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Revisiting Rockfall Catch Bench Design Criteria: Initial Rockfall Testing Results from the Golden Chest Mine, ID

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Abstract

Rockfall in open pit mines presents a continuous hazard to mine workers and is typically mitigated by designing catch benches to empirically determined widths. Industry geotechnical engineers have expressed interest in revisiting traditional bench design guidelines to better balance rockfall catchment performance and pit economics, or at least to quantify the performance of current methods. To begin this process, preliminary rockfall testing was conducted at the Golden Chest Mine in the USA, recording catch bench performance and runout distance according to rock size and shape. This paper presents preliminary rockfall testing results and lays out a path forward to evaluate and quantify the performance of the current state of practice in bench design. This work represents the start of a five-year Highwall Safety project to be conducted by the National Institute for Occupational Safety and Health (NIOSH) Spokane Mining Research Division (SMRD) in collaboration with industry recognized professionals and other research institutions. The overarching goal of the rockfall testing campaign is to revisit and possibly revise bench design guidelines to better balance rockfall catchment performance requirements and risk tolerance with pit economics.

1 Introduction

Rockfall potential is a significant geotechnical hazard to the workforce in the open pit mining environment [Audige et al. 2020] and is typically addressed by catch benches and other rockfall mitigation methods. The National Institute for Occupational Safety and Health (NIOSH) has teamed up with industry-recognized professionals to update minimum bench width design guidelines through a five-year (2022-2026) project titled *Highwall Safety: Rockfall Catchment Design and Slope Performance Monitoring*. A major goal of the project is to revisit minimum bench width design guidelines to allow more flexibility in catch bench design accounting for multiple input variables (bench geometry, geology, and operational practices) and risk tolerance.

In support of this effort, NIOSH is collaborating with industry professionals and academic institutions to conduct a campaign of rockfall testing in a variety of bench configurations, geologic conditions, and operational practices to quantify the rockfall catchment performance over a broad range of mining conditions. A suite of synthetic rocks has been fabricated and will be sent down multiple mine slopes to quantify the performance of the bench configuration by comparing the percent retained on each bench below the launch area until 100% of the rocks have been caught or the rock reaches the pit bottom.

A database of the same or similar set of synthetic rocks sent down a variety of slopes will allow the direct comparison of the rockfall Catch Bench Performance Index (CBPI) on a variety of bench configurations. The database will be analyzed to quantify the effect of multiple variables on the required bench width to match an appropriate acceptance criterion for catch bench performance at the design stage.

The first concept proving rockfall testing was conducted in Oct, 2020 at Sullivan Quarry in Spokane, Washington, USA, and the results were reported in [Warren et al. 2021]. The second rockfall test series was conduced in May

2022 at the Golden Chest Mine near Murray, Idaho, and the results and conclusions of that testing are the subject of this paper.

2 Background

2.1 Rockfall Catch Bench Design

Rockfall hazards are typically addressed through the implementation of rockfall catch benches as required by the Mine Safety and Health Administration [MSHA 2021]. The Modified Ritchie Criterion (MRC) is an industry-accepted standard in North America and South America for initial rockfall catch bench design [Lorig et al. 2009]. Call [1986] developed the MRC based on [Ritchie 1963] rockfall testing for highway design and Call's experience at Call and Nicholas Inc. (CNI) in the 1970s and is presented as Equation 1 [Ryan and Pryor 2000].

$$W = 0.2H + 15 \quad [1]$$

Where:

W = minimum catch bench width (ft)

H = bench height (ft)

The MRC has been accepted as the de facto industry standard in rockfall catch bench design primarily due to a lack of alternative criteria. As noted through discussions with industry experts, there are few design alternatives, and the performance of the MRC in terms of rockfall catchment performance is not consistent [Major 2021; Rose 2021; Armstrong 2019; Wellman 2021]. In certain situations, the MRC tends to be overly conservative, while, in other mining circumstances, dangerous rockfall conditions develop using the same MRC.

The main limitation of the MRC is that it only considers the minimum catch bench width as a function of bench height (Equation 1). First-hand experience [Armstrong 2019; Major 2021], individual mine studies [Mattern 2019; Veillette et al. 2019; Storey 2010], and modeling studies [Gibson et al. 2006; Alejano et al. 2007; Bourgeois et al. 2022] show that rockfall hazard and catch bench performance are a function of multiple variables, including bench height and face angle, rock size/shape (geology), operational practices (e.g. blasting), and the construction of bench berms.

2.2 NIOSH Highwall Safety project

In October of 2021, the Geomechanics Team at NIOSH, Spokane Mining Research Division (SMRD) started the Highwall Safety project, which is planned to run for five years through Sept 2026. This project is a continuation of a pilot project conducted by Warren et al. [2021] where one of the main goals is to evaluate potential research areas in open pit slope stability through collaborative partnerships with industry and to develop in-house rockfall testing logistic capabilities.

As discussed previously, the MRC only considers bench height in determining minimum rockfall bench width requirements. A major goal of this project is to quantify the effects of additional variables on rock rollout distance and catch bench performance, which could justify modifications to the MRC with criterion that can be objectively measured in the field. Potential variable categories that will be investigated as inputs into design criterion include bench configuration geometry, geology/geotechnical conditions, and operational practices. Specific variables are listed in Table 1.

