Slope Stability 2020 - PM Dight (ed.)

doi:10.36487/ACG_repo/2025_78

Analysis of the effect of back-break on rockfall trajectories

I García *SRK Consulting (UK) Limited, UK*

S Pastine *SRK Consulting (Argentina) S.A., Argentina*

Abstract

An effective bench design must arrest and mitigate the danger of rockfalls and contain ravelling from the benches above. Rockfall analyses based on 3D rigid body dynamics can be useful to assess the adequacy of a bench design in terms of risk of impact, as long as the slope geometry and the coefficients of restitution are estimated with enough accuracy.

This paper presents a study of the effect of back-break on the rockfall hazard at the bench stack toe. Back-break distributions are taken from measurements carried out at a mine in South America and then applied to the design bench geometry, whereby crests are displaced into the slope. This provides a more realistic slope surface for rockfall calculations. This work builds on Pastine et al. (2018) by incorporating the relationship between the mass of the falling rocks and the coefficient of restitution, as indicated in (Basson et al. 2013).

Keywords: *catch bench, rockfall analyses, back-break, coefficient of restitution*

1 Introduction

The main function of the catch bench is to provide a safe environment for personnel and equipment working near the slope free face. Berms must be wide enough to stop the fall of potentially unstable rocks, retain spillage from the upper benches and ensure long-term access for displacements and groundwater monitoring.

Generally, the berm width is designed to retain 70–85% of the potential failed material. Back-break plays a key role in catch bench performance as the effective berm width is reduced with respect to the design geometry (Read & Stacey 2009).

Rockfall hazard in open pit mines can be assessed by measuring the berm width in a region and quantifying what percentage achieves a minimum width specified as a cutoff criterion. This region can be defined from the structural model and stability assessment at bench scale. An example of minimum acceptable width is given by the modified Ritchie criterion (Ryan & Pryor 2000):

$$B = 0.2H + 4.5 \text{ m} \tag{1}$$

where:

B = berm width.

H = bench height.

The reliability of the bench system is defined as the percentage of berms with widths greater than or equal to (1).

2 Performance in terms of retention effectiveness

Defining a minimum berm width and assessing whether it is being achieved is important but ultimately, the bench system must be effective in mitigating the hazard of rockfalls. Hence, a rockfall activity/hazard map, for instance, that considers both the catch bench as-built surface (and so its retention capacity) and the equipment and personnel exposed at the toe, can be very valuable to evaluate the performance of the bench system and to plan palliative measures.

Risk mitigation may include passive measures (e.g. minimum working distances), active measures (e.g. barriers, nets and fences) or a re-design of the catch bench system. Rockfall analyses allow measuring the performance of mitigation measures and provide valuable information on the mechanics of falling rocks (Read & Stacey 2009).

Calibration of rockfall models—which boils down to establishing the restitution parameters—is essential for obtaining realistic results and for that detailed information about rockfall events must be gathered. It is also essential that the geometry used in the analyses is as close as possible to the as-built geometry; in open pit mines, this is generally the design geometry affected by back-break (Figure 1).

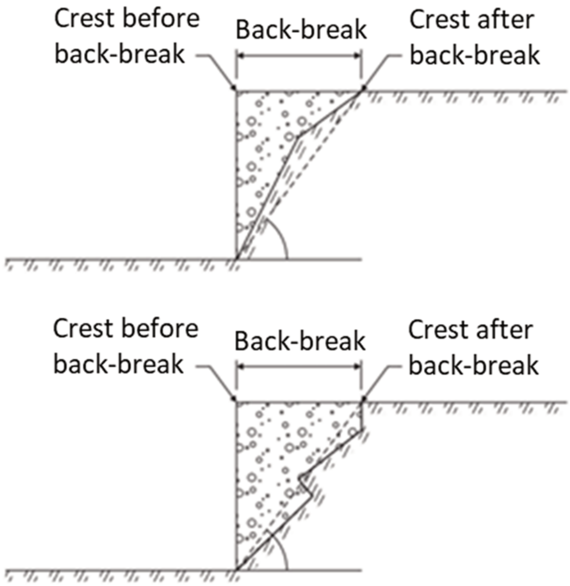


Figure 1 Back-break and effective bench face angle (Read & Stacey 2009; Ryan & Pryor 2000)

