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Designing a Rockfall Testing Program for Open-Pit Mines to Investigate Runout and Bench Catchment

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ABSTRACT

The potential of rockfall at open-pit mines presents a continuous hazard to mine workers and is typically mitigated by designing catch benches at empirically determined widths. The National Institute for Occupational Safety and Health (NIOSH) is working in conjunction with industry and academia to revisit and update current catch bench guidelines to better match acceptable risk tolerances for modern mining practices. To begin this process, a rockfall testing program was designed to gather empirical runout and bench catchment data at partnering mine sites in the Western United States. This paper presents a detailed description of each component of the rockfall testing program, including scouting and safety plan development, equipment requirements, synthetic rock development for uniform testing across varying bench configurations, local rock collection for testing of mine-specific geology, data acquisition during testing, and data processing. Additionally, this paper describes how the program has been updated over time according to lessons learned during initial rockfall testing.

INTRODUCTION

Rockfall can occur in open-pit mines 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 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].

$$W = 0.2H + 4.5 \quad (1)$$

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. [8] 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. Statistical analysis programs, such as RocFall [9], can be used to assist with the assessment of slopes at risk for rockfall events.

NIOSH Highwall Safety Project

In October of 2021, the Geomechanics Team at the National Institute for Occupational Safety and Health (NIOSH) Spokane Mining Research Division (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. [10] 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.

In 2022, researchers within the NIOSH Highwall Safety project team conducted a numerical sensitivity analysis using RocFall 2D 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 [11]. The conclusions gathered from the RocFall sensitivity analysis study included the following:

- Bench height and bench face angle are the dominant factors in forecasting runout distance compared to slope material type and rock size/shape with some cases showing bench face angle having more influence in forecasting rockfall runout distance than bench height;
- Modeling does not effectively 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; and
- 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 (lump mass versus rigid body).

The next step in the NIOSH Highwall Safety project's research agenda was to confirm the statistical modeling data with real-world rockfall studies, requiring the development of a rockfall testing program, which is the focus of this paper.

NIOSH ROCKFALL TESTING PROGRAM

There are several components to the NIOSH rockfall testing program including mine scouting and safety plan development, equipment requirements, synthetic rock development for uniform testing across varying bench configurations, local rock collection for testing of mine-specific geology, data acquisition during testing, and data processing.

Mine Scouting and Safety Plan Development

The most crucial element to successful empirical rockfall testing at a mine site is detailed scouting and safety planning. This allows for the gathering of runout data that is most useful to each individual mine site and allows the opportunity for proper identification of associated hazards with each rockfall test. To start, a trip is planned by the researchers on the Highwall Safety project team to visit the collaborating mine site and work with the mine staff to review what site safety requirements are needed to conduct rockfall testing while staying in compliance with MSHA standards and additional safety standards specific to the individual site. The NIOSH researchers visiting the site will undergo sites training if necessary for that trip, while the rest of the team will undergo sites training when they arrive for the testing dates. From there, the collaborating team will review maps of the open pits in question for rockfall testing and drive to the pits to further analyze the potential for successful testing. Bench configurations to be tested are subject to the desire of the mine staff which usually includes a mix of single bench testing for runout analysis and full highwall testing for bench catchment analysis.

If allowed, NIOSH researchers will send 6-inch synthetic rocks down the slope of the chosen test locations to establish rockfall trajectory and an approximate landing area. This helps in developing a site safety plan, identifying the ideal rock drop location, the rock trajectory, and a safe location of an observation area for camera recording of the rockfall tests. A drone flight of each testing location is acquired by NIOSH researchers using their own equipment to develop a photogrammetry model for planning purposes. An example of a rockfall test safety planning schematic with chosen zoning locations is shown in Figure 1.