Table 1. Potential rockfall catch bench design input variables that can be objectively measured in the field

Variable category	Variable	Anticipated effect on catch bench performance and minimum required bench width
Bench Geometry	Height	Taller benches typically require wider catch benches as noted by the MRC [Call 1986; Ryan and Pryor 2000].
	Face/batter angle	Experience and rockfall modelling indicate that steeper face/batter angles (70°+) typically induce less translational energy than shallower bench face angles possibly requiring less catch bench width.
Geology/Geotechnical	Rock size	Larger rocks contain more kinetic energy and can travel further than smaller rocks, potentially requiring relatively wider catch benches.
	Rock shape	Lower aspect ratio (flatter) rocks such as shale inherently do not roll well and could potentially require relatively less catch bench width as rocks with more even dimensions such as blocky or rounded rocks.
	Rock strength	Weaker rocks tend to break up while traveling down the slope potentially requiring less catch bench width to maintain safe operating conditions.
Operational Practices	Blasting	Pre-split and other controlled blasting measures typically result in smoother bench faces and less blast damaged rock. The outcome is typically fewer launch features and potential rockfall sources.
	Time	Catch benches tend to fill up over time and lose rockfall catchment capabilities.
	Multiple active mining benches	Certain mining situations can lead to one active bench being mined directly over another active bench. In these situations, there is potential for the upper bench to inadvertently send rockfall down towards the lower bench.

3 Initial catch bench performance parametric study (sensitivity analysis) rockfall modeling study

In support of the Highwall Safety project, rockfall modeling studies were completed as a first attempt at a sensitivity analysis looking into the various factors that influence how far rocks roll on a single bench configuration, and performance of the MRC criterion in different bench configurations. Variables included in the sensitivity analysis for rockfall runout distance include bench height (25-80 ft), bench face angle (50-80°), rock size (6-18 inch), bench material properties (coefficients of restitution, dynamic friction, rolling resistance, and friction angle), and model type (lump mass versus rigid body). Details of this modeling and conclusions are discussed in Bourgeois et al. [2022].

3.1 Modeling results in accordance with the Modified Ritchie Criteria (MRC)

Based on the resulting data, contour plots developed in MATLAB (Figure 1) help identify combinations of the bench geometry where the rockfall runout distance is relatively 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.