The back-break and effective bench face angle can be estimated primarily by wedge formation analyses (Langford et al. 2014). However, due to the multiple factors that affect the berm width reduction (e.g. orientation, spacing, strength and roughness of discontinuities, rock mass performance, blasting technique, environmental factors, life-of-mine, etc.), wedge formation analyses must ultimately be validated with in situ measurements. Periodic inspections and reports of failures are valuable to this end. If differences are substantial, a correction must be carried out on those parameters that most affect bench geometry.

3 Back-break incorporation to a design geometry

A mine in South America intended to implement double benches in order to reduce operational costs. In addition, they focussed on improving drilling techniques in order to achieve the required bench profile and to reduce rockfall hazards. They mined several test benches to assess the effectiveness of pre-split drilling and the quality of the double benching that could be achieved.

The mine retained SRK to assess the effectiveness of improved drilling techniques and to evaluate the impact of moving from single to double benches on rockfall hazard.

3.1 Site data

Improved drilling with pre-split blasting yielded benches of different quality. This quality was, for the purpose of assessing rockfall hazard, characterised through berm loss. For this, several profiles of the test benches were taken and the back-break and back-break angle were measured. Sectors with varying blast configurations and slightly different geotechnical characteristics yielded correspondingly different mean back-break distances. Three main bench qualities were identified (cases 1–3), of which back-break histograms are shown in Figures 2, 3, and 4.

