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Assessing rockfall retention strategies using field-calibrated rockfall modelling

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Abstract

This study extends a previously calibrated rockfall model developed using field data from full-scale tests on a single bench. The original model, based on RocFall2 simulations and using six-inch synthetic concrete blocks, was calibrated to match observed behaviour. It achieved 90% rock retention within 10.9 m from the bench toe. When the Modified Ritchie Criterion was applied, the resulting 9.4 m bench width produced approximately 80% retention at the first bench, with full containment achieved by the sixth.

In this second phase, the calibrated model was used to evaluate the effectiveness of integrating energy-absorbing barriers with reduced-width catch benches. A total of 24 two-dimensional simulations were conducted, combining four bench widths, three barrier setback distances, and two barrier heights. Each simulation recorded the percentage of rocks retained before reaching the barrier, intercepted by the barrier, and those that passed beyond the system.

The results show that optimised barrier configurations can compensate for reduced bench width. In several scenarios with bench widths as narrow as 5.2 m, near-complete rockfall containment was achieved. Barriers placed closer to the bench crest and constructed at greater heights consistently improved performance. The best-performing setups retained over 99% of rocks through a combination of effective bench designs and barrier placements.

In addition to improving safety, the use of barriers provides increased flexibility in pit design. By enabling steeper slopes and narrower benches without compromising rockfall control, barrier systems allow deeper ore recovery and improved overall pit economics. This study offers quantitative evidence supporting the application of barriers as an efficient and practical solution for rockfall mitigation in open pit mines.

Keywords: *rockfall, barriers, catch benches, retention performance, modelling simulation*

1 Introduction

Rockfall remains one of the most critical geotechnical hazards in open pit mining, capable of causing severe damage to infrastructure, equipment, and most importantly, endangering human lives. These hazards are particularly challenging in highwall operations, where rocks may be detached due to blasting, scaling, or natural weathering processes (Bar et al. 2016; Marchelli et al. 2023). Mitigating rockfall risk is thus a fundamental requirement for ensuring operational safety and efficiency in surface mining.

Traditionally, rockfall control in open pits has relied heavily on the implementation of catch benches designed using empirical criteria such as the Modified Ritchie Criterion (MRC) (Warren et al. 2024). This guideline relates bench height to minimum bench width to achieve a benchmark 90% rockfall retention rate on the

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first bench. However, research by Warren et al. (2024) and Bourgeois et al. (2023) has shown that these empirical methods may not fully capture the variability in rockfall behaviour under different site conditions. Site-specific factors such as slope angle, rock mass properties, and block geometry significantly influence retention efficiency, warranting more detailed analysis and potentially updated design practices.

Numerical modelling has emerged as an essential tool for analysing rockfall dynamics and evaluating slope performance. Two-dimensional rigid body models are capable of estimating rockfall trajectories, kinetic energies, and runout distances by incorporating simplified impact mechanics, providing valuable insights for slope design and hazard assessment (Bar et al. 2016). These models can be calibrated with real-world test data to enhance their predictive accuracy. Field testing conducted by the National Institute for Occupational Safety and Health (NIOSH) as part of their *Highwall Safety: Rockfall Catchment Design and Slope Performance Monitoring* (Highwall Safety Project) at the Bald Mountain Mine represents a notable example, where field-calibrated simulations closely matched observed retention behaviour for synthetic 0.15 m (≈ 6 in) blocks, leading to validated guidance on bench performance under realistic mining conditions (Warren et al. 2024).

While conventional catch benches provide a first line of defence, they are often insufficient in geometrically constrained conditions. As mining operations strive for steeper inter-ramp angles to improve ore recovery, catch benches may need to be reduced in width, potentially compromising rockfall retention. In response to this trade-off, attention has turned to the integration of engineered mitigation systems such as flexible barriers. These systems, commonly used in civil infrastructure, include energy-absorbing devices designed to intercept rocks that exceed bench capacity (Buzzi et al. 2013; Castanon-Jano et al. 2017). Their modular design and minimal footprint make them suitable for being installed onto existing bench configurations.

Studies on barrier performance have demonstrated their effectiveness even during high-speed impacts and spinning rock trajectories, which are common in steep pit walls (Fonseca et al. 2024). Energy dissipation devices within flexible barriers enable high energy absorption with minimal structural damage, offering a dependable solution for both low and medium-energy rockfall events. These systems are increasingly being adopted in mining operations, supported by field testing and full-scale deployment data. This integrated approach aligns with modern trends in mining geomechanics, where data-driven modelling and engineered solutions are becoming vital components of design practice (Macciotta et al. 2020; Meyer Nagera 2022).