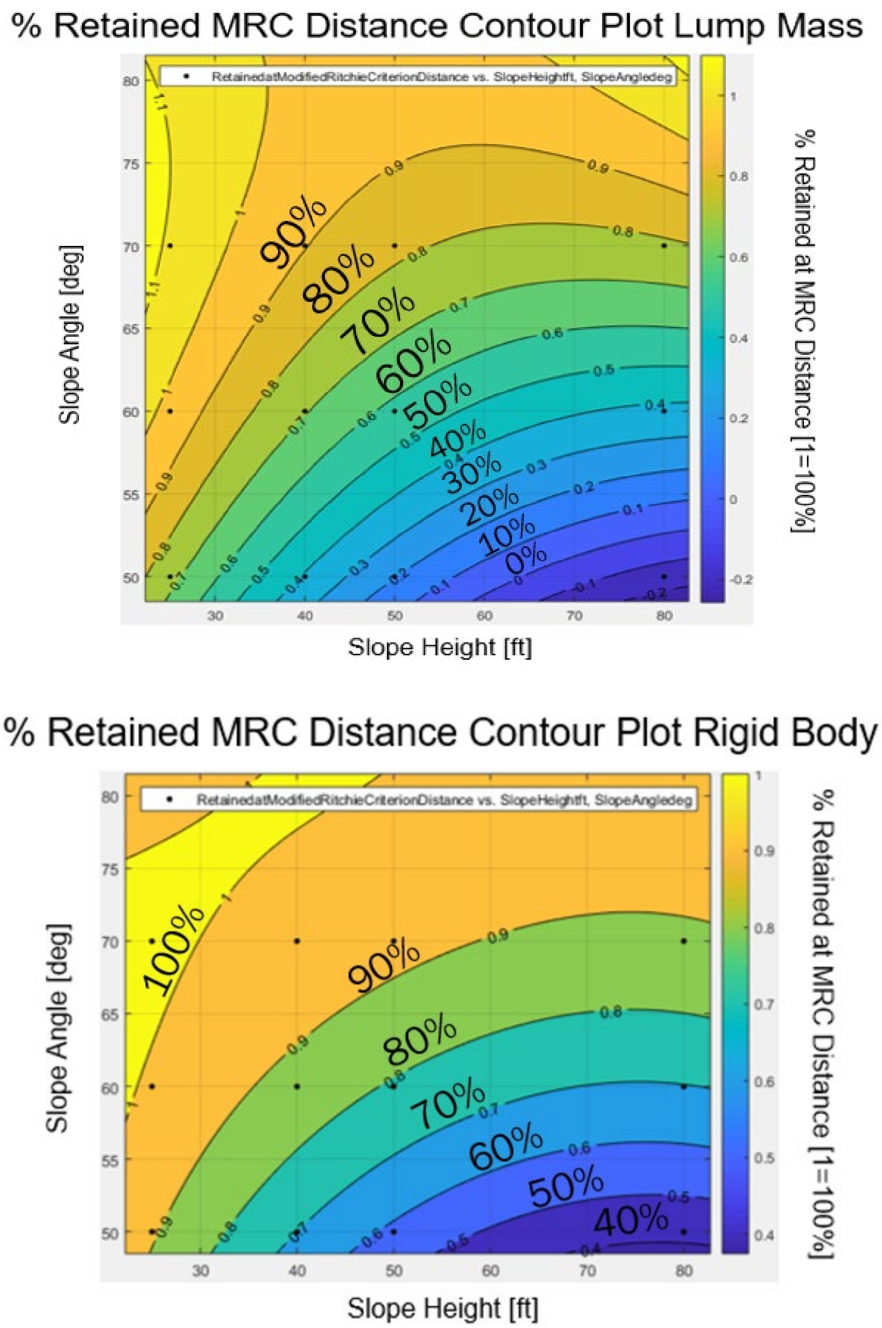

Figure 1. Percent (%) rocks retained at MRC distance for a variety of single bench configuration slope angles and heights. From Bourgeois et al. [2022]

3.2 Rockfall modeling conclusions from Bourgeois et al. [2022]

- 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, 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.

4 Rockfall testing at Golden Chest Mine, ID

4.1 Casting synthetic rocks

Synthetic rocks were cast out of 5,000+ psi fiber-reinforced concrete and painted to distinguish various sizes and shapes to aid in rock identification during post-testing analysis. Details of the synthetic rock construction are presented in Table 2, and photos of the rocks are shown in Figure 2.

Table 2. Synthetic rock construction attributes

Synthetic rock attribute	Attribute range	Notes
Rock size	3, 6, 12, and 18-inch diameter	Cast using reusable steel, wooden, and 3D-printed silicon moulds.
Rock shape	Cube, ETAG 27, and “flat” rocks	ETAG 27 [(EOTA) 2013] is the standard shape for testing of rockfall barriers in Europe. Flat rocks had an aspect ratio (height/length) of 0.1 to 0.2 to simulate shale, argillite, and other bedded/foliated rock fall behaviour.
Reinforcement	Synthetic and steel fibre, some steel mesh (flat rocks)	Several reinforcement methods tested to compare handling and durability characteristics of synthetic rocks.
Colour	Various	For identification during post-testing analysis.

Figure 2. Photos of synthetic rocks colored to distinguish size and shape during post testing analysis

4.2 Logistics and Transportation

The Highwall Safety project has purchased or retained the availability of multiple vehicles, logistical equipment, and funding to perform rockfall testing and other related project work throughout the duration of the project. A list of this equipment is presented in Table 3.

Table 3. NIOSH Highwall Safety project logistics items and uses

Logistics item	Use	Notes
Ford F-450 flat bed	Synthetic rock and other logistics hauling	2.5-ton capacity in bed. Potential to rent or purchase 6-ton GVW trailer for additional haulage capacity.
Genie GTH-5519 telehandler + trailer	Material handling and casting rocks down slopes	Max lift capacity 5,500 lbs, max forward reach 11 ft. Potential to purchase a bucket for berm construction and earth material handling.
Chevy 3500 truck	Haul telehandler	Can also haul telehandler bucket and other material.
Dodge 2500 truck	Personnel and material hauling	Has a canopy for secure storage.
Ford Expedition SUV	Personnel and material hauling	
25-ton overhead crane	Material handling	Located at NIOSH laboratory in Spokane, WA
Excavator (contract)	Larger jobs on site during rockfall testing	Ability to contract as needed

4.3 Field testing

4.3.1 Geology and pit slope configuration

Rockfall field testing was completed at the Golden Chest Mine's Idaho pit, which has been fully mined out and no longer in production, near Murray, ID, on May 27, 2022. Several site visits were completed prior to testing to scout the location and develop a detailed testing/safety plan and to deliver synthetic rocks to site. An aerial drone view of the test location is shown in Figure 3. Note that preliminary synthetic rockfall testing was completed during initial site visits to establish the rockfall trajectory, impact location, and safety of the observation area for data acquisition equipment and personnel.

Mineralization in the Idaho pit is controlled by the Idaho fault which strikes due-north and dips 45 degrees to the west, with bedding dipping generally to the west-northwest. The northeast (NE) pit sector is the footwall wall comprised mainly of quartzite and foliated argillite. Where the argillite is exposed, it typically dips moderately into the pit and benches in the NE sector of the pit filled after mining operations ceased primarily due to bedding orientation. The NW sector of the pit is in the hanging wall and is comprised primarily of foliated argillite dipping moderately away from the pit [Morgan and Hardy 2017]. The NW sector is where rockfall testing was completed. Benches in this sector have tended to hold, however several years of exposure have resulted in the benches being at least partially filled up. The overall slope angle of the Idaho pit is 45° and details of the slope deign configuration are presented in Table 4.

