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Forecasting Rockfall Retention Performance of catch Bench configurations in Mining Models Calibrated to Rockfall Field Data

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ABSTRACT: Rockfall hazards pose significant safety risks in open-pit mining, endangering both personnel and equipment. To mitigate these risks, catch benches are designed to retain falling rocks, with a common industry target of 90% retention on the first bench. However, quantifying retention rates remains challenging due to variable slope geometries and rockfall behaviors, necessitating calibrated predictive modeling. This study uses RocFall2 to simulate rockfall behavior based on field data from the Highwall Safety Project. A calibration was performed using single-bench tests, determining a 90% retention distance of 10.9 m (~35.76 ft) from the bench toe for 6-inch synthetic rocks. The calibrated model was then applied to a five-bench configuration, which showed a first bench retention efficiency of 88.7%, with cumulative retention reaching 100% by the fifth bench. To explore the impact of bench geometry, a second simulation was conducted using the Modified Ritchie Criterion (MRC), reducing the catch bench width to 9.4 m. In this scenario, a six-bench system was needed to achieve full containment. The results reveal that achieving similar retention outcomes with narrower benches requires more sequential benches. These findings demonstrate the effectiveness of multi-bench systems while highlighting areas for improvement in bench geometry and energy dissipation strategies.

1. INTRODUCTION

Rockfall is the movement of rock from a slope that is so steep that the rock continues to move down the slope (Bar et al., 2016), and the hazards associated to this kind of event pose significant safety and operational challenges in open-pit mining (Alejano et al., 2007; Bar et al., 2016; Bourgeois et al., 2023; Michelini et al., 2020; Robiati et al., 2019). Understanding the mechanics of rockfall events is crucial for developing effective mitigation strategies to protect personnel, infrastructure, and equipment (Dorren, 2003). In open-pit mining, highwalls and benches are designed to manage rockfall risk by containing falling rocks and reducing their kinetic energy (Warren et al., 2024). However, the effectiveness of these designs depends on various factors, including slope geometry, rockfall trajectory, and energy dissipation mechanisms (Alejano et al., 2007). One of the primary concerns in open-pit mining is the ability of catch benches to retain falling rocks and minimize runout distances. Previous research has demonstrated that the design of catch benches, including their width and inclination, plays a critical role in reducing rockfall hazards (Peik et al., 2020). Furthermore, other studies have shown that the geometry of benches, including their height, width, and face angle, significantly influences the probability of rock retention, as these factors control the kinematics of detached blocks and their likelihood of being intercepted before reaching the pit floor (Maddalena Marchelli et al., 2023). Recent advancements in numerical modeling have enhanced the ability to predict rockfall behavior, and model simulations can provide insight into ways to improve the slope design by modifying slope geometries or installing systems to mitigate rockfalls. One such approach involves the use of synthetic rockfall experiments to calibrate numerical models that simulate rockfall trajectories, impact forces, and energy dissipation. This study utilizes RocFall2 (Rocscience, 2024), a widely used rockfall analysis software, to assess rockfall dynamics in a five-bench slope configuration. By calibrating the model with controlled rockfall experiments using real data collected from an ongoing project from the National Institute of Occupational Safety and Health (NIOSH) the Highwall Safety Project (Warren et al., 2024), and extending the analysis to a synthetic multi-bench scenario, this study aims to improve the understanding of rockfall behavior in open-pit mines. A key method for model calibration involves conducting rockfall simulations with a predefined number of rocks to determine the 90% retention distance. Once this critical distance is established, the catch bench is modified to reflect real-world conditions, enabling multi-bench simulations that provide a more comprehensive understanding of rockfall behavior. By maintaining consistent input parameters, such as rock mass properties and slope geometries, this study extends previous research (McNabb et al., 2025 (in review)) by examining how rockfalls behave in a five-bench configuration under controlled conditions.