This study aims to evaluate the effectiveness of incorporating flexible energy-absorbing barriers into catch bench designs while considering different width constraints. The primary objective is to identify barrier configurations that enhance rockfall retention and assess their potential to support steeper pit slopes without compromising safety.

2 Background

In previous research, Restrepo et al. (2025) conducted a rockfall calibration process using experimental field data reported by Warren et al. (2024). The data were collected as part of a collaborative project between NIOSH and industry professionals, titled Highwall Safety Project, which in part seeks to update bench width design guidelines. The experimental campaign involved the controlled release of synthetic rocks from various single-bench configurations to evaluate the influence of geometric and material parameters on runout distances.

Restrepo et al. (2025) selected a 24.4 m high single bench for calibration and modelled the slope in RocFall2 (Rocscience Inc 2024). The bench was configured with a cleaned toe and composed of limestone, consistent with the field test conditions. The simulated rocks were fabricated from high-strength, fibre-reinforced concrete with a density of 2,483 kg/m^3 and an individual mass of 9.6 kg. In two-dimensional modelling, the blocks were represented as polygonal octagons approximating the cross-section of a rhombicuboctahedron with a nominal diameter of 0.15 m. The calibration process began by reconstructing the slope geometry and assigning material parameters to the bench face and catch bench. The normal and tangential restitution coefficients, which govern the energy loss during rock–surface interactions, were iteratively adjusted to reproduce the experimental results summarised in Table 1, which presents the normal restitution values, and

Table 2, which outlines the corresponding tangential restitution values. The calibration was successful when 90% of the simulated blocks were retained within a runout distance of 10.9 m from the bench toe. Figure 1 shows the simulation for the calibration process, where the grey area represents bench face, and the green area represents the catch bench.

Table 1 Bench face parameters

Parameter	Mean	Standard deviation
Normal restitution coefficient	0.40	0.04
Tangential restitution coefficient	0.84	0.03
Dynamic friction	0.52	0.13
Rolling friction	0.15	0.05

Table 2 Catch bench parameters

Parameter	Mean	Standard deviation
Normal restitution coefficient	0.30	0.028
Tangential restitution coefficient	0.79	0.04
Dynamic friction	0.60	0.13
Rolling friction	0.33	0.05

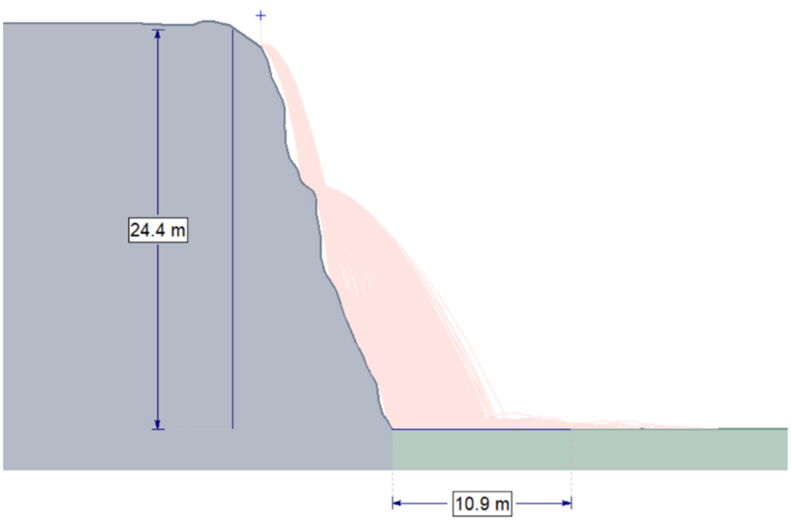

Figure 1 Rockfall model calibration (Restrepo et al. 2025)

Although achieving 90% rock retention on the first catch bench is widely recognised as an industry standard for safe slope design, this benchmark is not always attainable under economic and geometric constraints in active mining operations. To evaluate how typical design practices compare with the calibrated reference case, the bench width was modified to match the MRC, a commonly used empirical formula that defines the catch bench width as a function of slope height.

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

where:

W = catch bench width (m)

H = bench height (m).

For the 24.4 m high slope modelled in this study, the MRC yields a width of 9.4 m. When applied to the calibrated model, this reduced width resulted in approximately 80% of the blocks being retained on the first bench, falling short of the industry target. This outcome is consistent with field observations in many open pit mines, where benches designed strictly according to the MRC often exhibit diminished retention performance (Meyer Nagera 2022).

