefore, as a starting point for the NIOSH Highwall Safety project, the modeling executed in this paper is a first attempt at a sensitivity analysis looking into the various factors that influence how far rocks roll on a single bench to gain insight into required catch bench width to achieve safe mining conditions.

## Modeling Setup

The goals of this study were to: (1) investigate the influence of and, to some extent, quantify various rockfall catch bench parameters on rockfall runout distance, and (2) investigate the rockfall catch bench performance of the MRC under various bench configurations. The process that was followed to perform the sensitivity analysis of various factors that influence rockfall runout distance is shown in Figure 1. RocFall version 8.013 [9] was utilized to carry out each testing scenario and perform statistical analysis, while Excel and MATLAB were used to create a modeling matrix to analyze and interpret the data.

Ninety percent runout distance (catchment on the first bench) was chosen as the acceptable criteria-dependent variable in this study based on the research team's previous experience with bench design; however, it should be noted that other percentages are used in the mining industry. For example, with rockfall testing at the Goldstrike open pit mine in Nevada, the acceptability criteria used for calculating bench widths from modeled events is 80% retention on the first bench and greater than 95% for the next lower bench [5]. Table 1 shows the parameter set and specific range of each parameter tested in RocFall for this study.

Slope heights were chosen to simulate single and double stack heights of 25-foot and 40-foot benches. With regards to the parameter of slope material in Table 1, Bedrock Outcrops and Talus Cover are material types used from the Rocscience material library [9], while Sandstone CTQ [16] and Bedrock CR [8] are material types used in previous publications related to RocFall studies conducted at mining operations. Each slope material used for the purpose of this study was specifically chosen for their slight differences in restitution coefficient values as shown in Table 2. For each simulation, 100 rocks of each size were tested from the crest of the slope with a horizonal velocity of 1 foot per second. Overall, range selection on the modeling input parameters, including bench configurations, rocks size, etc., were informed by modern metal mining practices in the western United States.

Every combination of each parameter shown in Table 1 was tested as an individual simulation using both lump mass and rigid body models, resulting in 288 total simulations with a resulting 90% runout distance and rock percentage retained at the specific bench design's calculated MRC distance. Examples of the RocFall testing for both lump mass and rigid body models are shown in Figure A1 and Figure A2 (Appendix), while examples of the results, after being processed in Excel, are shown in Figure 2 and Figure 3.

## Modeling Results

Through RocFall simulation conducted in this study, the resulting 90% runout distance and rock percentage retained at the specific bench design's calculated MRC width are shown in Figure A3 (Appendix). Figures A4 and A5 (Appendix) were developed from the resulting data, outlining the differences between lump mass and rigid body models when using the same variation of input parameters. Correlation coefficient matrices were developed in Excel to identify the correlation between 90% rockfall runout distances and the input parameters (slope height, slope angle, slope material, and rock size) for both models as shown in Table 3.

The calculated correlation coefficients identified slope height and slope angle as the most influential parameters. To further analyze this, MATLAB software was utilized to visualize 90% runout distance and rock percentage retained at the specific bench design's calculated MRC width as contour plots in accordance with the slope height and slope angle (Figure 4 through Figure 7).

## Discussion

### Rockfall Runout Distribution between each Model

Within each individual RocFall test, differences in distribution of runout distance were easily identifiable between lump mass and rigid body models. For example, the specific tests shown in Figure 2 and Figure 3 show that, while runout distance of each rock size in the lump mass model were confined to distances between 10 feet and 27 feet from the toe of the slope, the runout distance of the same rock sizes ranged between 0 feet (not getting past the toe of the slope) and 29 feet for the rigid body model. These differences in runout distribution between each model were seen throughout the entirety of RocFall testing. This illustrates the effect of how the rigid body model accounts for the shape of the rocks. It is important to note that, for Figure 2 and Figure 3, while the runout distribution is vastly different between each model, the 90% runout distance only differs by a maximum of 2 feet. Therefore, the rock percentage retained at the calculated MRC width for each individual test is also noted (Figure A3) as this provides a better indication of runout distribution and whether this type of test would meet the criterion of catching 90% at the MRC.

### Correlation between Independent Variables and Rockfall Runout Distance

Figures A4 and A5 help provide an initial indication of which independent variables have a more significant influence over rockfall runout distance. For both lump mass and rigid body models, the slope height and slope angle have a greater influence than slope material and rock size, demonstrating that as the bench height increases and the slope angle decreases, the 90% rockfall runout distance increases. This is further exemplified by the correlation coefficients shown in Table 3. In this case, the correlation coefficient shown for slope angle is negative because, as previously stated, with shallower slope angles there will be higher rockfall runout. Based on previous literature associated with rockfall testing within the civil and mining industries, these findings are relatively common knowledge; however, this helps reiterate that the MRC should account for more than just bench height.

With regards to slope material and rock size, it was anticipated that both factors would have more influence than the results show. It is important to note that a roughness factor was not incorporated into the RocFall tests carried out in this study. As field testing occurs throughout the duration of the NIOSH Highwall Safety project, notes will be taken to further calibrate the RocFall models to the real-world tests with similar geometry so that factors such as slope roughness may be considered. Additionally, previous rockfall field testing by the NIOSH SMRD team showed that rock size had a higher effect on runout distance than the RocFall results in this study [20]. While it was expected that the lump mass model would show little difference in runout distance according to rock size, the rigid body also demonstrated relatively minor difference apart from certain tests at a bench height of 80 feet as shown in Figure A5. While these tests in RocFall mark a starting point in investigating the effect of certain parameters on rockfall runout, field testing will help further illustrate what changes need to occur to better link modeling to the real-world tests.

### Results in Accordance with the MRC

The contour plots developed in MATLAB based on the resulting data help identify combinations of the bench geometry where the rockfall runout is significantly high and the calculated MRC bench width does not come close to catching 90% of the rocks. Once the bench height reaches 40 feet and above, slope angles of 50 and 60 degrees create rockfall runout scenarios that far surpass the calculated MRC width with extreme cases of the rock percentage retained being 1% to 4% at a bench height of 80 feet and slope angle of 50 degrees. While this and some other bench configurations shown in this study may not be common in industry, these statistical modeling results indicate that the performance of the MRC is not consistent. Any criterion used in the mining industry for slope design should be relatively uniform in its performance expectation.

Through the NIOSH Highwall Safety project, field testing of bench configuration scenarios similar to those tested in this study will develop a more concrete correlation between not only bench height, but additional variables related to geology and operational practices, so that the MRC can be further updated for improved confidence and safety at mine sites.