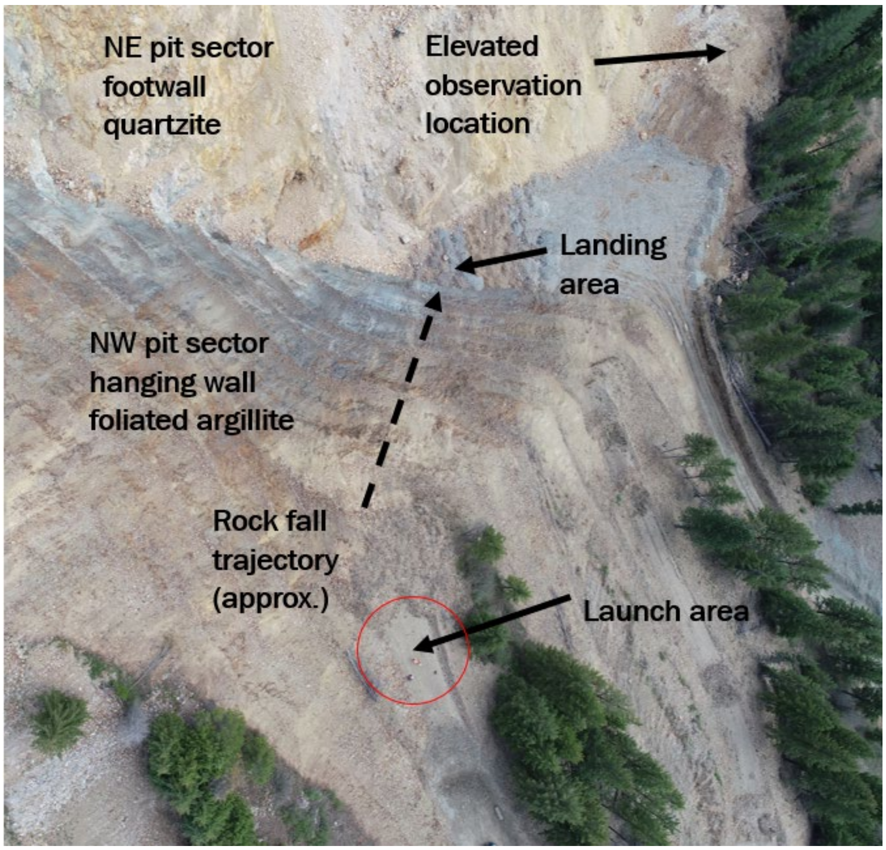

Figure 3. Aerial drone photo of the rockfall testing site, Idaho Pit at Golden Chest Mine, ID.

Table 4. Idaho Pit design bench configuration

Bench configuration attribute (design)	Design Value
Bench height	20 ft (6m)
Bench face angle	60°
Catch bench width	8 ft (2.5m)
Overall slope angle (OSA)	45°
Overall slope height (OSH)	Approximately 160 ft (48m)

4.3.2 Rockfall launching and data recording

Rockfall testing was broken up into separate launch volleys (Table 5) using a CAT 336 track hoe shown in Figure 4. Launched rock size gradually increased with each test so that smaller rocks were sent down earlier and would be less influenced by larger rocks either filling up benches or acting as obstacles. Periodic drone flights and aerial photography were flown between and during testing to record the location of synthetic rocks on the benches and to record video footage of rocks traveling down the slope. Thermal and red-green-blue (RGB) still and video photography were taken before, during, and after testing to record rockfall behaviour and for post testing analysis. Data recording devices and data use are presented in Table 6.

Data acquired during and after testing were used to determine the arrested location of each synthetic rock on the pit slope, and to quantify the performance of the bench configuration for each synthetic rock size and shape. Locations were documented as being arrested on benches one through seven or pit bottom shown on Figure 4.

Figure 4. CAT 336 used to cast synthetic rocks down the slope (left) and the view from observation area (right).

Table 5. Rock launch sequence from bucket of CAT 336

Launch series	Rock sizes
1	All 3-inch synthetic rocks
2	All 6-inch synthetic rocks
3	12-inch flat synthetic rocks
4	1st half of 12-inch synthetic ETAG 27 and cubes
5	2nd half of 12-inch synthetic ETAG 27 and cubes
6	18-inch flat synthetic rocks
7	1st half of 18-inch synthetic ETAG 27 and cubes
8	2nd half of 18-inch synthetic ETAG27 and cubes
9	Natural rocks from Golden Chest Mine

Table 6. Data recording equipment used during rockfall testing

Observation Equipment	Model	Use
Drone-based camera	DJI Phantom 4	Aerial photography recognizance and photogrammetry test result photo acquisition, and aerial video photography
Thermal camera*	FLIR T620	Thermal still and video photography
RGB Camera	Nikon D8000	Still and video photography
Various phone cameras	I-Phone 10 & 11	Still and video photography

* Thermal camera recordings of the rockfall testing were taken in support of the Geotechnical Center of Excellence (GCE) NIOSH-funded thermal camera project described in Wellman et al. [2022].