After the site visit, a rockfall testing proposal plan is developed by the NIOSH Highwall Safety project team outlining the following:

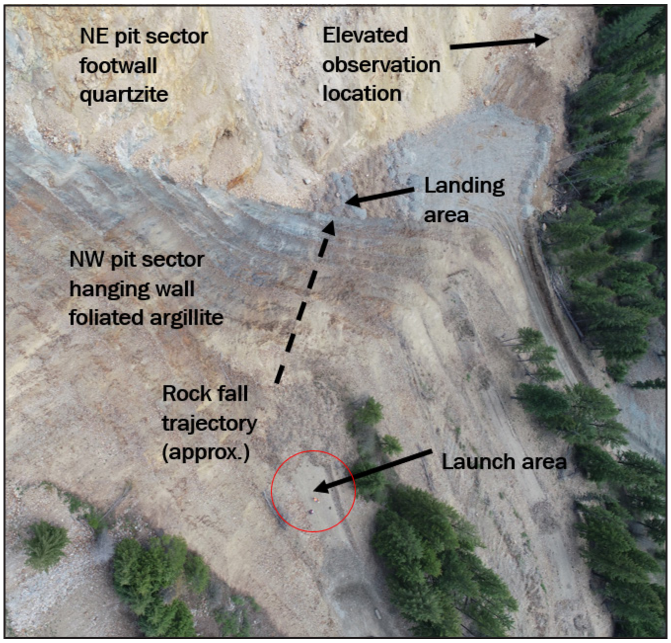

Figure 1. Example of rockfall test safety planning schematic developed after small-scale 6-inch rockfall testing using aerial drone photo.

- Overview of rockfall testing to be performed including who is involved, what type of testing will occur, where testing will occur, the dates NIOSH will be on site, and the benefit of the testing to take place;
- A planned schedule for each day NIOSH will be on site;
- Testing roster including NIOSH staff, mine staff, and all collaborating partners involved;
- Detailed photos and models outlining testing locations, rockfall trajectory, and observation points;
- Safety considerations and potential hazard analysis;
- Transportation and equipment used by NIOSH on the mine site;
- Data acquisition equipment list used by NIOSH on the mine site;
- Outline of both synthetic rocks and local/natural rocks to be used for rockfall testing;
- Procedures to follow pre-rockfall test, during rockfall test, and post-rockfall test; and
- Details of routes between hotel and collaborating mine site as well as directions to nearest hospital from both the hotel and mine site.

This testing proposal, developed by the NIOSH Highwall Safety project team, will be provided to the collaborating mine staff prior to arrival on site to allow for needed revisions and approval. Communication is key in development of a successful rockfall testing program with each individual mine site.

Equipment Requirements

Researchers on the Highwall Safety project recognize the importance of mitigating the effect on mine production during rockfall testing. Employees at NIOSH SMRD have access to a fleet of trucks for field work purposes which includes driving on mine sites. Additionally, project funds were used to purchase a GTH Telehandler with a 10-foot reach and 5,000 pounds lifting capacity as well as a bucket attachment and trailers to transport both the NIOSH-owned telehandler and synthetic rocks used for rockfall testing.

With that, the NIOSH team has all the necessary equipment for transportation of materials from the Spokane Research Lab to mine sites and conducting rockfall testing, meaning that the mine does not need to provide any equipment or operators. However, it is understood that some mines may prefer to provide equipment and operators due to mine policy not allowing outside contractors to operate on site. Table 1 outlines the minimum equipment provided by NIOSH that is required for successful rockfall testing.

Table 1. Equipment needed for NIOSH rockfall testing program, provided by the Highwall Safety project team.

Equipment	Use
Chevy 2500	Hauling of project materials and synthetic rock trailer
Chevy 3500	Hauling of project materials, personnel, and telehandler trailer
Ford F450	Hauling of project materials and additional synthetic rocks
GTH Telehandler with Bucket Attachment	Loading/unloading of synthetic and local rocks for transportation and rockfall testing
Trailer 1	Used to transport GTH telehandler
Trailer 2	Used to transport synthetic rocks

Synthetic Rock Development

While the main goal in the rockfall program is to understand the runout distance of rocks local to the participating mine site, NIOSH researchers decided there was also a need to test a set of synthetic rocks of controlled size and shape across all mine sites for uniform runout comparison across varying bench configurations and conditions. Table 2 outlines details of the synthetic rocks developed for the rockfall testing program. All molds were either developed in-house at the Spokane Research Lab or through a local sheet metal fabrication specialist. All synthetic rocks are cast by NIOSH researchers at the Spokane Research Lab out of

Figure 2. Completed and demolded synthetic rocks colored to distinguish size and shape during post-test analysis.