In response to these limitations, the current study explores the potential of incorporating low-profile energy-absorbing barriers, such as wire-rope fences, into catch bench designs. These systems are widely used in civil infrastructure applications for their ability to intercept and absorb the energy of falling rocks without requiring significant geometric expansion(Federal Highway Administration, Central Federal Lands Highway Division 2011). Building on the validated calibration framework developed in Restrepo et al. (2025), this study simulates the effects of catch bench width reduction, barrier height and barrier location on rock retention efficiency and energy distribution. By isolating these variables while maintaining the same slope geometry and block properties, the analysis aims to quantify the incremental benefits of barrier integration and establish a preliminary framework for exploring practical design guidelines to improve slope performance under constrained conditions.

3 Methodology

This study employs two-dimensional rockfall simulations in RocFall2 (Rocscience Inc 2024) to assess the effect of catch bench width reduction and the integration of flexible barriers on rock retention efficiency. The aim is to evaluate the extent to what energy-absorbing systems, such as flexible rockfall barriers, can compensate for reductions in catch bench width while maintaining the required level of block retention and effective rockfall control.

3.1 Slope geometry and catch bench configurations

A single-bench slope profile, taken from one of the NIOSH single-bench tests, was used for all simulations, with a height of 24.4 m and an inclination of 70˚, consistent with the geometry used in the calibration study by Restrepo et al. (2025). The initial catch bench width was determined using the MRC, which yielded a width of 9.4 m. From this baseline, three additional configurations were created by reducing the catch bench width by 15, 30, and 45%, resulting in a total of 4 geometric scenarios, as illustrated in Figure 2.

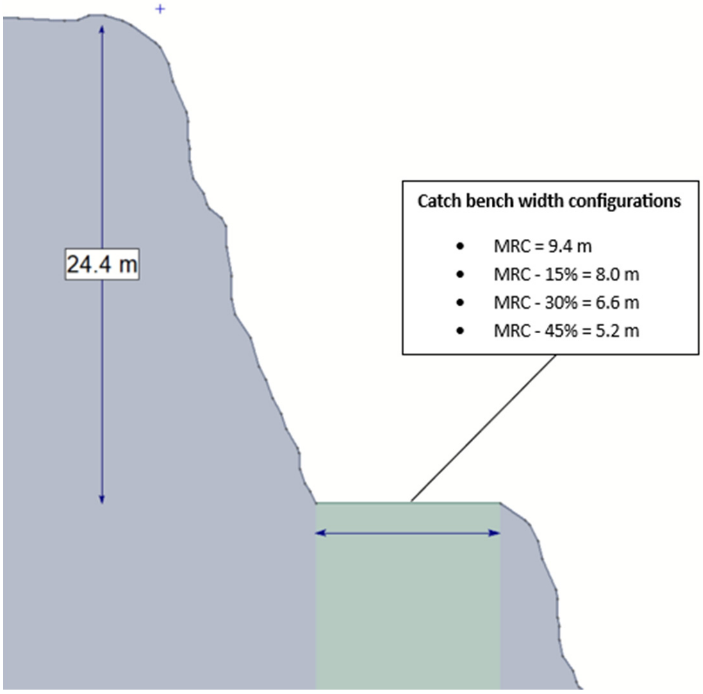

Figure 2 Catch bench width configurations evaluated for rockfall simulations

3.2 Barrier properties and placement

For each bench width scenario, simulations were conducted with two barrier heights, specifically 2.0 and 2.5 m. Barriers were modelled using the predefined GBE-100A-R system from the RocFall2 internal barrier library. This system, developed by Geobrugg and certified by the European Organisation for Technical Approvals (EOTA), has a tested capacity of 106 kJ, a residual height of 78%, and an elongation capacity of 2.45 m (Geobrugg 2024). In all simulations, barriers were installed vertically at an angle of 90˚ relative to the catch bench surface and modelled as active energy-absorbing elements.

Three barrier locations were examined in the simulations. The first barrier was placed 1 m behind the catch bench crest, the second was placed 2 m behind the crest, and the third was located 3 m behind the crest. At each location, 2 barriers were positioned adjacent to one another, one with a height of 2.0 m and one with a height of 2.5 m, resulting in 6 barriers per simulation, as shown in Figure 3. This configuration was consistently applied across all catch bench width cases. A total of 24 simulations were conducted, resulting from the combination of 4 catch bench widths, 3 barrier locations, and 2 barrier heights.