4.4 Results – Catch bench performance

Results from a single bench configuration rockfall test such as in this testing can only be used to develop relative comparisons between rock size and shape in this bench configuration. However, examination of the resulting data (Table 7 and Figure 5) indicates that synthetic rocks behaved in a similar fashion to anecdotal observations from the field, namely:

- Larger rocks travel farther than smaller rocks and are more difficult to arrest.
- Rocks with more even aspect ratios (1:1 H/L), including ETAG 27 and cube-shaped rocks, went farther than flatter rocks with lower aspect ratios (0.2:1 H/L).

The authors are not aware of any unique or regulatory acceptance criterion for rockfall catch bench performance in the hardrock mining industry. However, examples of acceptance criteria from the literature include retention of 80% first bench, 90% subsequent benches [Gonzaga et al. 2016] and 80% first bench, 95% second bench [Mattern 2019]. In the case of the Golden Chest Mine, the Idaho Pit slope design would pass the acceptance criterion for the 3-inch flat synthetic rocks as well as the 6-inch flat synthetic rocks if one were using the criterion from Gonzaga et al. [2016]. It should be noted that the slope at Idaho Pit has been mined out and is inactive, with some of the benches being deteriorated in sections and all remaining benches having been partially filled over time. Additionally, some of the synthetic rocks designed for rockfall testing, such as the 12- and 18-inch cube and ETAG 27, do not give an accurate representation of rocks local to the pit, and it was expected that they would travel to the pit bottom due to their size and shape. Further discussion of how the designed synthetic rocks relate to natural rocks on this slope is discussed in Section 4.4.3 of the paper.

Table 7. Synthetic rockfall results from the Golden Chest Mine

Synthetic Rock Diameter (in)	Rock Shape	Count	Description of Catch Bench Performance
3	Flat/plates	35	100% caught by 3rd bench
	Cube	36	70% caught by 7th (last) bench
	ETAG 27	36	55% caught by 7th (last) bench
6	Flat/plates	34	100% caught by 7th (last) bench
	Cube	47	32% caught by 7th (last) bench
	ETAG 27	30	32% caught by 7th (last) bench
12	Flat/plates	16	63% caught by 7th (last) bench
	Cube	9	0% caught on benches (100% to pit bottom)

	ETAG 27	9	0% caught on benches (100% to pit bottom)
18	Flat	10	82% caught by 7th (last) bench
	Cube	4	0% caught on benches (100% to pit bottom)
	ETAG 27	4	0% caught on benches (100% to pit bottom)

