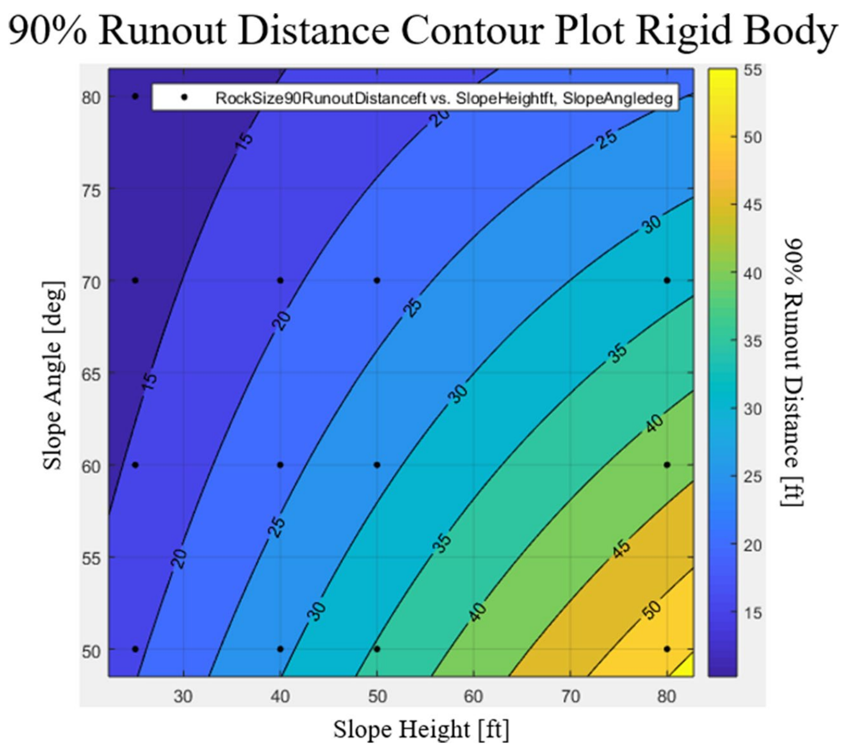


Fig. 6 MATLAB analysis of 90% runout distance plotted according to slope angle and slope height (rigid body)

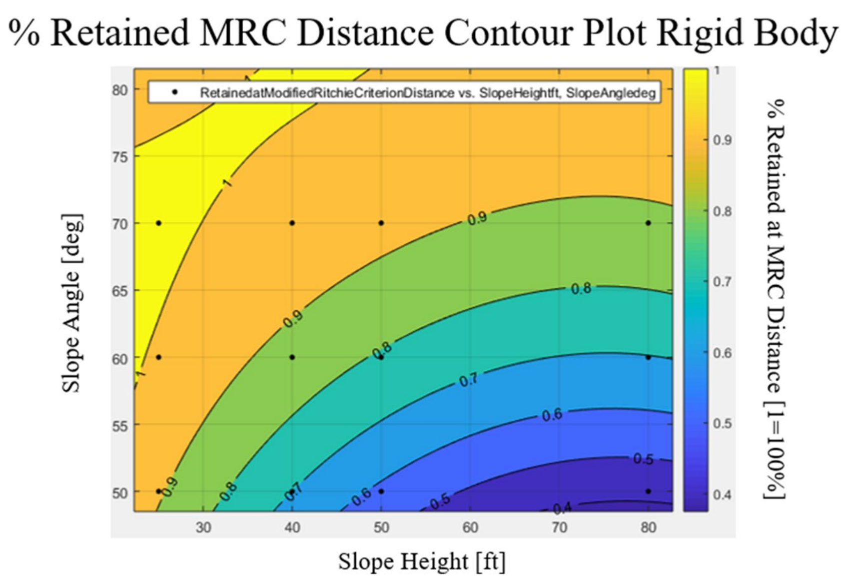


Fig. 7 MATLAB analysis of rock 90% retained at MRC width plotted according to slope angle and slope height (rigid body)

for Figs. 2 and 3, while the runout distribution is vastly different between each model, the 90% runout distance only differs by a maximum of 2 ft. Therefore, the rock percentage retained at the calculated MRC width for each individual test is also noted (Table 4 in the Appendix) 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.

6.2 Correlation Between Independent Variables and Rockfall Runout Distance

Figures 10 and 11 (Appendix) 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 ft as shown in Fig. 11 in the Appendix. 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.

6.3 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 ft and above, slope angles of 50 and 60° 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 ft and slope angle of 50°. 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.

7 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.