2. ROCKFALL FIELD TEST

The project, Highwall Safety: Rockfall Catchment Design and Slope Performance Monitoring led by the National Institute for Occupational Safety and Health (NIOSH) is an ongoing project that seeks to evaluate the performance of existing rockfall catchment guidelines (Warren et al., 2024). The study employed a combination of field testing and analysis to evaluate rockfall behavior under controlled conditions at the Bald Mountain Mine located in Nevada, USA. One of the main objectives of this study was to determine what was the distance where 90% of the rocks were retained. Synthetic rocks were fabricated using high-strength, fiber-reinforced concrete and shaped to match different forms and dimensions to simulate real-world rockfall conditions as shown in Figure 1.

Figure 1. Different rock shapes and sizes tested in the Highwall Safety Project (from Warren et al., 2024).

As part of the study, rockfall testing was conducted on five single bench configurations with varying bench heights and slope angles. Synthetic rocks were released from the bench crest using a forklift, with minimal initial force to limit rotational and translational velocities. Then the runout distance of each rock was measured from the toe of the bench to the point where the rock came to rest.

This study utilizes the results from the single bench tests conducted at the Top Pit as the baseline for calibrating the rockfall simulations performed using the software Rocfall2 (Figure 2). The testing was conducted on September 13, 2023, at a gold mine in Nevada, USA, on a single bench with a total height of 24.4 m (80 ft). The main parameters that describe this bench configuration are summarized in Table 1.

Figure 2. Single bench crest view and landing area

Table 1. Top bench configuration.

Bench Height (m)	24.4
Slope Angle (deg)	70
Cleaned Toe	Yes
Lithology	Limestone

Among the three rock shapes used in the Highwall Safety Project, the rhombicuboctahedron shape (Figure 3) with a diameter of 0.152 m (6 in) was selected for calibration in the model for this study. The rockfall testing results revealed that 90% of the 39 rhombicuboctahedron-shaped rocks were retained within 10.9 m (~35.76 ft) from the toe of the bench.

Figure 3. Rhombicuboctahedron synthetic rock (from McNabb et al., 2025 (in review)).

3. METHODOLOGY

3.1. *Rockfall Modelling Calibration*

For the 2D rockfall modeling calibration, a section of the single bench was generated in CloudCompare (CloudCompare, 2024) using a 3D point cloud. This section was then exported to Rocfall2 for rockfall modeling. To avoid calibration errors caused by slope intersections, the slope geometry was simplified. The slope parameters (Bench Face and Catch Bench), as determined by McNabb et al., 2025 (in review), were used in the model. These parameters, detailed in Table 2 and Table 3, were adjusted to align with the results from the rockfall field tests conducted by Warren et al. (2024). Table 2 outlines the slope parameters for the bench face, while Table 3 provides the parameters for the catch bench.

Table 2. Bench Face parameters used in the calibration model for the single bench

Parameters	Mean	Standard Deviation
Normal Restitution	0.40	0.04
Tangential Restitution	0.84	0.03
Dynamic Friction	0.52	0.13
Rolling Friction	0.15	0.05

Table 3. Catch Bench parameters used in the calibration model for the single bench

Parameters	Mean	Standard Deviation
Normal Restitution	0.30	0.028
Tangential Restitution	0.79	0.04
Dynamic Friction	0.60	0.13
Rolling Friction	0.33	0.05

This numerical rockfall model employs the rigid-body approach, which accounts for both the shape and mass of the rock. The rock properties used in the field testing were incorporated into the calibration model. In RocFall2, the selected rock shape was the polygon octagon, which approximates the rhombicuboctahedron in two dimensions. The synthetic rock had a density of 2,483 kg/m³ (155 lb/ft³) and a diameter of 0.152 m (6 in), resulting in a calculated mass of 9.6 kg (~21.16 lb). Using these slope and rock parameters, a simulation of 1000 rockfalls was conducted, showing that 90% of the rocks were retained within 10.9 m (~35.76 ft) from the bench toe. Figure 4 presents the simulation results, where two areas can be identified: the gray area represents the bench face parameters, and the green area represents the catch bench parameters.