5,000-plus PSI fiber-reinforced concrete. Once cured and removed from molds, the rocks are painted in different color schemes to distinguish various sizes and shapes to aid in rock identification during post-test runout or bench catchment analysis. Examples of the finished product of varying synthetic rocks are shown in Figure 2.

Local Rock Collection

In order to analyze runout of rocks that are representative of the geology of the specific bench configuration, local rocks of three size categories are collected and tested for runout analysis. The three size categories are small (3-to-6-inch diameter), medium (6-to-12-inch diameter), and large (12-inch and larger diameter). A minimum of 15 rocks are chosen for each size category. A rockfall testing form is used to note each rock's type as well as dimensions (short, intermediate, and long axis). The rocks are then spraypainted according to size category for easy detection when measuring runout distance. An example of collected, measured, and spray-painted local rocks is shown in Figure 3.

Data Acquisition

Researchers at NIOSH collaborated with project partners to develop a data acquisition program that captures the rockfall test from multiple angles using several imagery methods. The current project data acquisition equipment used by researchers on the Highwall Safety project team is outlined in Table 3. It is important to note that the data acquisition methodology is always evolving as more project partners get involved and procedures are refined. This is further explained in the Lessons Learned section of this paper.

Data Processing

Each rockfall test will have a set of associated data collected from each piece of equipment outlined in Table 3. The photos taken from the DJI Phantom 4 Pro Drone to scan the bench/slope pre and post rockfall test are uploaded into Agisoft Metashape Pro to develop photogrammetry models using the following procedure:

Table 2. Characteristics of synthetic rocks used for rockfall testing across varying bench configurations

Synthetic Rock Attribute	Attribute Range	Notes
Rock Size	3, 6, 12, and 18-inch diameter	Cast using reusable steel, wood, and 3D printed silicon molds.
Rock Shape	Cube, European Technical Approval Guideline (ETAG) 27, and plates	ETAG 27 is the standard shape for testing of rockfall barriers in Europe [12]. Plate rocks have an aspect ratio of 0.1 to 0.2 to simulate shale, argillite, and other bedded/foliated rockfall behavior.
Reinforcement	Synthetic and steel fiber, steel wire mesh used for plates	Several reinforcement methods tested to compare handling and durability characteristics of synthetic rocks.

Table 3. NIOSH Highwall Safety project data acquisition equipment

Equipment	Use
DJI Phantom 4 Pro Drone	Taking photos for photogrammetry model development (pre and post rockfall testing) which is used for measuring rockfall runout distance; taking videos during rockfall testing.
Sony 4K Handycam FDR-AX53	Taking videos during rockfall testing from a distance that best captures the entire slope; taking videos to document the testing process.
FLIR T620 Thermal Camera	Taking thermal videos during rockfall testing from a distance that best captures the entire slope; taking pictures before or after the rockfall test to make sure temperature range is captured (due to video not showing temperature range)

Figure 3. Example of local rocks collected and spray painted prior to rockfall testing

- Organize drone photos taken from fieldwork in folders according to location and pre and post rockfall test flight sequences;
- Start a new project in Agisoft Metashape by adding photos from a drone flight sequence into a chunk;
- Start the workflow process – align photos, go with the preselected properties;
- For rock runout distance models, take the necessary steps to minimize error in the alignment:
  - Create two markers in Agisoft Metashape on one of the cameras (photos) on known reference spots (2-by-2-foot X's spray painted by NIOSH researchers on the ground near the rockfall drop location on the crest of the bench).
  - Go to a second camera and make sure the markers are on the same exact spot. This should adjust it for every camera, feel free to double check.
  - Go to workflow, batch process, click "Add…." For Job Type, choose "Optimize Alignment" and apply to all chunks. Check "Save project" after each step.
  - Under the reference for each marker, check to see if their error is less than 0.03 m. If not, repeat the steps until the error is less than 0.03 m, if possible.
- Continue the workflow process – build dense point cloud, choose your quality; and
- Export points as a .ply file for runout/bench catchment analysis in Cloud Compare software. When exporting the points, make sure to use the Local Coordinates (m) coordinate system. The runout/bench catchment analysis can also be performed in Agisoft Metashape if preferred.