Appendix

25ft Slope Height, 50deg Slope Angle, Bedrock Outcrops, Lump Mass Post-test

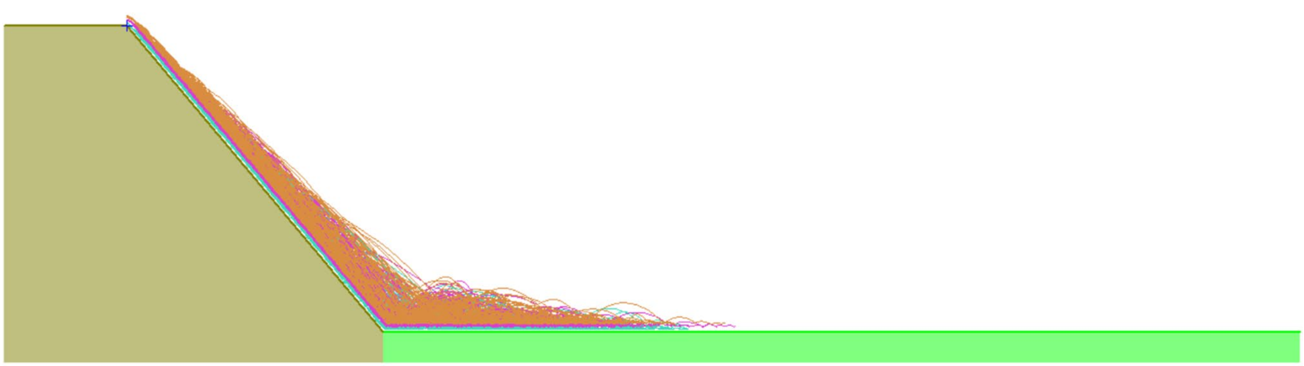
Material Name	Color	Normal Restitution	Tangential Restitution	Friction Angle	Slope Roughness (deg)
Bedrock Outcrops		0.5	Normal Mean: 0.85 Std Dev: 0.04 Rel. Min: 0.12 Rel. Max: 0.12	30	0
Talus Cover		Normal Mean: 0.32 Std Dev: 0.04 Rel. Min: 0.12 Rel. Max: 0.12	Normal Mean: 0.8 Std Dev: 0.04 Rel. Min: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

Fig. 8 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)

25ft Slope Height, 50deg Slope Angle, Bedrock Outcrops, Rigid Body Post-test



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

Fig. 9 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)

Table 4 Resulting values from RocFall parametric analysis

			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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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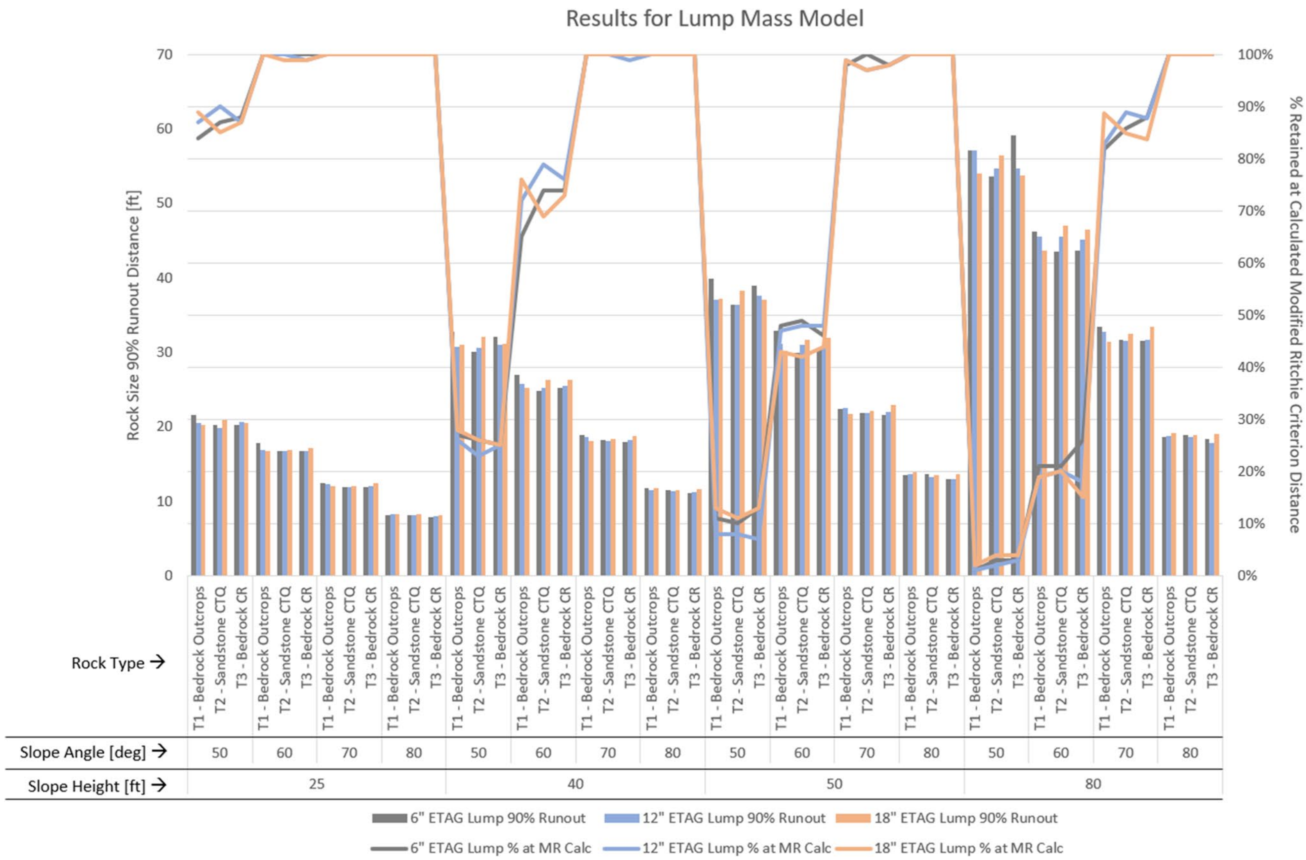