## Conclusions

The following is a synopsis of the prominent technical conclusions discovered over the duration of this rockfall modeling study:

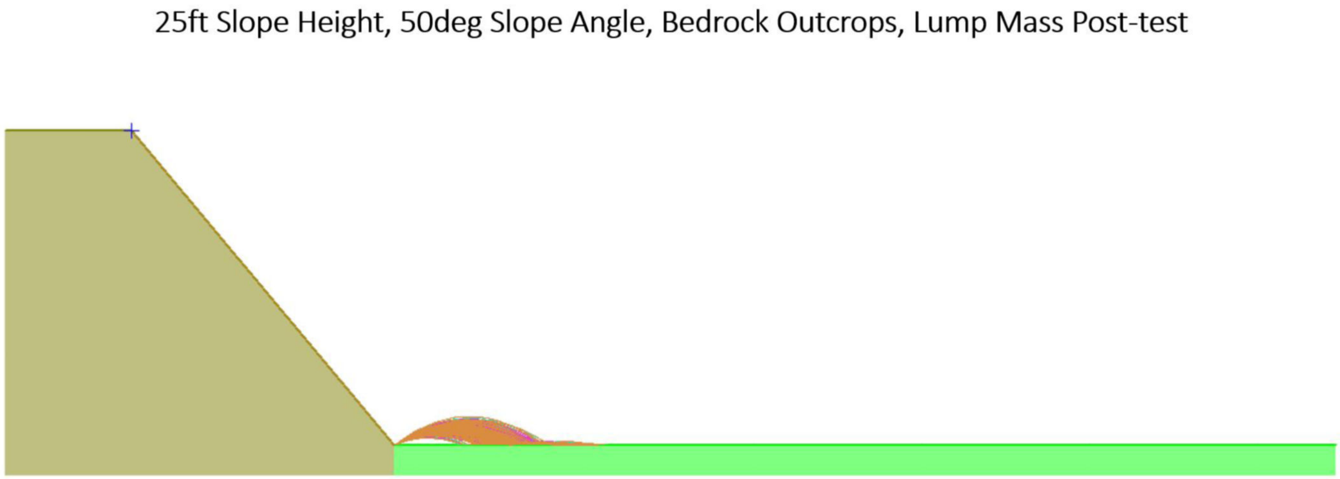
- Bench height and bench face angle are the dominant factors in forecasting runout distance compared to slope material type and rock size/shape. In some cases of bench configuration, bench face angle has more influence in forecasting rockfall runout distance than bench height. This leads to the notion that there should be some kind of modification to the MRC to at least incorporate bench face angle.
- Modeling does not effectively capture the effect of rock size on runout distance. Lump mass methods completely ignore the size of rocks, which has implications for calibrating real-world rockfall testing. Based on a previous field study conducted by the NIOSH SMRD team [20], it appears that the rigid body method does not adequately capture the effect of rock size on runout distance.
- The coefficient of restitution plays a minor role in predicting rockfall runout distance when compared to bench configuration (height/angle); however, it does influence runout distance.
- The MRC rockfall catchment performance can vary widely over different bench configurations, from very good (100%) to poor (1%–2%) rockfall catchment depending on the model used. This needs to be confirmed with real-world rockfall studies, which will be carried out by the NIOSH SMRD team throughout the duration of the Highwall Safety project.

Note that these conclusions are based on modeling studies and need to be confirmed with field testing. The findings in this paper represent a first step in quantifying the effect of individual slope parameters on rockfall runout distance, as well as identifying potential issues and changes that can be implemented within the MRC based on future field testing. Moving forward, additional statistical modeling programs, other than RocFall, need to be tested in both 2D and 3D using similar parameters utilized in this study to gain a better understanding of what to expect when implementing the models at specific mine sites. Overall, the goals and activities associated with this study and the NIOSH Highwall Safety project are all designed for the betterment and improved safety of open pit mining projects worldwide.

## Acknowledgements

Data from this manuscript have been presented at the MINEXCHANGE 2022 SME Annual Conference & Expo, February 27–March 2, 2022, Salt Lake City, UT.

## Appendix

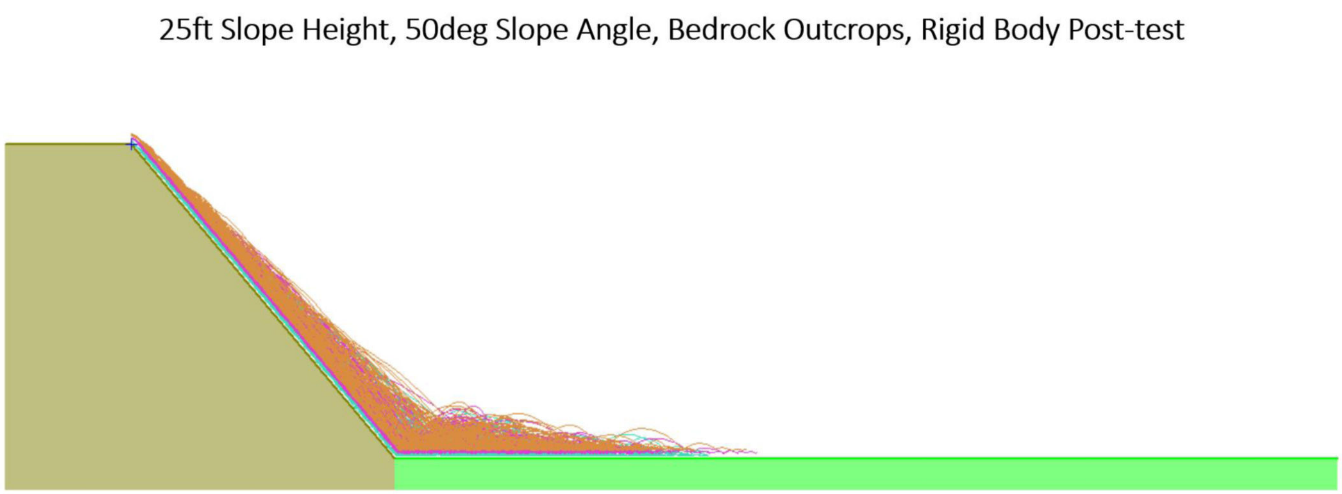



| Material Name | Color | Normal Restitution | Tangential Restitution | Friction Angle | Slope Roughness (deg) |
|---|---|---|---|---|---|
| Bedrock Outcrops | | 0.5 | Normal Mean: 0.85 Std Dev: 0.04 Rel. Min: 0.12 Rel. Max: 0.12 | 30 | 0 |
| Talus Cover | | Normal Mean: 0.32 Std Dev: 0.04 Rel. Min: 0.12 Rel. Max: 0.12 | Normal Mean: 0.8 Std Dev: 0.04 Rel. Min: 0.12 Rel. Max: 0.12 | 30 | 0 |