The pre-rockfall test photogrammetry model is used for reference to analyze the bench/slope configuration and characteristics associated with geology, blasting practices, and talus buildup at the toe. The post-rockfall test photogrammetry models are used for runout analysis of the synthetic and local rocks from the toe of the slope if it was a single bench test or for bench catchment analysis if it was a full highwall test.

The video camera footage gathered by the Sony 4K Handycam FDR-AX53 is used to analyze the behavior of rocks traveling down the slope and how factors such as rock size, rock shape, geology, blasting practices, and talus buildup can affect the behavior of the rock while in motion. Additionally, with regards to full highwall rockfall tests, the video camera footage can be extremely useful in bench catchment analysis, especially for the smaller sized rocks.

The thermal video camera footage gathered by the FLIR T620 Thermal Camera is used to aid the University of Arizona Geotechnical Center of Excellence (GCE) in their research to detect and monitor rockfall events in surface mines using existing thermal camera technology [13].

LESSONS LEARNED

Pre-Rockfall Testing

The development of synthetic rocks for each rockfall test takes a significant amount of time and resources from the NIOSH research team. After a couple rounds of testing at mines within a 2-hour radius of Spokane, WA, it was decided that the number of rocks to be developed according to each size and shape for a single rockfall test are as follows:

- 3-inch diameter – 50 cubes, 50 ETAG, and 50 plates
- 6-inch diameter – 40 cubes, 50 ETAG, and 40 plates
- 12-inch diameter – 12 cubes, 12 ETAG, and 20 plates
- 18-inch diameter – 8 cubes, 8 ETAG, and 10 plates

This provides a total of 340 rocks (one suite of rocks) per rockfall test. The chosen number of rocks per rock size was decided upon according to weight limitations of NIOSH hauling equipment and having enough samples per size for statistical runout analysis. At this time, the Highwall Safety project team has developed and purchased enough rock molds to make an entire suite of rocks per concrete pour. One suite of rocks is used per rockfall test trip to a collaborating mine site. One rockfall testing trip takes a week, which includes final scouting and sites training, at least two single bench rockfall tests, and a full highwall test to finish. Each rockfall test takes a full day for set up, testing, clean-up, and loading of rocks to take to the next testing location. The highwall test is purposely left as the final rockfall test for the week due to the rocks being unretrievable, which also explains why one suite of rocks is used per trip. Moving forward, NIOSH researchers are working with concrete mixing/pouring companies local to collaborating mine sites to develop suites of synthetic rocks using the already developed molds to reduce travel time with heavy loads from Spokane, WA.

Another lesson was learned with regards to data acquisition prior to testing. While there are times where ideal rock drop locations are limited for full highwall rockfall tests due to accessibility, the NIOSH research team learned that it is important to get a drone photogrammetry model developed of each testing location for analysis before each test occurs to ensure the drop point is as realistic to mining conditions as possible. For example, there was a case where a highwall with 6 benches of double 40-foot bench height to the pit bottom was chosen for rockfall testing. A drop point was chosen without acquiring a drone photogrammetry model and testing commenced. It was later discovered that the first bench was a single 40-foot height with the remaining benches being double 40 foot, causing inconsistency in bench catchment from the very start. This is shown in Figure 4.

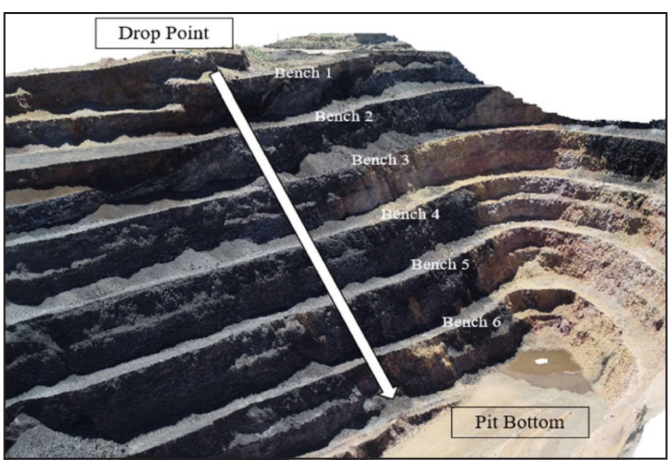

Figure 4. Photogrammetry model of sample highwall test showing single 40-foot bench followed by remaining double 40-foot benches.