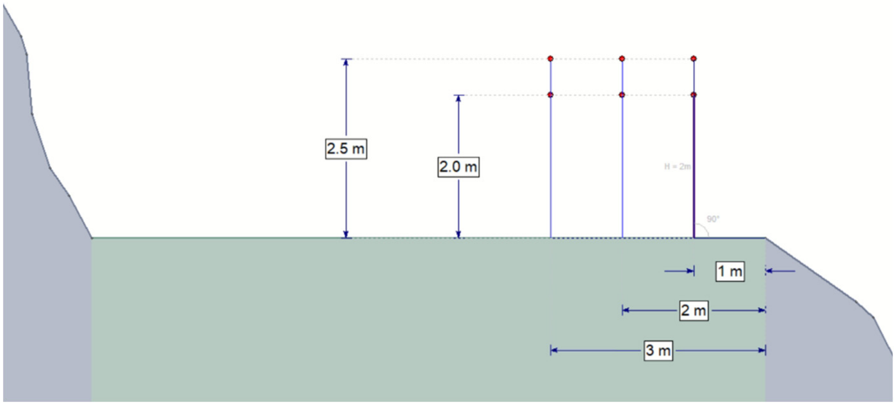

Figure 3 Barrier height and placement configurations evaluated in simulation

Four outcome variables were measured in each scenario. These included the percentage of rocks retained before reaching the barrier, rocks that impacted the barrier, rocks that were retained in the catch bench, and the percentage that passed beyond it.

4 Results and implications

Figures 4 to 7 present the rockfall simulation results for 5.2, 6.6, 8.0, and 9.4 m catch bench widths. Each figure contains six panels, representing all combinations of barrier height and location. The pink trajectories illustrate the path of falling rocks, while the active barrier configuration is highlighted in bold purple.

The overall trend observed across the 4 configurations shows that wider catch benches lead to increased rock retention on the bench surface. At the maximum width of 9.4 m, most blocks are intercepted before reaching the barrier, with minimal interaction beyond the bench edge. As the width decreases to 8.0 and 6.6 m, the number of trajectories that bypass the catch bench increases noticeably, resulting in greater reliance on barrier systems for containment. In the narrowest configuration, with a bench width of 5.2 m, very few rocks are retained directly on the bench. In these cases, the barrier becomes the primary line of defence, as shown by the concentration of impact points on the structure.

The figures also reveal that placing the barrier closer to the crest tends to reduce the runout distance of blocks and improve overall containment. This effect is especially apparent in narrower configurations, where barriers installed near the slope crest are more likely to intercept trajectories before the rocks reach higher energy states. Taller barriers also perform better in scenarios with limited bench width, as they are more likely to intercept rocks that are not stopped by the catch bench. Despite the reduced width, some configurations in the 5.2 and 6.6 m scenarios still achieve near-complete containment, indicating that optimised barrier placement and sizing can compensate for geometric constraints.