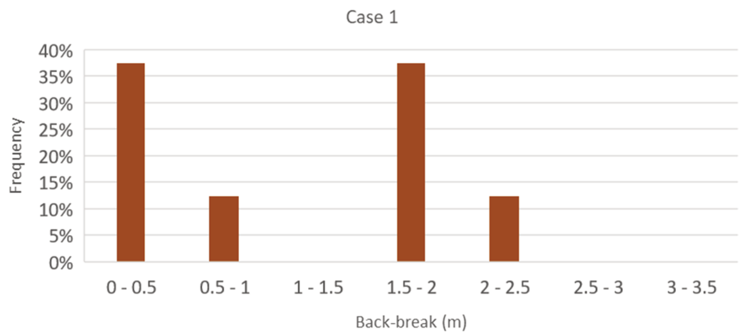


Figure 2 Case 1: measured back-break histogram

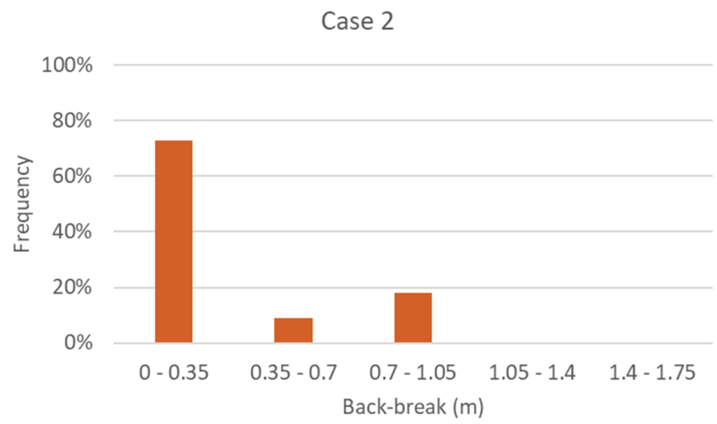


Figure 3 Case 2: measured back-break histogram

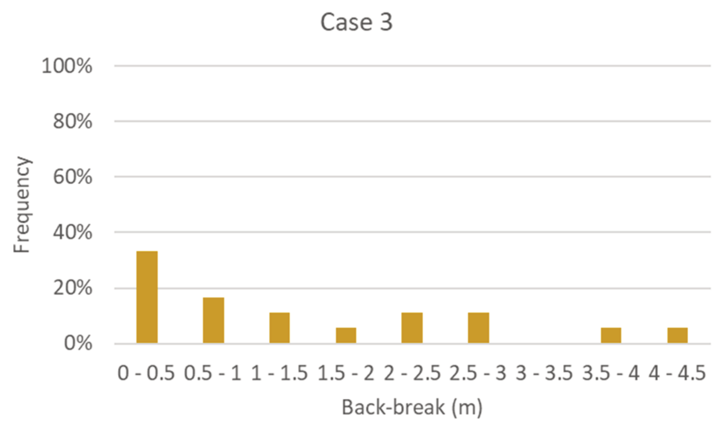


Figure 4 Case 3: measured back-break histogram

Exponential distributions were then fitted to the cumulative distribution functions (CDF) arising from the histograms (Figure 5). These were then used to sample back-breaks in the simulations. The sample sizes and exponential distribution mean (μ) for each case are presented in Table 1.

Table 1 Input parameters for single and double benches

Case	Sample size	μ (m)
1	8	0.75
2	12	0.38
3	18	1.5

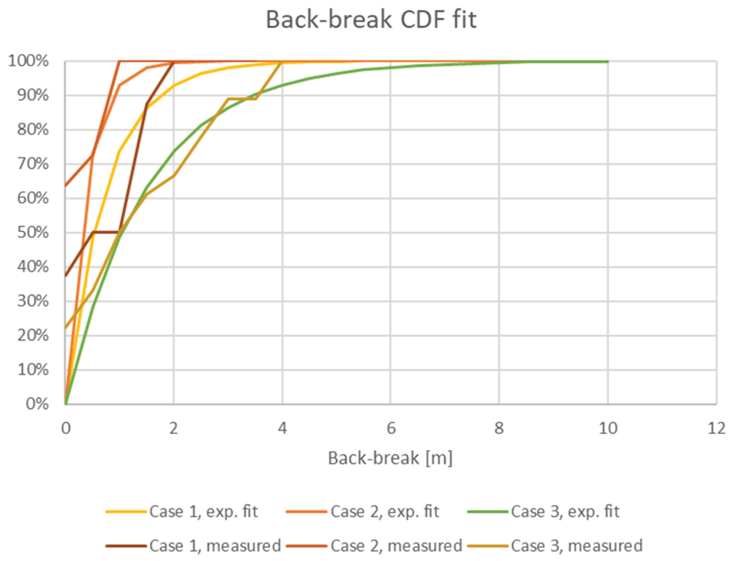


Figure 5 Exponential fitting of back-break histograms

For the rockfall hazard assessment to be of real value, it should incorporate the berm loss that can be expected for the three main cases presented above. Thus, a method to modify a design geometry by incorporating back-break was developed and is presented.

Back-breaks are sampled from the fitted CDFs shown above and then the failed volume is estimated via the back-break angle. The latter was taken from test bench profiles and then modelled as a normally distributed random variable (Table 2). Figure 6 shows a typical cross-section with the design geometry, the failed volume, back-break and back-break angle.

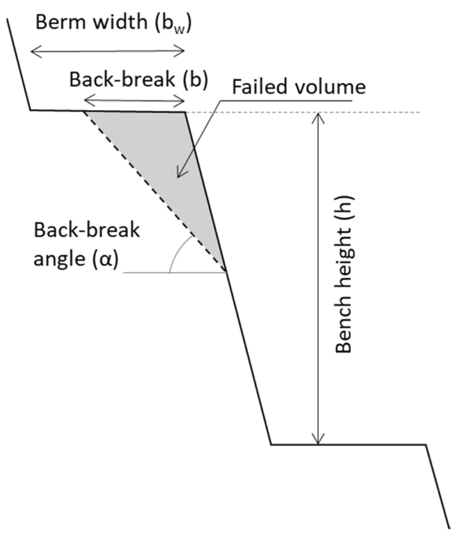
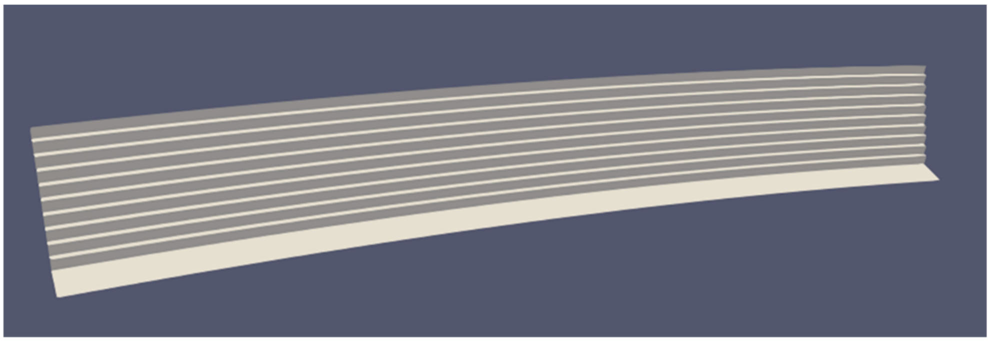