| Rock Name | Color | Mass (lb) | Density (lb/ft3) |
|---|---|---|---|
| 6 inch ETAG | | 14.1 | 150 |
| 12 inch ETAG | | 112.5 | 150 |
| 18 inch ETAG | | 379.7 | 150 |

| Seeder Name | Number of Rocks | Rock Types | Horizontal Velocity (ft/s) | Vertical Velocity (ft/s) | Rotational Velocity (rads/s) | Initial Rotation (deg) |
|---|---|---|---|---|---|---|
| Seeder 1 | 100 | 6 inch ETAG 12 inch ETAG 18 inch ETAG | 1 | 0 | 0 | Uniform Mean: 0 Rel. Min: 0 Rel. Max: 360 |

**Figure A1.**
RocFall results of lump mass model simulation incorporating 25-ft slope height, 50-deg slope angle, bedrock outcrops as the slope material (talus for the slope floor).




| Material Name | Color | Normal Restitution | Tangential Restitution | Dynamic Friction | Rolling Friction |
|---|---|---|---|---|---|
| Bedrock Outcrops | | 0.5 | Normal Mean: 0.85 Std Dev: 0.04 Rel. Min: 0.12 Rel. Max: 0.12 | Normal Mean: 0.55 Std Dev: 0.04 Rel. Min: 0.12 Rel. Max: 0.12 | Normal Mean: 0.15 Std Dev: 0.02 Rel. Min: 0.06 Rel. Max: 0.06 |
| Talus Cover | | Normal Mean: 0.32 Std Dev: 0.04 Rel. Min: 0.12 Rel. Max: 0.12 | Normal Mean: 0.8 Std Dev: 0.04 Rel. Min: 0.12 Rel. Max: 0.12 | Normal Mean: 0.55 Std Dev: 0.04 Rel. Min: 0.12 Rel. Max: 0.12 | Normal Mean: 0.3 Std Dev: 0.04 Rel. Min: 0.12 Rel. Max: 0.12 |

| Rock Name | Color | Mass (lb) | Density (lb/ft3) | Shapes |
|---|---|---|---|---|
| 6 inch ETAG | | 14.1 | 150 | Polygon Hexagon |
| 12 inch ETAG | | 112.5 | 150 | Polygon Hexagon |
| 18 inch ETAG | | 379.7 | 150 | Polygon Hexagon |

| Seeder Name | Number of Rocks | Rock Types | Horizontal Velocity (ft/s) | Vertical Velocity (ft/s) | Rotational Velocity (rads/s) | Initial Rotation (deg) |
|---|---|---|---|---|---|---|
| Seeder 1 | 100 | 6 inch ETAG 12 inch ETAG 18 inch ETAG | 1 | 0 | 0 | Uniform Mean: 0 Rel. Min: 0 Rel. Max: 360 |

**Figure A2.**

RocFall results of rigid body model simulation incorporating 25-ft slope height, 50-deg slope angle, bedrock outcrops as the slope material (talus for the slope floor).