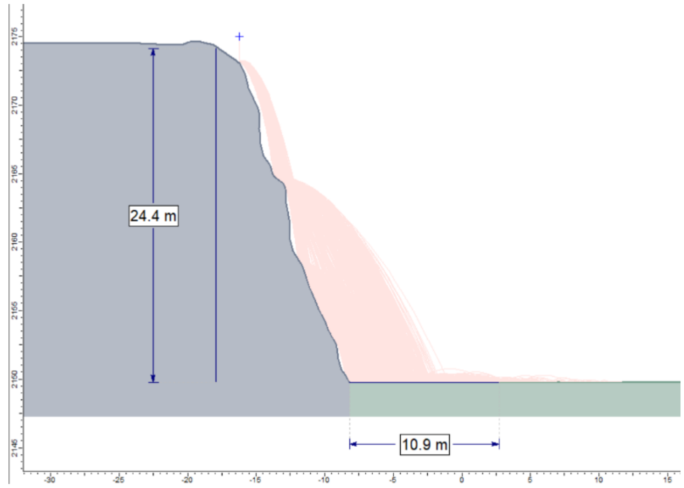

Figure 4. Single Bench rockfall calibration model simulation

3.2. *Multiple Bench Rockfall Modelling*

A synthetic five-bench configuration was created using the same section employed in the calibration process. The catch benches areas were defined at 10.9 m (~35.76 ft) from the toe, corresponding to the distance at which 90% of the rocks were retained. All five bench heights were set at 24.4 m (80 ft). Using the same bench face and catch bench parameters established during calibration, the five-bench configuration was tested with one thousand polygon octagon rocks, all sharing the same characteristics as those used in the calibration. Figure 5 illustrates the retention distribution across the five benches.

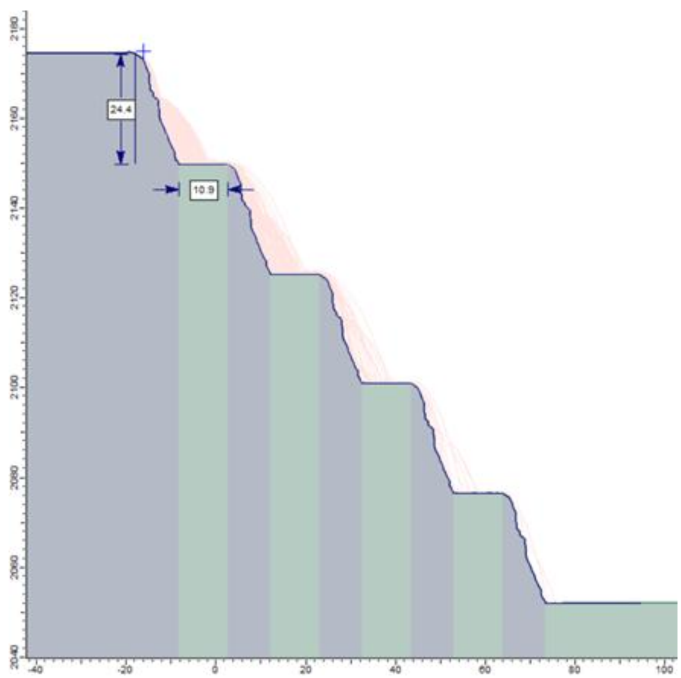

Figure 5. Five-bench configuration rockfall simulation with 10.9 meter catch benches

3.3. *Modified Ritchie Criteria Rockfall Modelling*

To evaluate the effectiveness of narrower catch benches, a six-bench slope configuration was modeled using the

Modified Ritchie Criteria (MRC), which is widely recognized in North and South America as a guideline for preliminary rockfall catch bench design (Bourgeois et al., 2023). According to this approach, the minimum required bench width is defined as a function of the bench height, as shown in Eq. (1).