Additionally, it was discovered that the second bench had a slight berm which increased catchment potential early in the rock's path of travel. Factors such as these need to be analyzed prior to rockfall testing to ensure that the chosen drop point provides the most useful data for collaborating mine sites.

During Rockfall Testing

In the early stages of the rockfall testing program, all rock sizes and shapes were sent down the bench or highwall, either a pallet at a time or by bucket load, until testing was completed, and a single drone flight was acquired to develop a photogrammetry model and to measure/identify where all the rocks had traveled. It was quickly discovered that this caused issues in identification of rocks 6 inches and smaller in diameter due to being buried or destroyed by the larger synthetic/local rocks. Additionally, the final resting place of some rocks altered or even completely stopped the path of travel of others. To fix both issues for single bench testing scenarios, a methodology was developed where each size of rocks was sent down the slope as individual sets. For each set, a drone flight was acquired after all the rocks of that specific size category were dropped, and then the rocks were cleared before dropping the next size set. This methodology cannot be applied in full highwall testing scenarios because the rocks cannot be cleared between size sets due to inaccessibility on benches below the drop point. Therefore, for highwall testing scenarios, the rocks are dropped from the largest size (18-inch diameter) to smallest size (3-inch diameter) as the larger sizes typically travel farther and would not hinder the travel path or destroy/cover up the smaller rock sizes.

Another lesson was learned with regards to initial velocity of the rocks from the drop point. Prior to the Highwall Safety project team owning the Genie telehandler, rocks were dropped from a bucket on an excavator or other piece of loading equipment, which typically gave them a larger rotational velocity than desired. Once the Genie telehandler with the fork attachment was acquired, a new methodology was developed in which the synthetic rocks, sizes 6-inch diameter and larger, would be loaded on a pallet, placed on flat ground at the drop point, and slowly pushed off the pallet using another pallet on the forks of the telehandler. For all the local rocks and synthetic rocks sized 3 inch in diameter, they were similarly loaded on a pallet and placed at the drop point but then manually pushed individually using a 6-foot steel rod with a plate on the end. This all allowed for the least initial velocity possible to best simulate a natural rockfall scenario.

Finally, it is important to note the evolution of the data acquisition component of the rockfall testing program. At the start of the project, NIOSH researchers manually flew the DJI Phantom 4 Pro Drone to acquire the photos with exceeding overlap for photogrammetry model development which took a significant amount of time during rockfall testing, especially when drone flights took place for each size set. To better refine the drone flight process, NIOSH researchers collaborated with Call & Nicholas, Inc. to build flight plans specific to each testing scenario and carry out the flights using the Lichi flight control application. These flights along with surveyed control points helped in building photogrammetry models with known resolution as well as cutting down time spent flying the drone between sets of rockfall testing. With regards to use of the FLIR T620 Thermal Camera, NIOSH researchers have worked closely with the GCE to ensure they are acquiring thermal videos that enhance their research to detect and monitor rockfall events using that specific technology. At the start of the project, NIOSH researchers operated the FLIR T620 under remote guidance from the GCE. Since 2022, a member of the GCE has joined the NIOSH team during each rockfall testing trip to operate the FLIR T620. More recently, during the 2023 field season, along with continuing operation of the FLIR T620, members of the GCE tested the operation of a new standalone thermal camera system which will be used to further advance detection and alerting capabilities.

CONCLUSIONS

The overall success of the NIOSH rockfall testing program lies in the support from the mining industry, specifically the collaborating mine staff and partners to the Highwall Safety project. The program will continue to evolve as testing commences at additional mining properties to better streamline each of its individual components. The goal is to acquire empirical data that helps quantify the performance of available criterion for rockfall catchment bench design in a variety of bench configurations and optimizes said criterion based on field calibration. While the NIOSH research team will collect as much data as possible throughout the duration of the Highwall Safety project (ending in 2026), it is the hope that individual mine sites can take the framework and lessons learned from the described rockfall testing program to gather empirical data specific to their bench configurations. 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.

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.

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.

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