| | | | Rock Size 90% Runout Distance [ft] | | | | | | | % Retained at Modified Ritchie Criterion Distance | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slope Height [ft] | Slope Angle [deg] | Rock Type | 6" Rigid | 12" Rigid | 18" Rigid | 6" Lump | 12" Lump | 18" Lump | Modified Ritchie Criterion Distance Calc [ft] | 6" Rigid | 12" Rigid | 18" Rigid | 6" Lump | 12" Lump | 18" Lump |
| 25 | 50 | Bedrock Outcrops | 21 | 19 | 20 | 22 | 20 | 20 | 20 | 86% | 93% | 90% | 84% | 87% | 89% |
| 25 | 50 | Sandstone CTQ | 20 | 21 | 21 | 20 | 20 | 21 | 20 | 92% | 88% | 89% | 87% | 90% | 85% |
| 25 | 50 | Bedrock CR | 14 | 16 | 16 | 20 | 21 | 21 | 20 | 99% | 94% | 99% | 88% | 87% | 87% |
| 25 | 60 | Bedrock Outcrops | 18 | 16 | 18 | 18 | 17 | 17 | 20 | 96% | 97% | 96% | 100% | 100% | 100% |
| 25 | 60 | Sandstone CTQ | 17 | 16 | 17 | 17 | 17 | 17 | 20 | 96% | 98% | 98% | 100% | 100% | 99% |
| 25 | 60 | Bedrock CR | 14 | 14 | 14 | 17 | 17 | 17 | 20 | 99% | 100% | 99% | 100% | 99% | 99% |
| 25 | 70 | Bedrock Outcrops | 13 | 14 | 14 | 12 | 12 | 12 | 20 | 100% | 100% | 99% | 100% | 100% | 100% |
| 25 | 70 | Sandstone CTQ | 13 | 14 | 13 | 12 | 12 | 12 | 20 | 100% | 99% | 99% | 100% | 100% | 100% |
| 25 | 70 | Bedrock CR | 12 | 14 | 13 | 12 | 12 | 12 | 20 | 100% | 100% | 100% | 100% | 100% | 100% |
| 25 | 80 | Bedrock Outcrops | 9 | 12 | 12 | 8 | 8 | 8 | 20 | 100% | 100% | 100% | 100% | 100% | 100% |
| 25 | 80 | Sandstone CTQ | 10 | 12 | 11 | 8 | 8 | 8 | 20 | 100% | 100% | 100% | 100% | 100% | 100% |
| 25 | 80 | Bedrock CR | 10 | 11 | 11 | 8 | 8 | 8 | 20 | 100% | 100% | 99% | 100% | 100% | 100% |
| 40 | 50 | Bedrock Outcrops | 34 | 32 | 31 | 33 | 31 | 31 | 23 | 54% | 55% | 61% | 27% | 26% | 28% |
| 40 | 50 | Sandstone CTQ | 31 | 31 | 32 | 30 | 31 | 32 | 23 | 60% | 69% | 73% | 26% | 23% | 26% |
| 40 | 50 | Bedrock CR | 24 | 26 | 25 | 32 | 31 | 31 | 23 | 86% | 83% | 83% | 25% | 25% | 25% |
| 40 | 60 | Bedrock Outcrops | 27 | 26 | 24 | 27 | 26 | 25 | 23 | 82% | 82% | 87% | 65% | 72% | 76% |
| 40 | 60 | Sandstone CTQ | 26 | 26 | 27 | 25 | 25 | 26 | 23 | 85% | 83% | 89% | 74% | 79% | 69% |
| 40 | 60 | Bedrock CR | 18 | 21 | 20 | 25 | 25 | 26 | 23 | 96% | 94% | 95% | 74% | 76% | 73% |
| 40 | 70 | Bedrock Outcrops | 17 | 20 | 21 | 19 | 19 | 18 | 23 | 97% | 93% | 92% | 100% | 100% | 100% |
| 40 | 70 | Sandstone CTQ | 18 | 20 | 20 | 18 | 18 | 18 | 23 | 99% | 95% | 97% | 100% | 100% | 100% |
| 40 | 70 | Bedrock CR | 17 | 18 | 20 | 18 | 18 | 19 | 23 | 100% | 99% | 96% | 100% | 99% | 100% |
| 40 | 80 | Bedrock Outcrops | 13 | 16 | 17 | 12 | 11 | 12 | 23 | 100% | 100% | 97% | 100% | 100% | 100% |
| 40 | 80 | Sandstone CTQ | 13 | 16 | 16 | 11 | 11 | 11 | 23 | 100% | 99% | 99% | 100% | 100% | 100% |
| 40 | 80 | Bedrock CR | 14 | 14 | 16 | 11 | 11 | 12 | 23 | 100% | 100% | 99% | 100% | 100% | 100% |
| 50 | 50 | Bedrock Outcrops | 39 | 38 | 38 | 40 | 37 | 37 | 25 | 40% | 53% | 44% | 11% | 8% | 13% |
| 50 | 50 | Sandstone CTQ | 37 | 38 | 35 | 36 | 36 | 38 | 25 | 54% | 39% | 53% | 10% | 8% | 11% |
| 50 | 50 | Bedrock CR | 28 | 30 | 32 | 39 | 38 | 37 | 25 | 78% | 75% | 73% | 13% | 7% | 13% |
| 50 | 60 | Bedrock Outcrops | 32 | 30 | 33 | 33 | 31 | 30 | 25 | 70% | 77% | 78% | 48% | 47% | 43% |
| 50 | 60 | Sandstone CTQ | 29 | 30 | 30 | 30 | 31 | 32 | 25 | 72% | 71% | 77% | 49% | 48% | 42% |
| 50 | 60 | Bedrock CR | 21 | 26 | 25 | 30 | 31 | 32 | 25 | 97% | 89% | 90% | 46% | 48% | 44% |
| 50 | 70 | Bedrock Outcrops | 24 | 26 | 22 | 22 | 23 | 22 | 25 | 94% | 89% | 95% | 98% | 99% | 99% |
| 50 | 70 | Sandstone CTQ | 24 | 23 | 24 | 22 | 22 | 22 | 25 | 94% | 94% | 92% | 100% | 97% | 97% |
| 50 | 70 | Bedrock CR | 20 | 21 | 22 | 21 | 22 | 23 | 25 | 99% | 97% | 96% | 98% | 98% | 98% |
| 50 | 80 | Bedrock Outcrops | 16 | 20 | 18 | 13 | 14 | 14 | 25 | 99% | 97% | 98% | 100% | 100% | 100% |
| 50 | 80 | Sandstone CTQ | 17 | 17 | 18 | 14 | 13 | 13 | 25 | 99% | 98% | 98% | 100% | 100% | 100% |
| 50 | 80 | Bedrock CR | 17 | 17 | 20 | 13 | 13 | 14 | 25 | 99% | 100% | 98% | 100% | 100% | 100% |
| 80 | 50 | Bedrock Outcrops | 61 | 56 | 59 | 57 | 57 | 54 | 31 | 28% | 35% | 39% | 1% | 1% | 2% |
| 80 | 50 | Sandstone CTQ | 58 | 56 | 56 | 54 | 55 | 56 | 31 | 33% | 32% | 42% | 3% | 2% | 4% |
| 80 | 50 | Bedrock CR | 46 | 46 | 46 | 59 | 55 | 54 | 31 | 62% | 60% | 62% | 3% | 3% | 4% |
| 80 | 60 | Bedrock Outcrops | 46 | 46 | 47 | 46 | 45 | 44 | 31 | 57% | 63% | 55% | 21% | 19% | 19% |
| 80 | 60 | Sandstone CTQ | 46 | 44 | 45 | 43 | 45 | 47 | 31 | 62% | 66% | 60% | 21% | 20% | 20% |
| 80 | 60 | Bedrock CR | 31 | 38 | 39 | 44 | 45 | 46 | 31 | 91% | 77% | 80% | 26% | 18% | 15% |
| 80 | 70 | Bedrock Outcrops | 30 | 32 | 38 | 33 | 33 | 31 | 31 | 92% | 85% | 84% | 82% | 83% | 89% |
| 80 | 70 | Sandstone CTQ | 31 | 34 | 35 | 32 | 32 | 32 | 31 | 91% | 87% | 82% | 86% | 89% | 85% |
| 80 | 70 | Bedrock CR | 30 | 34 | 30 | 32 | 32 | 33 | 31 | 93% | 86% | 92% | 88% | 88% | 84% |
| 80 | 80 | Bedrock Outcrops | 22 | 24 | 28 | 19 | 19 | 19 | 31 | 97% | 100% | 92% | 100% | 100% | 100% |
| 80 | 80 | Sandstone CTQ | 24 | 25 | 25 | 19 | 19 | 19 | 31 | 99% | 96% | 98% | 100% | 100% | 100% |
| 80 | 80 | Bedrock CR | 27 | 27 | 24 | 18 | 18 | 19 | 31 | 98% | 98% | 99% | 100% | 100% | 100% |

**Figure A3.**

Resulting values from RocFall parametric analysis.