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

In this simulation, the catch bench width was reduced from 10.9 meters to 9.4 meters. The vertical height of each bench was maintained at 24.4 meters, and the same calibrated slope and rock parameters from the previous simulation were applied to ensure consistency. Of the 1,000 rockfall simulations initially executed, 2 failed to run successfully due to software constraints related to slope geometry intersections, resulting in a total of 998 valid rockfall trajectories analyzed. This additional simulation was incorporated to enable a direct comparison with the original five-bench model and assess how a reduced catch bench width influences overall retention performance. Figure 6 presents the simulation outcome, in which six benches were required to successfully contain all rockfall trajectories under the narrower bench design.

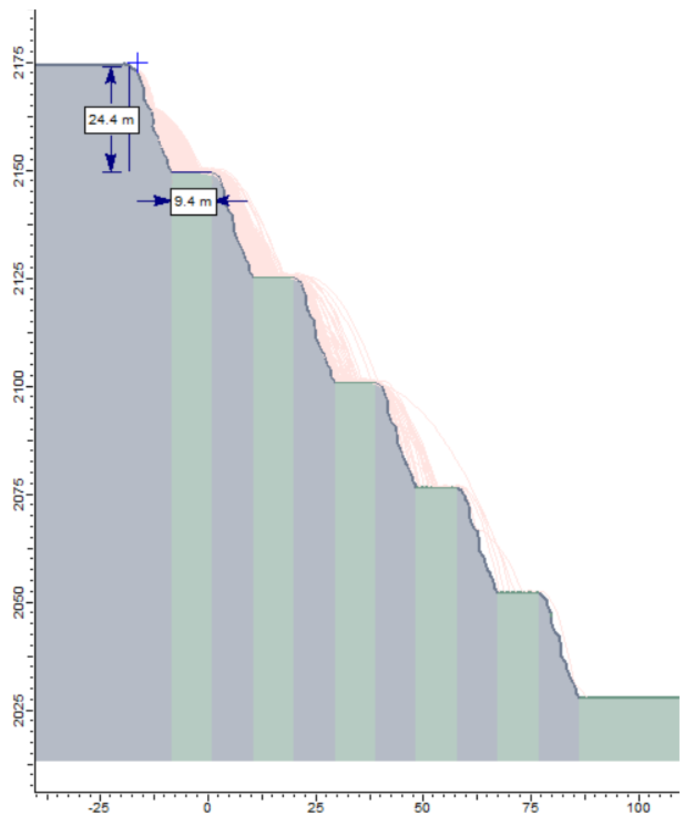

Figure 6. Six-bench configuration rockfall simulation with 9.4 meter catch benches

4. RESULTS

A summary of the results from the five-bench configuration with 10.9 meter catch benches is shown in Table 4 that presents a detailed analysis of rock retention and bypass rates.

Table 4. Results from the five-bench configuration with 10.9 meter catch benches.

Description	First Bench	Second Bench	Third Bench	Fourth Bench	Fifth Bench
Rocks reaching bench	1000	113	26	8	2
Rocks retained by bench	887	87	18	6	2
Cumulative rocks retained	887	974	992	998	1000
Rocks bypassing bench	113	26	8	2	0
Bench retention efficiency (%)	88.7	77.0	69.2	75.0	100.0
Cumulative retention efficiency (%)	88.7	97.4	99.2	99.8	100.0
Bypass rate per bench (%)	11.3	23.0	30.8	25.0	0.0
Bypass rate relative to total rocks (%)	11.3	2.6	0.8	0.2	0.0

The first bench intercepts 1000 rocks, retaining 884 (88.7% retention efficiency), while 113 rocks bypass it. The second bench retains 87 of the 113 incoming rocks (77.0% retention efficiency), with 26 rocks bypassing. The third bench retains 18 of the 26 incoming rocks (69.2% retention efficiency), allowing 8 rocks to bypass. The fourth bench retains 6 of the 8 incoming rocks (75.0% retention efficiency), with 2 rocks bypassing. The fifth bench retains all 2 incoming rocks (100% retention efficiency). Figure 7 shows the distribution of rocks retained on each bench in the five-bench configuration with 10.9 meter catch benches. The bench retention efficiency data highlights the critical role of individual catch benches in mitigating rockfall hazards. While the first bench captures the majority of falling rocks (88.7%), subsequent benches exhibit varying efficiencies, with the lowest retention observed at the third bench (69.2%).