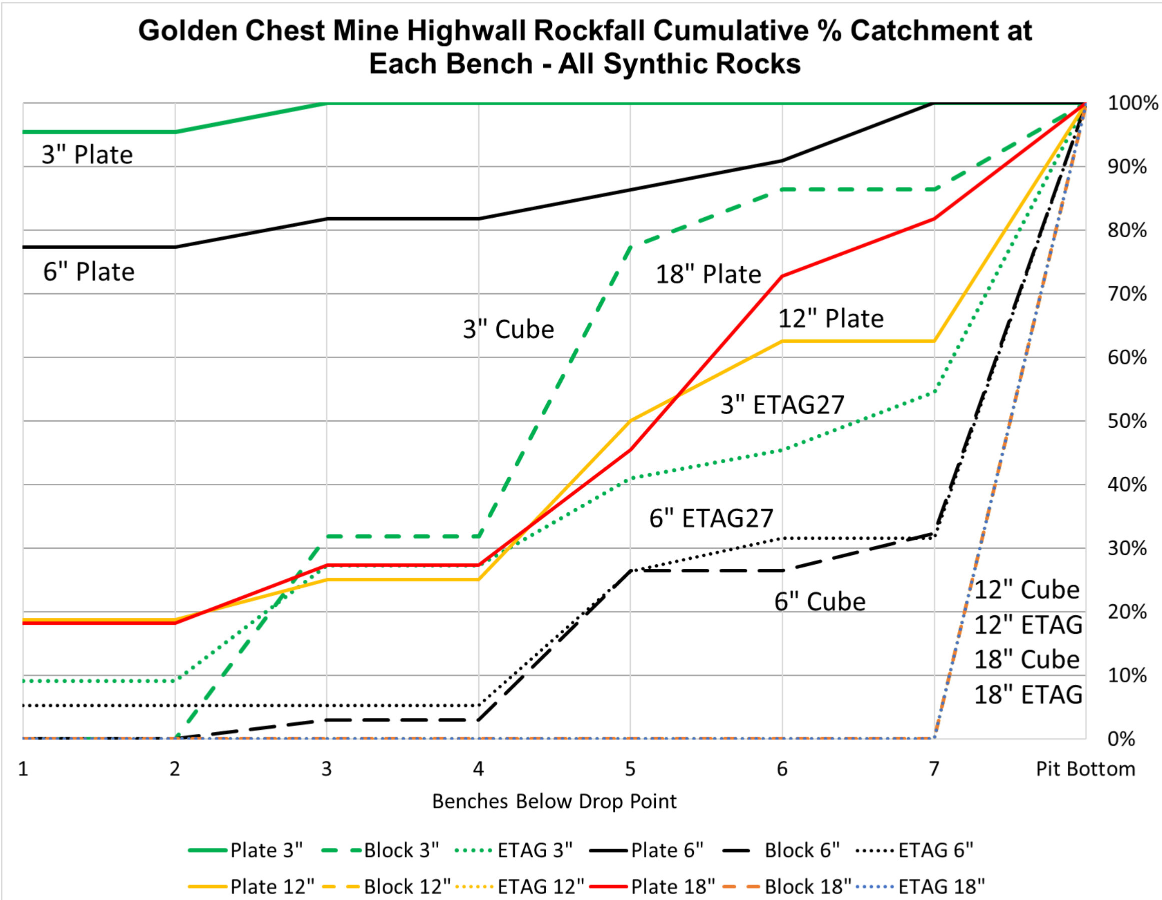

Figure 5. Golden Chest Mine rockfall catch bench performance cumulative frequency.

4.4.1 Effect of rock shape

Geologists have observed that particle shape can dramatically influence particle behaviour in a variety of depositional settings, and a review of particle shape and quantification is presented in Blott and Pye [2008]. In that paper, the Elongation Ratio, intermediate/long axis (I/L), and Flatness Ratio, short/intermediate axis (S/I), are presented (Figure 6) as the most important aspects of particle form and are widely applicable to a range of sedimentological problems. By placing a number on rock shape, it may be possible to incorporate this attribute into future rockfall behaviour forecasting tools developed through rockfall testing during the Highwall Safety project. Note that particle “roundness,” “sphericity,” and “irregularity” are other identified important shape attributes that can influence particle behaviour, and methods to quantify these attributes are currently being explored by the authors. Figure 6 presents the Elongation and Flatness ratio visually and compares synthetic rocks to the “local” rocks sent down the Idaho pit wall during rockfall testing.

The effect of rock shape from this testing event is easily compared by observing cumulative frequency data from a single size synthetic rock. In this case, the 3-inch diameter rocks offer the best comparison with results shown in Figure 7. The 3-inch diameter plates are 100% arrested by bench 3, while the 3-inch cubes and ETAG27 shapes are 86% and 55% arrested by the 7th bench, respectively. This indicates, and to some extent quantifies, that more rounded shapes travel further than flatter lower-aspect shapes. This has major implications in that mine operations with shale-type or foliated lithologies may be able to design narrower catch benches compared to a sand and gravel quarry with fluvial subrounded clasts and achieve a similar catch bench performance.

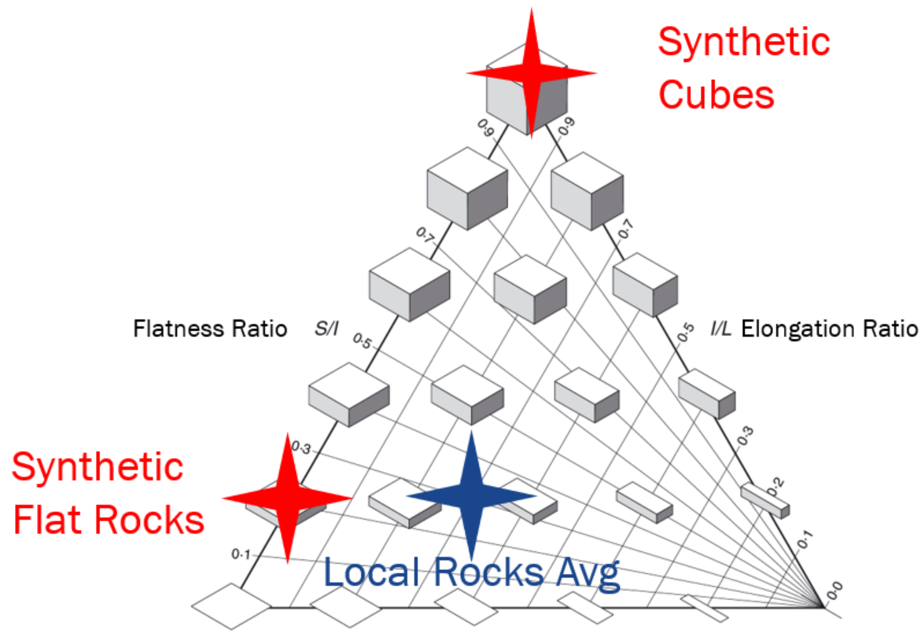

Figure 6. Chart of Elongation and Flatness Ratio [Blott and Pye 2008] with synthetic and local (Golden Chest Mine) rocks plotted for reference.