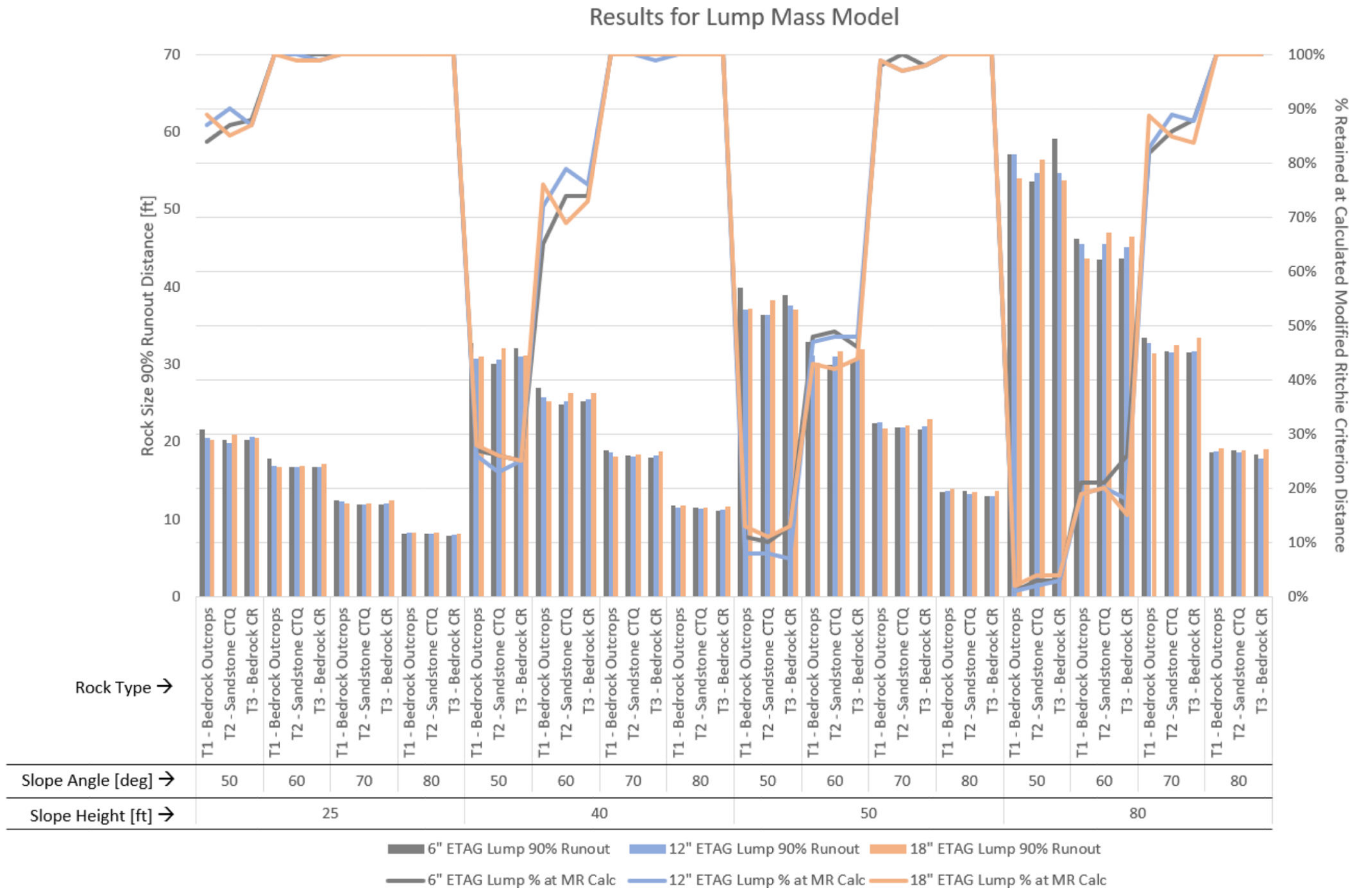



**Figure A4.**

Results of all iterations of lump mass model simulations showing variance in 90% runout distance and % retained at calculated MRC distance according to the change in input parameters.