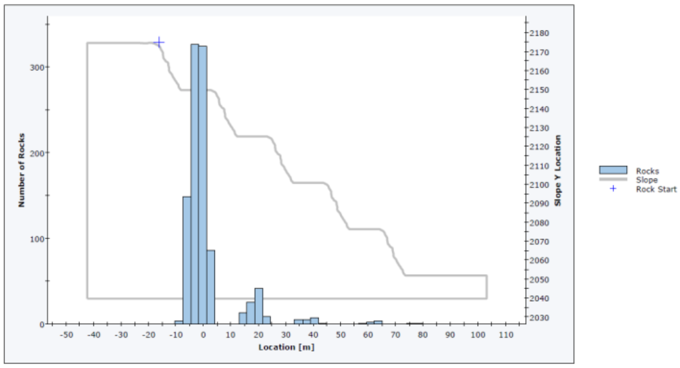

Figure 7. Distribution of rocks retained per bench in the five-bench configuration with 10.9 meter catch benches

A summary of the results from the six-bench configuration with 9.4 meter catch benches is shown in Table 5 that presents a detailed analysis of rock retention and bypass rates. Of the 1,000 rockfall simulations, 2 failed to run successfully due to software constraints.

Table 5. Results from the six-bench configuration with 9.4 meter catch benches.

Description	First Bench	Second Bench	Third Bench	Fourth Bench	Fifth Bench	Sixth Bench
Rocks reaching bench	998	201	56	20	5	1
Rocks retained by bench	797	145	36	15	4	1
Cumulative rocks retained	797	942	978	993	997	998
Rocks bypassing bench	201	56	20	5	1	0
Bench retention efficiency (%)	79.9	72.1	64.3	75.0	80.0	100
Cumulative retention efficiency (%)	79.9	94.4	98.0	99.5	99.9	100
Bypass rate per bench (%)	20.1	27.9	35.7	25.0	20.0	0.0
Bypass rate relative to total rocks (%)	20.1	5.6	2.0	0.5	0.1	0.0

In the six-bench configuration using the Modified Ritchie Criterion (MRC) and a reduced catch bench width of 9.4 meters, the first bench retained 79.9% of rocks, resulting in a bypass rate of 20.1%. As rocks continued to descend, each subsequent bench intercepted a proportion of the remaining rocks, with the second and third benches achieving retention efficiencies of 72.1% and 64.3%, respectively. Notably, retention efficiency improved in the fourth and fifth benches to 75.0% and 80.0%, respectively, while the sixth bench captured the final rock with a 100% retention efficiency. Figure 8 presents the distribution of retained rocks across the benches in the six-bench configuration with 9.4 meter catch benches.

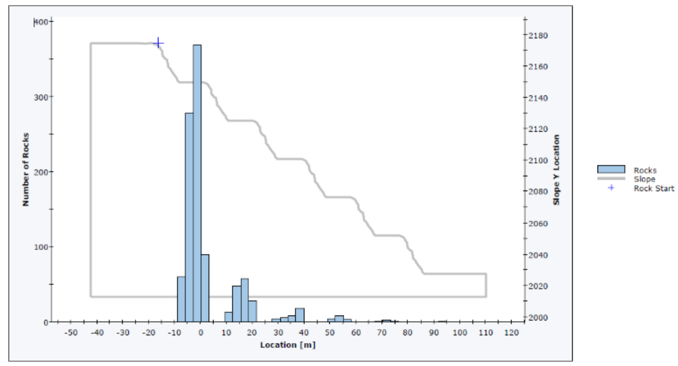

Figure 8. Distribution of rocks retained per bench in the six-bench configuration with 9.4 meter catch benches

Figure 9 compares the cumulative retention efficiency between two multi-bench configurations: one using a 10.9-meter catch bench and the other using a reduced 9.4-meter catch bench based on the Modified Ritchie Criterion (MRC). A notable difference appears at the first bench, where the wider 10.9-meter bench achieved a retention efficiency of 88.7%, while the narrower 9.4-meter bench retained only 79.9% of the rocks. This result highlights a proportional relationship between catch bench width and initial retention performance—the wider the bench, the greater its capacity to intercept rockfalls early in their trajectory. Despite the reduced width, the six-bench configuration with the 9.4-meter catch benches showed a steady increase in cumulative retention, ultimately reaching 100% by the sixth bench. In contrast, the five-bench system with the 10.9-meter benches achieved full containment by the fifth bench.