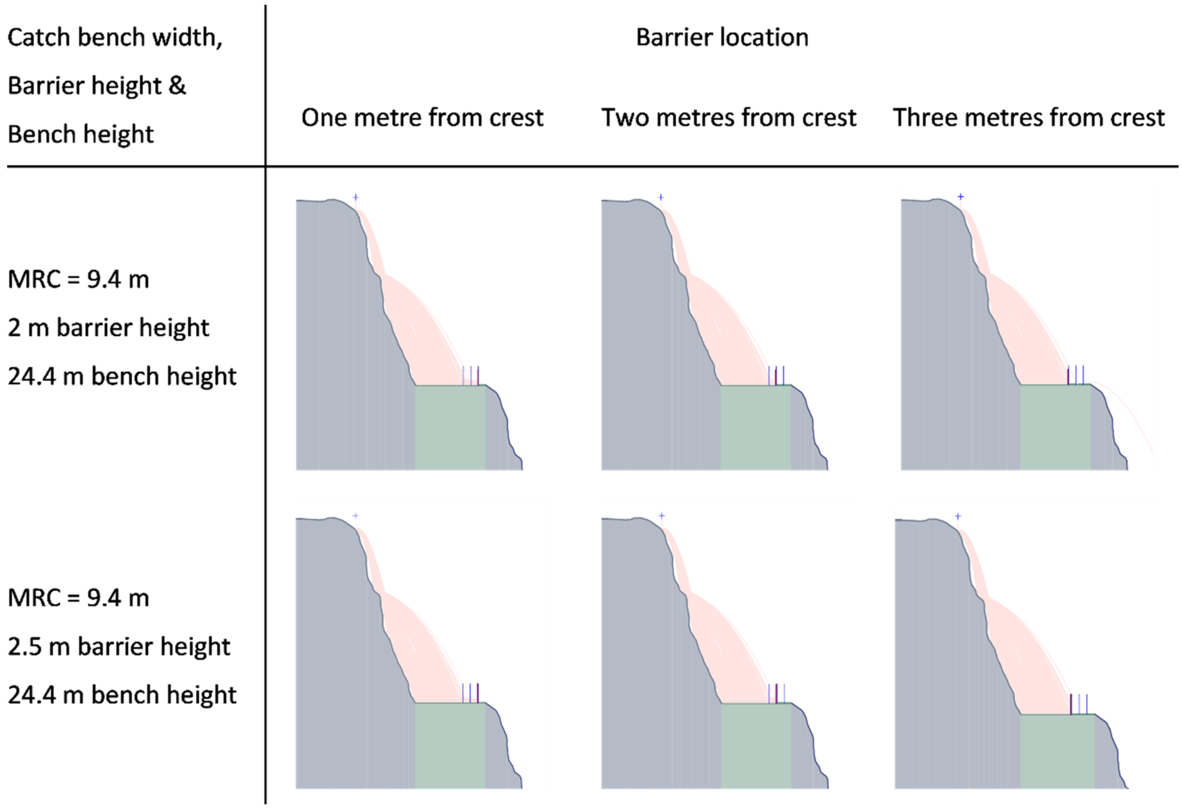

Figure 4 **Results from simulation using 9.4 m catch bench width**

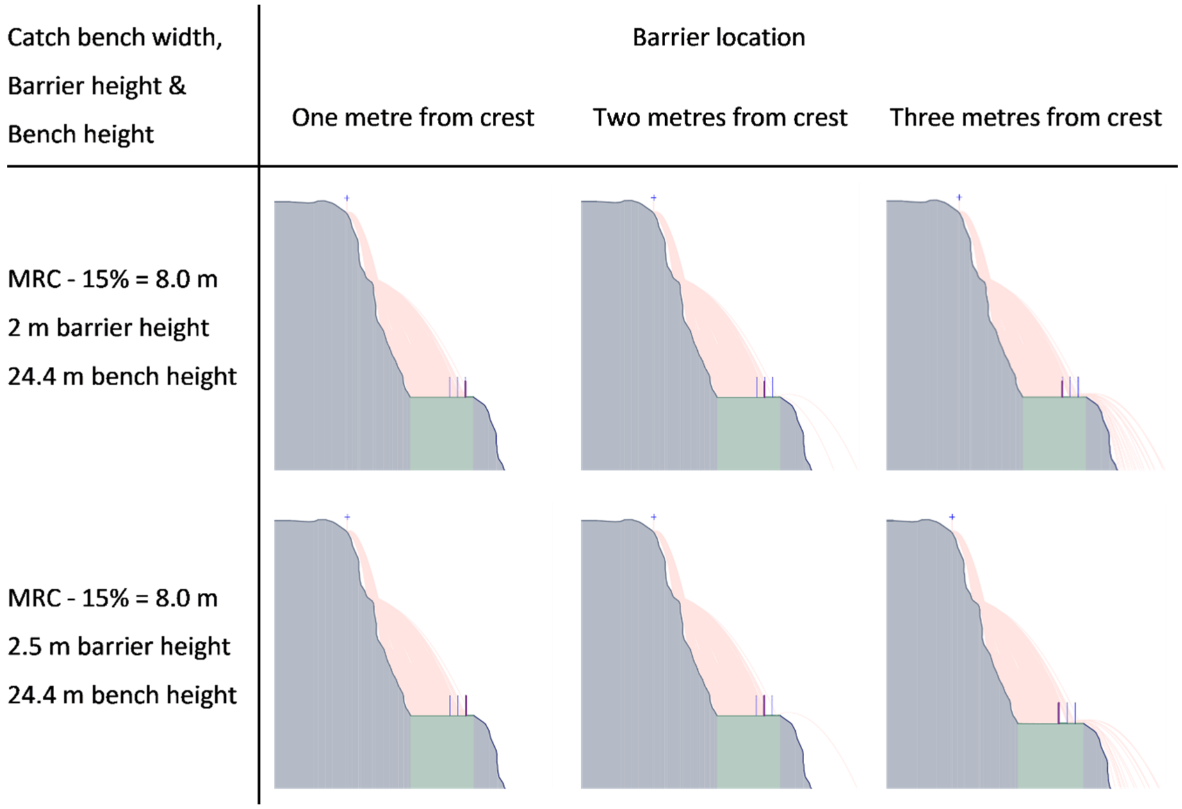

Figure 5 **Results from simulation using 8 m catch bench width**

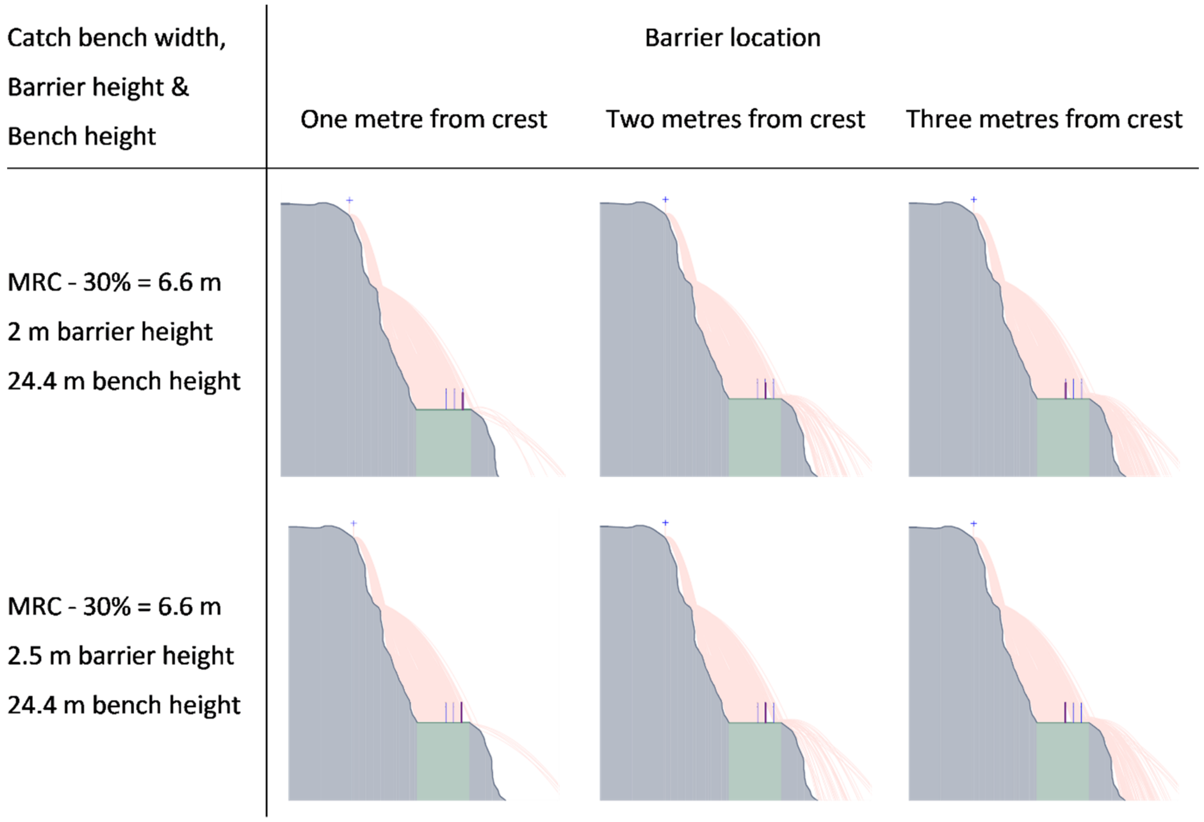

Figure 6 Results from simulation using 6.6 m catch bench width

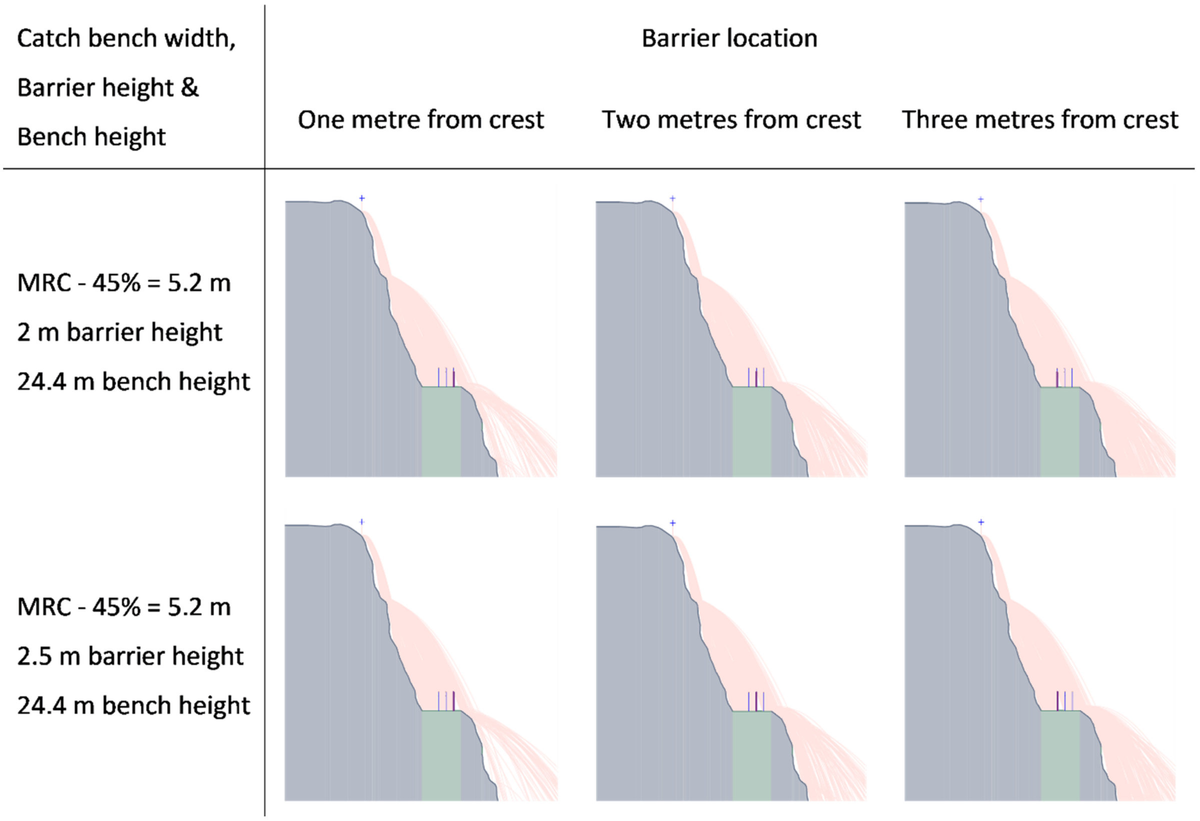

Figure 7 Results from simulation using 5.2 m catch bench width

Table 3 presents the rockfall retention results for all 24 simulation scenarios. These include 4 catch bench widths, 3 barrier locations, and 2 barrier heights. The results show a consistent trend in which wider catch benches retain a larger percentage of rocks before they reach the barrier. In the 9.4 m bench configurations, more