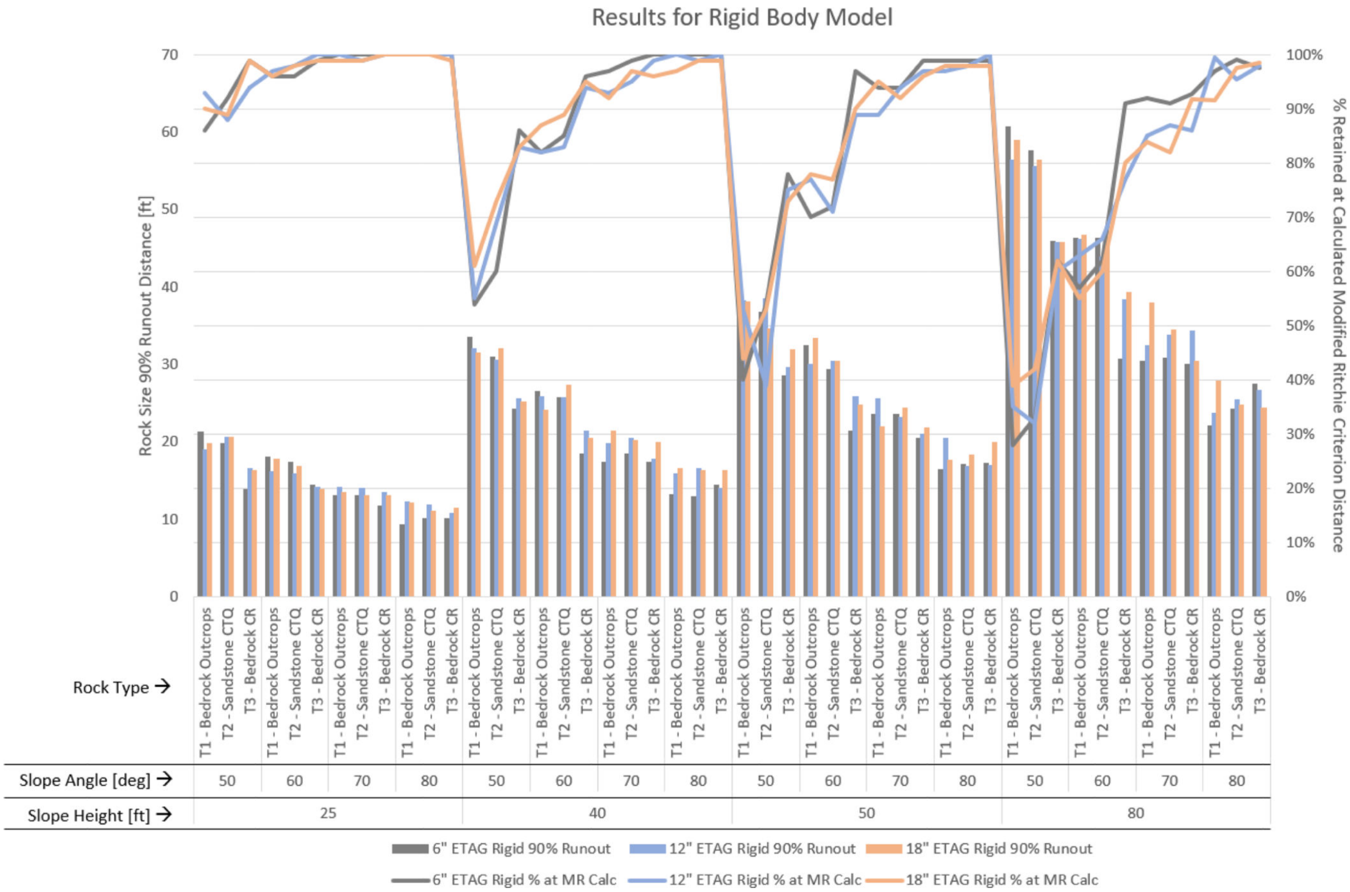



**Figure A5.**

Results of all iterations of rigid body model simulations showing variance in 90% runout distance and % retained at calculated MRC distance according to the change in input parameters.

## References

[1]. Ku C-Y, “Assessing Rockfall Hazards Using a Three-Dimensional Numerical Model Based on High Resolution DEM,” in Proceedings of the International Offshore and Polar Engineering Conference, Rhodes, Greece, June 17–22 2012.

[2]. Audige C. et al., “Monitoring requirements, limitations and applications,” in Guidelines for slope performance monitoring, Sharon R. and Eberhardt E, Eds. Clayton, Australia: CSIRO, 2020.

[3]. Lorig L, Stacey P, and Read J, “Slope design methods,” in Guidelines for open pit slope design, Read J. and Stacey P. (Eds). Collingwood, Australia: CSIRO, 2009, ch. 10, pp. 237–263.

[4]. Ryan T. and Pryor P, “Designing catch benches and interramp slopes,” in Slope Stability in Surface Mining, Hustrulid W, McCarter M, and Van Zyl D. (Eds). Littleton, CO: Society for Mining, Metallurgy, and Exploration, 2000, ch. 3.

[5]. Mattern J, “Using slope design fundamentals and technology for slope steeping on a final wall at the Goldstrike open pit,” Mining Engineering, vol. no. 2019. February, 2019.

[6]. A. Story, “Design optimization of safety benches for surface quarries through rockfall testing and evaluation,” Mining Engineering M.S. thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2010.

[7]. Veillette M, Rose N, and King M. (2019) Slope steepening investigations for the Valley Pit at the Teck Highland Valley copper mine using presplit blasting. Min Eng. 16–30.

[8]. Williams C, Morkeh J, Dorfschmidt K, Poon C, Matlashewski P, and Carvalho J, “Innovative Rockfall Solutions Based on Calibration and Field Testing,” Mining, Metallurgy & Exploration, vol. 37, no. 1, pp. 101–116, 2019, doi: 10.1007/s42461-019-0092-4.

[9]. RocFall. (2021). Version 8.013. Rocscience Inc.

[10]. Dorren LKA, Domaas U, Kronholm K, and Labiouse V, “Methods for predicting rockfall trajectories and run-out zones,” Rockfall engineering, pp. 143–173, 2011.

[11]. Rocscience. “Analysis Method Setting in RocFall.” https://www.rocscience.com/help/rocfall/rocfall/analysis_method.htm (accessed September 15, 2021).

[12]. Alejano LR, Pons B, Bastante FG, Alonso E, and Stockhausen HW, “Slope geometry design as a means for controlling rockfalls in quarries,” International Journal of Rock Mechanics and Mining Sciences, vol. 44, no. 6, pp. 903–921, 2007, doi: 10.1016/j.ijrmms.2007.02.001.

[13]. Almandalawi M, You G, Dahlhaus P, Dowling K, and Sabry M, “Slope stability and rockfall hazard analysis in open pit zinc mine,” International Journal of GEOMATE, vol. 8, no. 1, pp. 1143–1150, 2015.

[14]. Ruvin Wijesinghe D. and You G, “Optimization of the catch bench design using a genetic algorithm,” International Journal of Mining Science and Technology, vol. 26, no. 6, pp. 1011–1016, 2016, doi: 10.1016/j.ijmst.2016.09.008.

[15]. Bar N, Nicoll S, and Pothitos F, “Rock fall trajectory field testing, model simulations and considerations for steep slope design in hard rock,” presented at the Proceedings of the First Asia Pacific Slope Stability in Mining Conference, 2016.

[16]. Tuan NQ, “Analysis of Rock Slope Failure and Rockfall for Preliminary Hazard Assessment of the Cliff at Chau Thoi Quarry,” in Proceedings of the International Conference on Innovations for Sustainable and Responsible Mining, Lecture Notes in Civil Engineering, 2021, Chapter 12, pp. 230–249.

[17]. Mostafa MMH et al. , “Analysis of Rockfall Hazards Stopping position and Energy Dissipation Based on Orthogonal Experiment,” E3S Web of Conferences, vol. 261, 2021, doi: 10.1051/e3sconf/202126101004.

[18]. Nagendran SK and Ismail MAM, “Analysis of Rockfall Hazards Based on the Effect of Rock Size and Shape,” International Journal of Civil Engineering, vol. 17, no. 12, pp. 1919–1929, 2019, doi: 10.1007/s40999-019-00418-1.

[19]. Ansari MK, Ahmad M, Singh R, and Singh TN, “Rockfall slope angle and its effect on the impact and runout distance of falling block: A numerical approach,” presented at the INDOROCK 2016: 6th Indian Rock Conference, June 17–18, 2016.

[20]. Warren S, Chambers D, Stopka C, and Armstrong J, “Rockfall catch bench design guidelines - revisited,” in Minexchange: 2021 SME Annual Conference & Expo, Virtual, March 1–5 2021: Society for Mining, Metallurgy & Exploration.