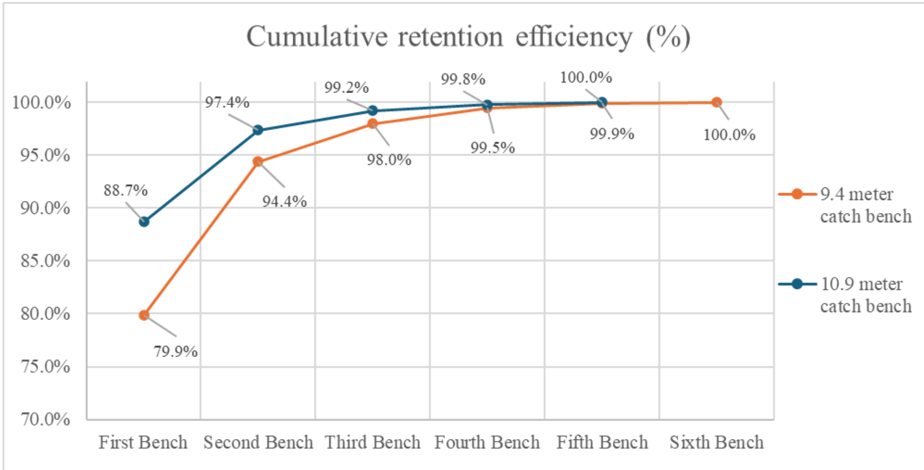

Figure 9. Comparison of Cumulative Retention Efficiency Between Standard and MRC

Figures 10 and 11 present the total kinetic energy distributions for two slope configurations. Figure 10 corresponds to the five-bench configuration with a 10.9-meter catch bench, while Figure 11 represents the six-bench configuration with a 9.4-meter catch bench designed according to the Modified Ritchie Criterion (MRC). In both simulations, kinetic energy trends increase progressively downslope, reflecting cumulative effects of bouncing, impact, and sliding behavior.