Fig. 10 **Results of all iterations of lump mass model simulations showing variance in 90% runout distance and % retained at calculated MRC distance according to the change in input parameters**

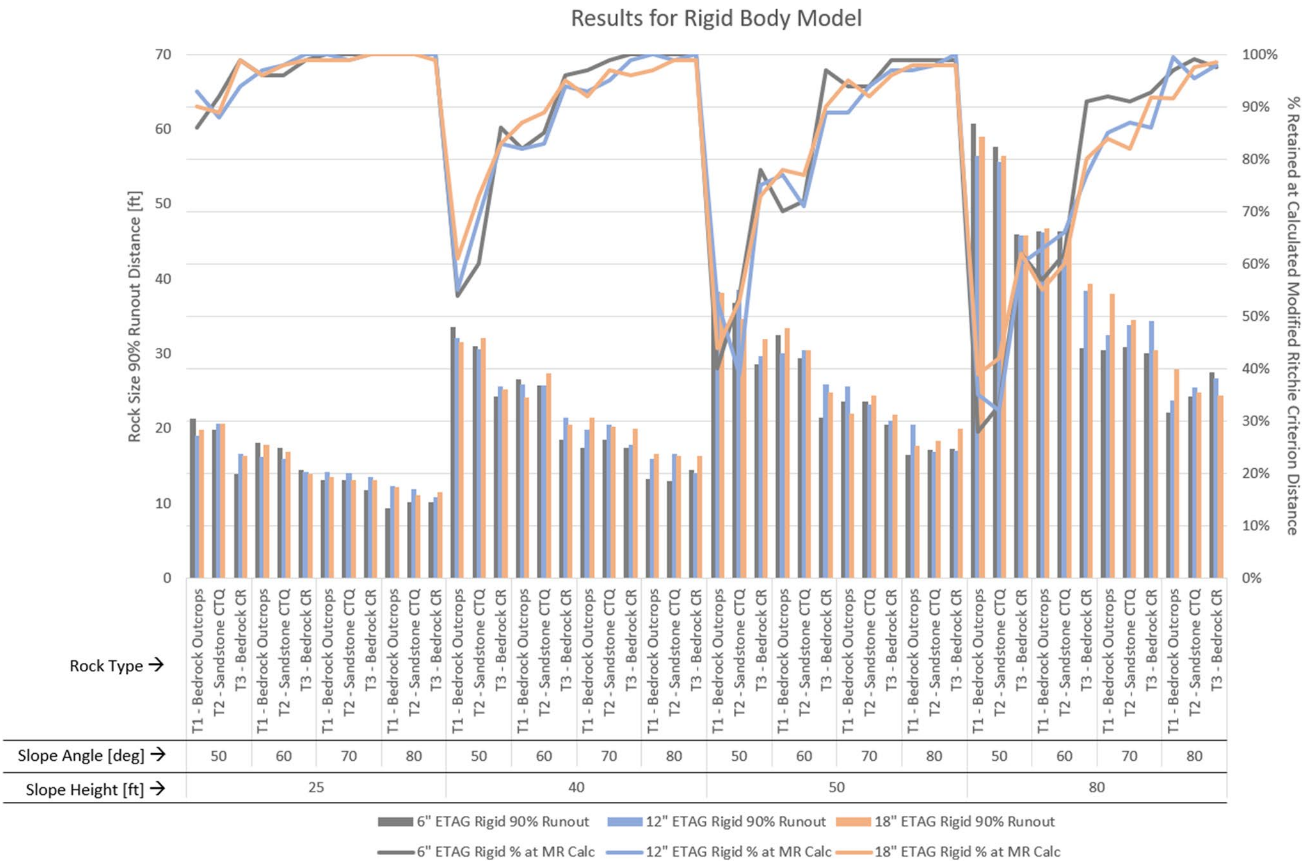

Fig. 11 **Results of all iterations of rigid body model simulations showing variance in 90% runout distance and % retained at calculated MRC distance according to the change in input parameters**

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Data Availability **Due to the nature of my work through the federal government at NIOSH, the data presented in the paper is all I can present.**

Declarations

Competing Interests **The authors declare no competing interests.**

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.**

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