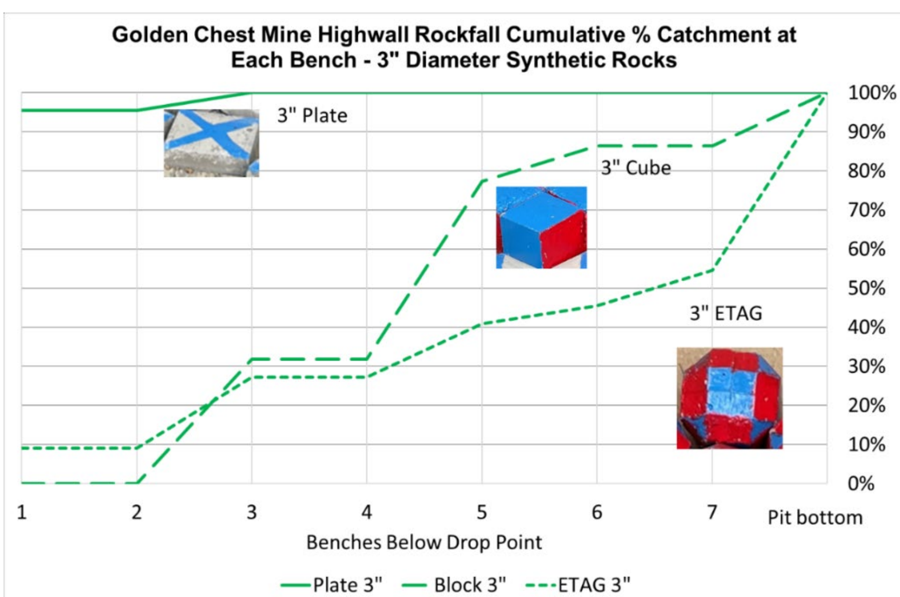

Figure 7. Golden Chest Mine rockfall cumulative percent catchment for 3-inch diameter synthetic rocks.

4.4.2 Effect of rock size

The effect of rock size on catch bench performance is easily compared by isolating the data to a single shape and comparing the cumulative arrested locations based on synthetic rock size. Figure 8 isolates the data to flat rocks/plates, showing that smaller plates are arrested much quicker than larger 6-, 12-, and 18-inch diameter sizes. It is also apparent that the 12- and 18-inch diameter sizes performed similarly in terms of cumulative catch bench location of arrested rocks. Again, there are implications for how geology and block size may play a role in deciding minimum catch bench requirements based on block or rock size distribution. For example, geotechnical core logging may be able to roughly estimate block size during any level of a feasibility geotechnical drilling program. In addition, blasting practices can influence the amount and size of blast damaged/loose rocks on the bench face available as rockfall potential.

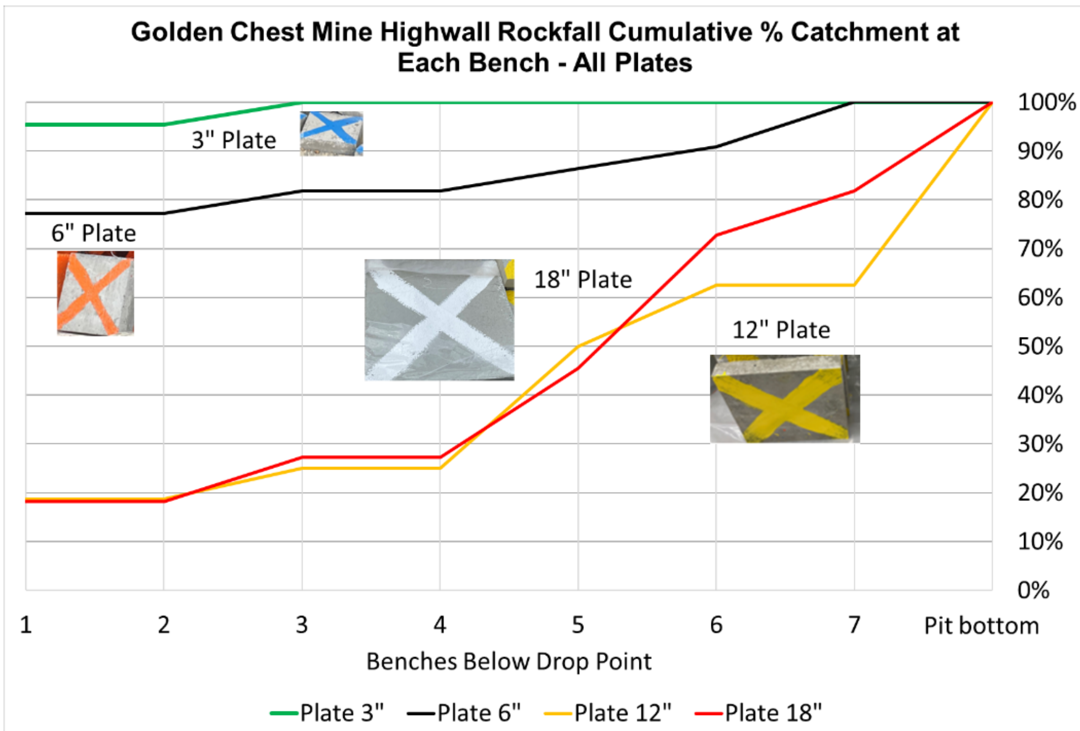

Figure 8. Golden Chest Mine highwall rockfall cumulative percent catchment for all plate sizes.