Figure 6 Input data and methodology applied

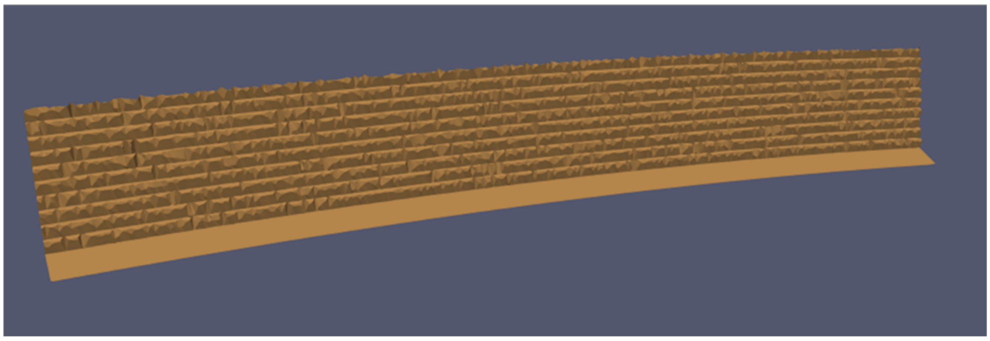
3.2 Back-break incorporation

The analysis described herein entails determining the influence of back-break on rockfall hazard for single (15 m) and double benches (30 m). Simulations were carried out for the three mean back-break cases presented earlier, and in each case, the percent of rocks that reached the toe of the slope and their final distance were measured.

The bench stacks had a total height of 150 m and an inter-ramp angle of 55°, with 10 single benches and five double benches, respectively. The design geometry and an example of modified geometry for single and double benches are presented in Figures 7 and 8, respectively. Input parameters for each geometry are summarised in Table 2.

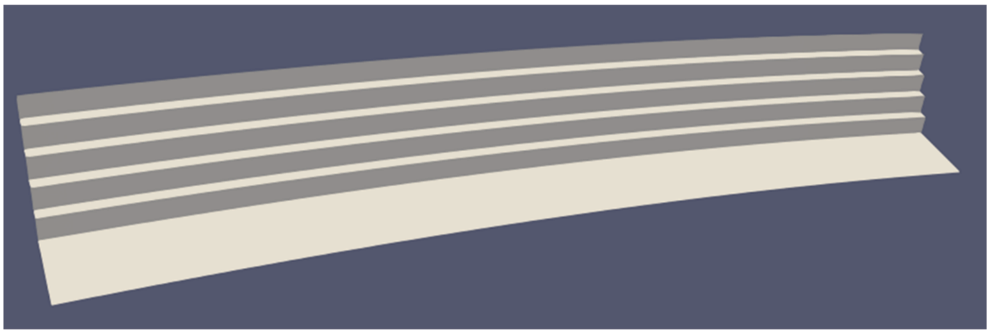


(a)