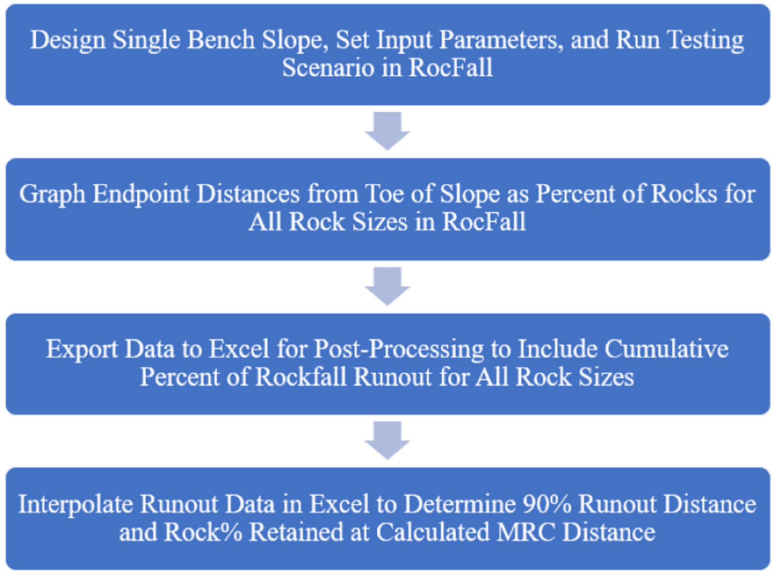



**Figure 1.**
Process followed for each RocFall testing scenario.

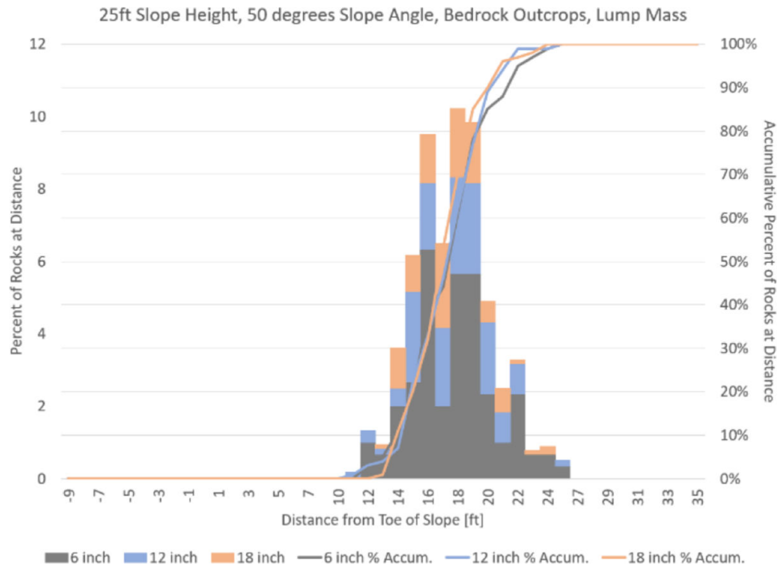



**Figure 2.**

Example of lump mass model results.

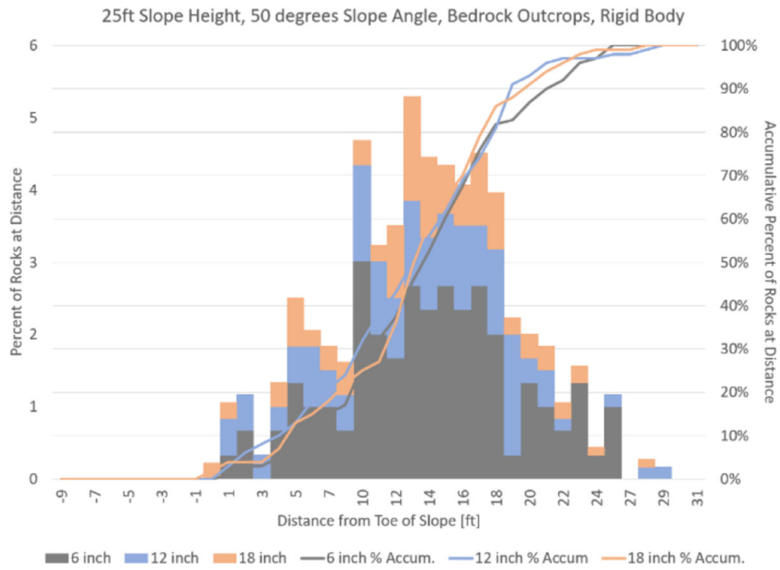



**Figure 3.**
Example of rigid body model results.

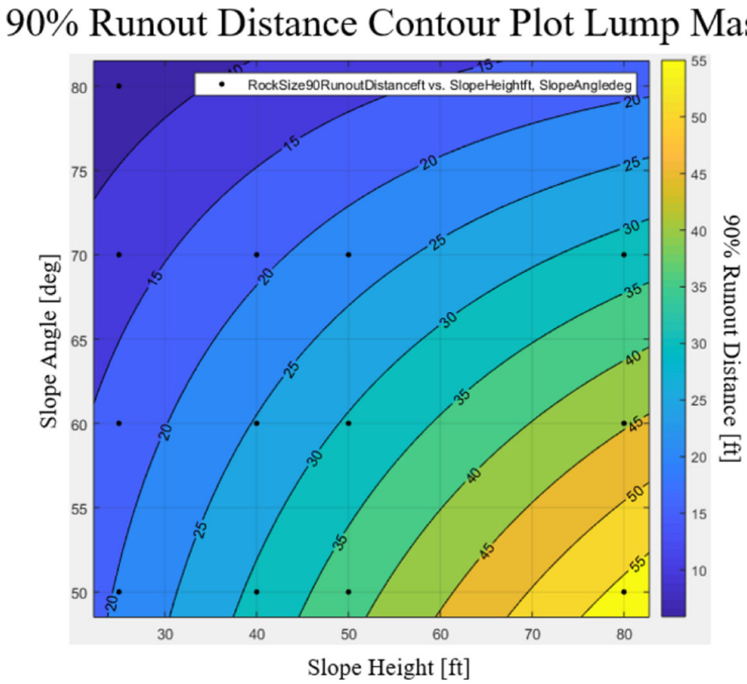



**Figure 4.**

MATLAB analysis of 90% runout distance plotted according to slope angle and slope height (lump mass).

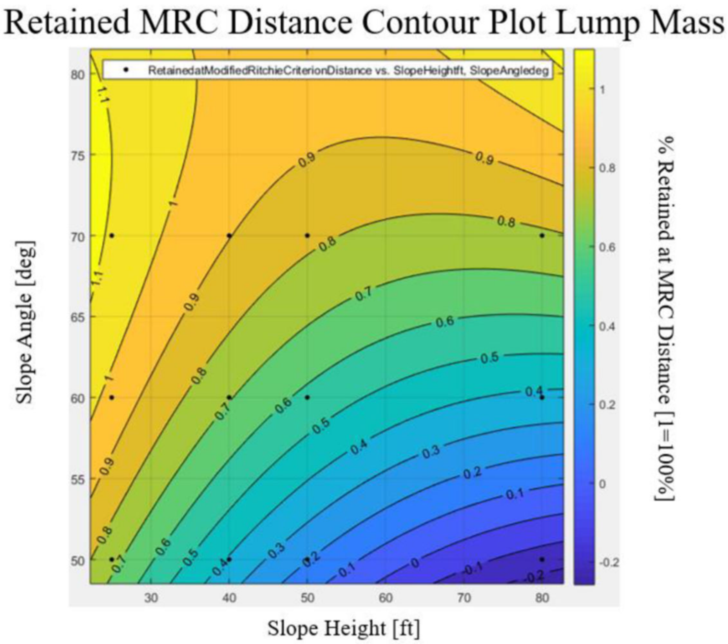



**Figure 5.**

MATLAB analysis of Rock 90% retained at MRC width plotted according to slope angle and slope height (lump mass).