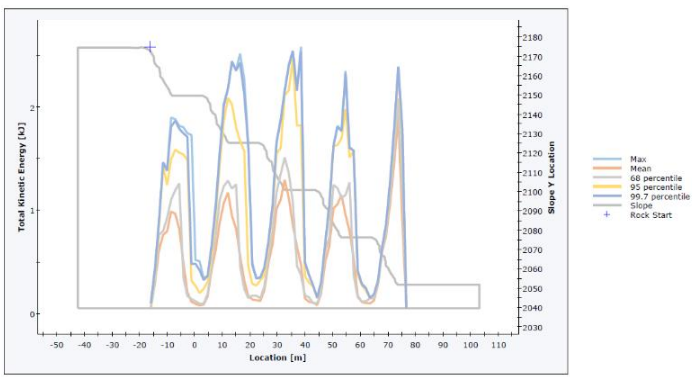

Figure 10. Total kinetic energy on slope five-bench configuration

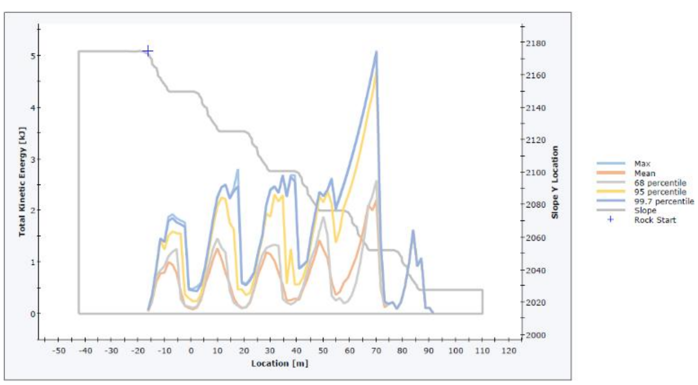

Figure 11. Total kinetic energy on slope six-bench configuration

The analysis of total kinetic energy along the slope profile reveals significant fluctuations corresponding to impact and rebound events, with energy dissipation occurring at catch benches. The inclusion of percentiles provides valuable insight into the variability of rockfall behavior. The 68th percentile represents moderate-energy rockfalls, which occur frequently, while the 95th percentile captures higher-energy events that are less common but still significant. The 99.7th percentile marks extreme rockfall events, which, although rare, can have substantial impacts on slope stability and safety measures. Notably, the maximum energy value exceeds the 99.7th percentile at multiple points, indicating that a subset of rockfalls attains significantly higher energy levels, posing increased risks to mining infrastructure and personnel. As the rocks move down the benches, there is a clear uptrend in the total kinetic energy of the rocks that reach each of the benches. However, a notable spike in kinetic energy is observed at the fifth bench in the six-bench configuration with 9.4-meter catch benches (Fig. 11). This anomaly is attributed to a rock that bypassed the fourth bench entirely, traveling from the third to the fifth bench without contact. This behavior resulted in a concentrated impact at the fifth bench, momentarily elevating the local energy profile above neighboring zones.

5. DISCUSSION

The results of this study emphasize the importance of proper calibration in rockfall modeling to improve predictions of runout distances and enhance the effectiveness of catch bench designs. The calibration process, which was based on field tests conducted at the Bald Mountain Mine, established that 90% of 6-inch diameter synthetic rocks were retained within 10.9 m (~35.76 ft) of the bench toe in a single-bench configuration. When this calibration was applied to a five-bench system, the retention efficiency of the first bench decreased slightly from 90% to 88.7%, indicating a minor deviation from the calibration results. This reduction may be attributed to variations in rock trajectories and energy dissipation as rocks interact with the first bench.

A key finding of this study is the cumulative retention efficiency, which increased progressively from 88.7% at the first bench to 100% at the fifth bench. This result demonstrates the effectiveness of a multi-bench system in intercepting rockfalls, even when individual bench efficiencies fluctuate. However, the third bench exhibited the lowest retention efficiency (69.2%), possibly due to increased kinetic energy and unpredictable bounce trajectories at this location. This highlights the need for targeted modifications, such as adjusting bench widths or adding energy-dissipating features, to optimize retention performance.

The additional simulation using the Modified Ritchie Criterion (MRC) provided valuable insight into the performance implications of bench width reduction. By decreasing the catch bench width from 10.9 meters to 9.4 meters, the first bench retention efficiency dropped from 88.7% in the original five-bench configuration to 79.9% in the six-bench MRC setup. This result aligns with the expected proportional relationship between catch bench width and initial rockfall interception. Despite the lower efficiency at the first bench, the system still achieved full cumulative retention by the sixth bench, demonstrating that the addition of benches can offset the effects of narrower widths. The kinetic energy profile also revealed a more gradual dissipation along the slope, although a noticeable energy spike occurred at the fifth bench due to a rock that bypassed the fourth bench entirely. This highlights the importance of accounting for complex rockfall trajectories when evaluating slope performance.

Another critical aspect to consider is the influence of rock size on retention outcomes. While this study focused on 6-inch diameter synthetic rocks, real-world rockfall events involve a range of rock sizes, each exhibiting distinct energy and motion characteristics. Future calibration efforts should incorporate a broader distribution of rock sizes to refine predictive capabilities and develop more robust slope designs. Additionally, variations in rock shape, density, and impact mechanics should be further explored to enhance model reliability.

In conclusion, the calibration of rockfall models is essential for accurately predicting rockfall behavior and optimizing catch bench designs. While the first bench is critical in retaining the majority of falling rocks, the cumulative retention efficiency of a multi-bench system ensures that even the most challenging rockfalls are contained.

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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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