than 46% of the rocks are retained directly on the bench, and up to 70% are retained in the most favourable configuration. All 6 scenarios with the 9.4 m bench achieved 100% total retention when combining the effects of the bench and the barrier.

Table 3 Summary of rockfall retention results across all catch bench widths and barrier configurations

Catch bench width (m)	Distance from crest (m)	Barrier height (m)	Retained before barrier (%)	Hit barrier (%)	Retained in catch bench (%)	Passed barrier (%)
9.4	3	2	46.9	53	99.9	0.1
9.4	3	2.5	46.9	53.1	100	0
9.4	2	2	60.2	39.8	100	0
9.4	2	2.5	60.2	39.8	100	0
9.4	1	2	70.5	29.5	100	0
9.4	1	2.5	70.5	29.5	100	0
8	3	2	26.1	71.2	97.3	2.7
8	3	2.5	26.1	72.1	98.2	1.8
8	2	2	40	59.8	99.8	0.2
8	2	2.5	40	59.9	99.9	0.1
8	1	2	53.4	46.6	100	0
8	1	2.5	53.4	46.6	100	0
6.6	3	2	13.2	68.8	82	18
6.6	3	2.5	13.2	72.3	85.5	14.5
6.6	2	2	22.2	72.6	94.8	5.2
6.6	2	2.5	22.2	74.1	96.3	3.7
6.6	1	2	36.4	62.8	99.2	0.8
6.6	1	2.5	36.4	63.1	99.5	0.5
5.2	3	2	3.8	50.8	54.6	45.4
5.2	3	2.5	3.9	57.8	61.7	38.3
5.2	2	2	10.2	64.1	74.3	25.7
5.2	2	2.5	10.2	68.1	78.3	21.6
5.2	1	2	18.5	71.7	90.2	9.8
5.2	1	2.5	18.5	74.4	92.9	7.1

As the bench width decreases, the number of rocks retained before the barrier drops, and the barrier plays a more significant role in overall retention. With an 8.0 m bench, pre-barrier retention ranges from 26 to 53%, depending on barrier placement and height. All scenarios in this group still achieved 98% or greater total retention, confirming the barrier's effectiveness.