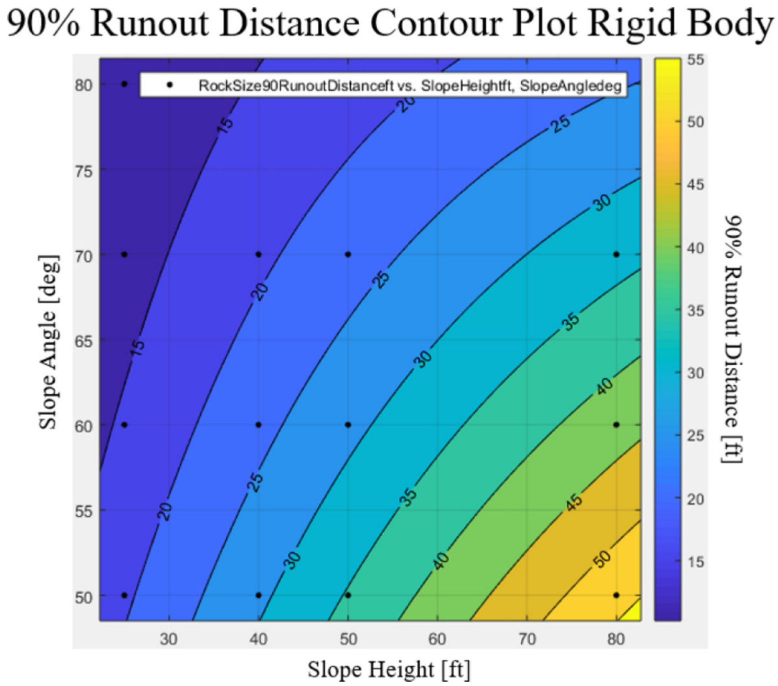



**Figure 6.**

MATLAB analysis of 90% runout distance plotted according to slope angle and slope height (rigid body).

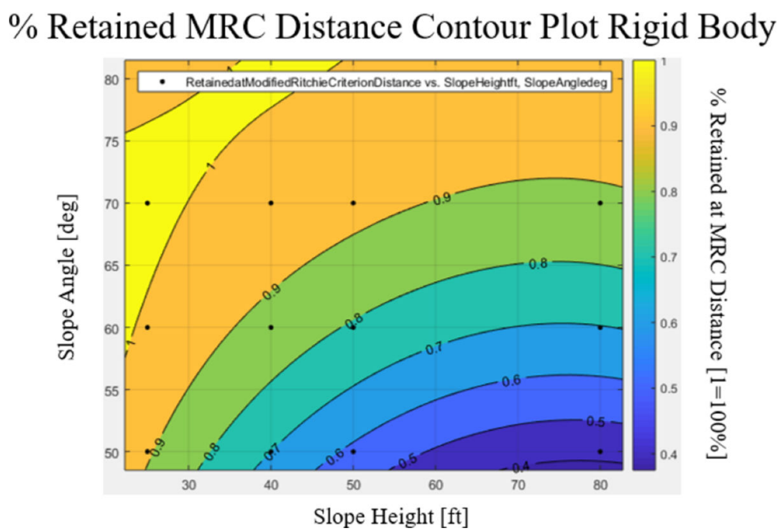



**Figure 7.**

MATLAB analysis of Rock 90% retained at MRC width plotted according to slope angle and slope height (rigid body).

**Table 1.**

Input parameters used for RocFall study

| Slope Height [ft] | Slope Angle [deg] | Slope Material | Rock Size |
|---|---|---|---|
| 25 | 50 | Bedrock Outcrops | Lump Mass – 6 in. (14.1 lbs) |
| 40 | 60 | Sandstone CTQ[1] | Lump Mass – 12 in. (112.5 lbs) |
| 50 | 70 | Bedrock CR[2] | Lump Mass – 18 in. (379.7 lbs) |
| 80 | 80 | Talus Cover - Slope Floor (all) | Rigid Body – 6 in. (14.1 lbs), Polygon Hexagon Shape |
| | | | Rigid Body – 12 in. (112.5 lbs), Polygon Hexagon Shape |
| | | | Rigid Body – 18 in. (379.7 lbs), Polygon Hexagon Shape |

[1]CTQ stands for Chau Thoi Quarry

[2]CR stands for Colorado Region

Author Manuscript

Author Manuscript

Author Manuscript

**Table 2.**

RocFall Slope Material Properties

| Slope Material | Bedrock Outcrops | Sandstone CTQ | Bedrock CR | Talus Cover - Slope Floor (all) |
|---|---|---|---|---|
| **Normal Restitution** | 0.5 | 0.45 +/− 0.04 | 0.32 +/− 0.025 | 0.32 +/− 0.04 |
| **Tangential Restitution** | 0.85 +/− 0.04 | 0.85 +/− 0.04 | 0.85 +/− 0.05 | 0.80 +/− 0.04 |
| **Dynamic Friction** | 0.55 +/− 0.04 | 0.55 +/− 0.04 | 0.5 +/− 0.04 | 0.55 +/− 0.04 |
| **Rolling Resistance** | 0.15 +/− 0.02 | 0.15 +/− 0.02 | 0.15 +/− 0.02 | 0.30 +/− 0.04 |
| **Friction Angle** | calc from Rt | calc from Rt | calc from Rt | calc from Rt |

**Table 3.**

Correlation coefficients between 90% runout distance and input parameters for lump mass and rigid body models

| | 90% Runout Distance | |
|---|---|---|
| **Input Parameters** | **Lump Mass** | **Rigid Body** |
| Slope Height | 0.67 | 0.75 |
| Slope Angle | −0.69 | −0.55 |
| Normal Restitution (slope) | 4.85E-3 | 0.16 |
| Rock Diameter | 2.50E-5 | 4.23E-2 |