4.4.3 Discussion

Synthetic rocks can be used to quantify and compare the Catch Bench Performance Index (CBPI) of various bench configurations, geology types, and mining practices. However, this information is limited in value if it cannot be used to help inform decisions regarding “natural” rockfall hazards that are encountered during normal mining operations.

As part of the rockfall test procedure, local rocks of small (3-6 inch), medium (6-12 inch), and large (>12-inch) were gathered, measured, and painted prior to sending down the highwall with final resting locations being recorded similarly to the synthetic rocks. A cumulative frequency chart of the catch bench performance for local rocks and similar performing synthetic rocks is presented in Figure 9. Note that the small, medium, and large local rocks compared relatively well with the 3-, 6-, and 12/18-inch synthetic rocks, respectively. A comparison of the Flatness and Elongation Ratios of the natural rocks to those of the synthetic flat rocks is presented in Figure 6, showing the similarity, especially with regards to the Flatness ratio. The fact that their relative size and shapes are similar leads to the indication that one could use this information to forecast a similar behaviour in the rockfall environment.

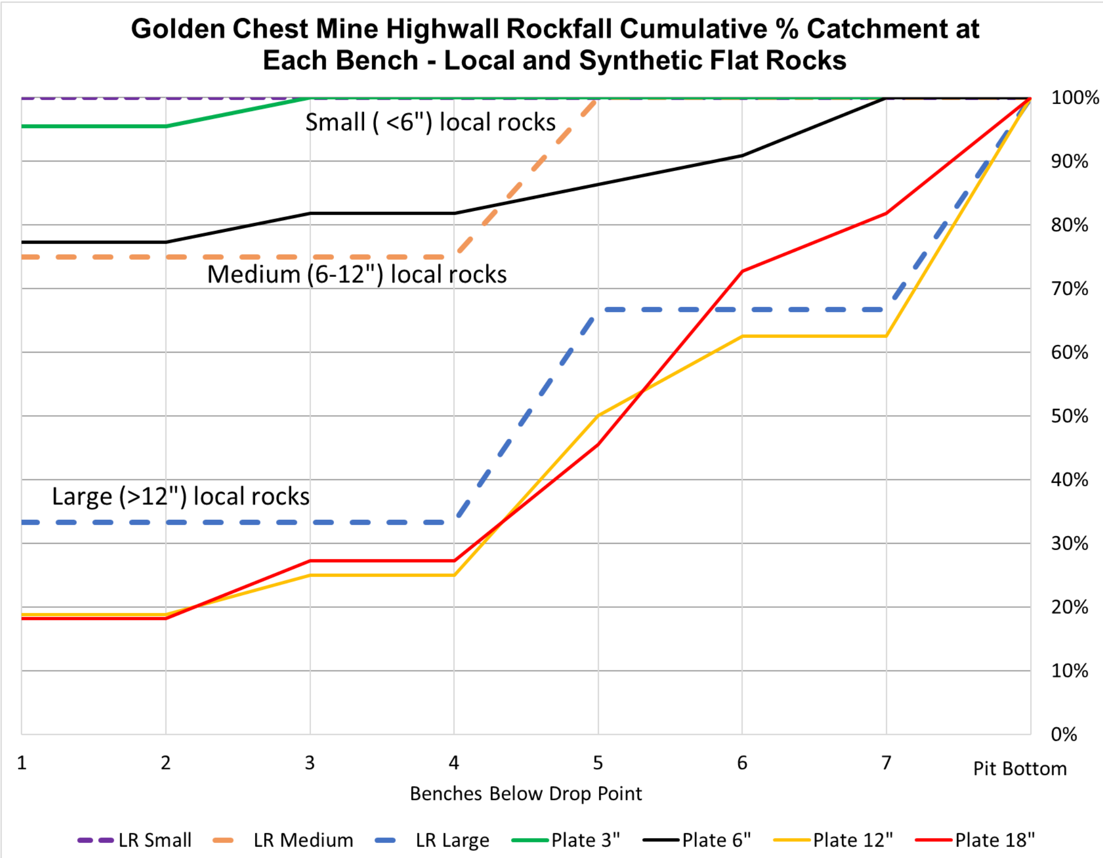

Figure 9. Comparison of local and flat rock catch bench performance at the Golden Chest Mine.

5 Path forward – Rockfall Testing at Mines in the Western USA

Rockfall modeling and testing presented in this paper represent a start to a multi-year project with the goal of evaluating and potentially updating rockfall catch bench design guidelines for the mining industry. To this end, rockfall testing is planned to be carried out in a variety of bench configurations, geology types, and operational practices for metal and nonmetal open pit mines across the western United States. This will facilitate the development of an empirical rockfall database that can be analyzed to potentially develop design guidelines that the engineer can tailor to their specific mining situation and acceptance criterion. The authors of this paper hope this will lead to mining situations that correctly balance mine safety with pit economics, leading to safer and more predictable mine environments.

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7 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. Mention of any company or product does not constitute endorsement by NIOSH, CDC.

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Slope Stability 2022 is being held at the Westin La Paloma Resort in Tucson, Arizona, USA from October 17 through October 21, 2022. The program is currently being developed and will include keynote presentations from academic and industry thought leaders, workshops and tours.

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