In the 6.6 m bench configuration, retention before the barrier drops further, with values ranging from 13 to 36%. However, several configurations still reached over 99% total containment, especially when the barrier was placed closer to the crest and had a height of 2.5 m.

The most constrained case, using a 5.2 m wide catch bench, shows the lowest levels of retention before the barrier. In these scenarios, less than 20% of rocks are retained on the bench, and up to 45% pass beyond the final barrier in the least favourable configuration. However, improvements in barrier height and placement still led to nearly 93% retention in the best case for this group, demonstrating that properly placed barriers can significantly improve containment even when bench space is limited. As stated by Warren et al. (2024), a 90% rockfall retention rate on the first bench is commonly accepted as an acceptable Factor of Safety in open pits. Therefore, the 93% retention achieved in the most effective 5.2 m scenario meets this general industry standard and may be considered operationally acceptable

These results confirm that both bench geometry and barrier design play critical roles in rockfall retention. Wider benches are more effective at intercepting rocks early, while well-positioned and taller barriers are essential in compensating for narrower catch bench widths.

Although the catch bench widths were reduced, several configurations within the 5.2 and 6.6 m scenarios still achieved near-complete rockfall containment. This outcome demonstrates that effective barrier design can offset the decline in natural retention capacity associated with narrow benches. Specifically, placing barriers closer to the bench crest and increasing their height improved interception rates, even when the bench alone was unable to retain the majority of falling rocks. Based on all simulation results, the utilisation of proper engineering, such as barrier systems, can serve as a viable alternative to bench widening in space-constrained conditions. This has significant implications for operational pit design, particularly in environments where widening benches is not feasible due to ore recovery priorities. Moreover, the strategic use of barriers may allow mine operators to design steeper inter-ramp angles, enabling deeper economic access to ore zones near the base of the pit without compromising safety.

Although this study assumes idealised barrier performance without accounting for post-impact deformation, real-world systems often experience considerable deflection that must be incorporated into spatial design. Buzzi et al. (2013) reported that low-energy flexible barriers subjected to 35 kJ impacts showed measurable deflections, which varied depending on system stiffness and configuration, with modifications such as the removal of intermediate cables increasing deflection by approximately 20 cm. Similarly, Castanon-Jano et al. (2017) emphasised that the energy dissipating components in barrier systems significantly influence dynamic elongation and deflection behaviour, particularly under low to moderate energy levels. These findings underscore the importance of accounting for barrier deflection distances when designing for constrained bench widths to ensure effective interception performance.

While this study provides valuable insights into the potential of barrier systems to improve rockfall retention in narrow catch benches, several limitations must be acknowledged. The use of two-dimensional modelling simplifies the complex three-dimensional nature of rockfall trajectories, potentially under-representing lateral dispersion and rotational dynamics. Additionally, the simulations were based on a uniform block size and shape, which may not fully capture the variability in real-world rockfall events. The representation of barriers was also idealised, assuming consistent energy absorption performance without accounting for potential structural damage, anchoring effects, or installation constraints. These simplifications highlight the need for future work using three-dimensional modelling, diverse block geometries, and more realistic barrier mechanics to validate and extend these findings.

5 Conclusion

This study evaluated the influence of barrier integration on rockfall retention performance in catch benches of varying widths using a field-calibrated RocFall2 model. A total of 24 simulation scenarios were assessed, combining four catch bench widths with varying barrier heights and setback distances. The results confirmed that wider benches provide higher pre-barrier retention, while narrower benches increasingly rely on barriers for effective containment. However, even in highly constrained configurations, several barrier setups achieved near-complete retention, demonstrating the potential for barriers to offset geometric limitations.

Barriers placed closer to the bench crest and configured at greater heights consistently outperformed other setups, particularly in narrow bench cases. The best-performing configurations were able to retain over 99% of falling blocks, either directly on the bench or through barrier interception. These findings emphasise that barrier design parameters, including height and placement, are critical to achieving effective rockfall control, especially when widening the catch bench is not feasible.

Beyond improving containment, barrier systems offer operational flexibility by enabling steeper slope angles and narrower catch benches. This design flexibility has important implications for open pit mining operations, allowing for deeper ore access and improved overall pit economics without compromising safety. The outcomes of this study provide data-driven support for the strategic use of barriers as an effective rockfall mitigation measure in modern slope design. Future research could expand on these findings through three-dimensional rockfall simulations to capture complex terrain effects and barrier interactions, as well as controlled field experiments to empirically validate model predictions and refine barrier performance guidelines.

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