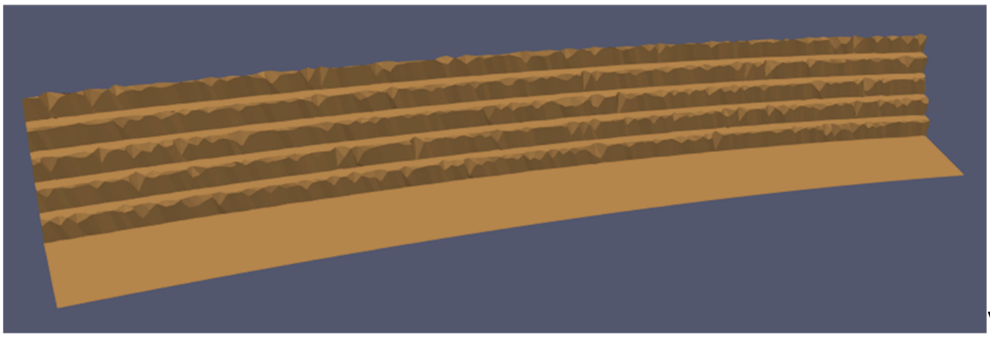


(b)

Figure 7 Single benches: (a) Design model; (b) As-built model



(a)



(b)

Figure 8 Double benches: (a) Design model; (b) As-built model

Table 2 Input parameters for single and double benches

Geometry	Single benches	Double benches
Length (m)	1,500	1,500
Bench height (m)	15	30
Bench face angle (°)	75	75
Berm width (m)	7	16
Number of benches	10	5
Backbreak angle, mean (°)	50	50
Back-break angle, standard deviation (°)	8	8

4 Rockfall analyses

Rockfall analyses with the simulated topography were performed using the software RFall_3D (Gibson 2018), which allows simulation of the behaviour of a falling rock impacting a 3D topography model. A 3D software was used because, in a later stage, the same method is intended to be used on more involved (curved) pit topographies. 3D models are adequate to model such cases because they ensure that rocks fall along the steepest pathway and consider the additional loss of energy due to impacts in gully walls (Mears 2017).

Gravity, density, mass and moment of inertia are the inputs for RFall_3D analyses. The first two take fixed (deterministic) values for all simulations. Mass and moment of inertia can be simulated as deterministic or stochastic (characterised by their mean value and standard deviation). As the latter depends on the geometry of the rock, RFall_3D allows entry of the ratio of moments along the principal axes of the rocks. The moments of inertia on three axes are then calculated based on this and on the mass and density of the rock.

Rocks were dropped from all the bench crests, except the bottom-most, at a rate of one rock every 2 m for single benches and one rock per metre for double benches.

4.1 Input parameters

Coefficients of restitution (COR) and mass distributions of falling rocks were adopted from a mine in South America. Due to the limited working area and operational constraints, it was not possible to carry out onsite back analyses. Therefore, the CORs had to be adopted from reference values according to the rock type and surface characteristics (Rocscience 2019).

To account for the fact that larger rocks tend to break (i.e. lose energy) more than smaller rocks—and given that the available software cannot directly capture this behaviour—a relationship between the mass of the falling rocks and the COR was adopted in accordance with Basson et al. (2013), whereby the COR decreases linearly with rock weight. Table 3 summarises the range of masses, mean values, standard deviations, rocks per unit length and normal (k_n) and tangential (k_t) COR. Pictures of fallen rocks were all the information available to define their shape, which showed that they were mostly similar in all dimensions. In absence of more data and as a conservative approach (Romer et al. 2015), rocks were modelled as spheres.

Figure 9 presents an output for the single bench geometry; rock trajectories are coloured according to their velocity.

Table 3 Mass of falling rocks, rocks per unit length and coefficients of restitution

Mass of falling rocks				Single benches	Double benches	Coefficient of restitution	
From	To	Mean	Standard deviation	Rock per unit length	Rock per unit length	k_n	k_t
0	820	410	4.1	0.25	0.5	0.43	0.91
820	1,640	1,230	12.3	0.125	0.25	0.33	0.71
1,640	2,460	2,050	20.5	0.05	0.1	0.24	0.50
2,460	3,280	2,870	28.7	0.05	0.1	0.14	0.30
3,280	4,100	3,690	36.9	0.025	0.05	0.04	0.09

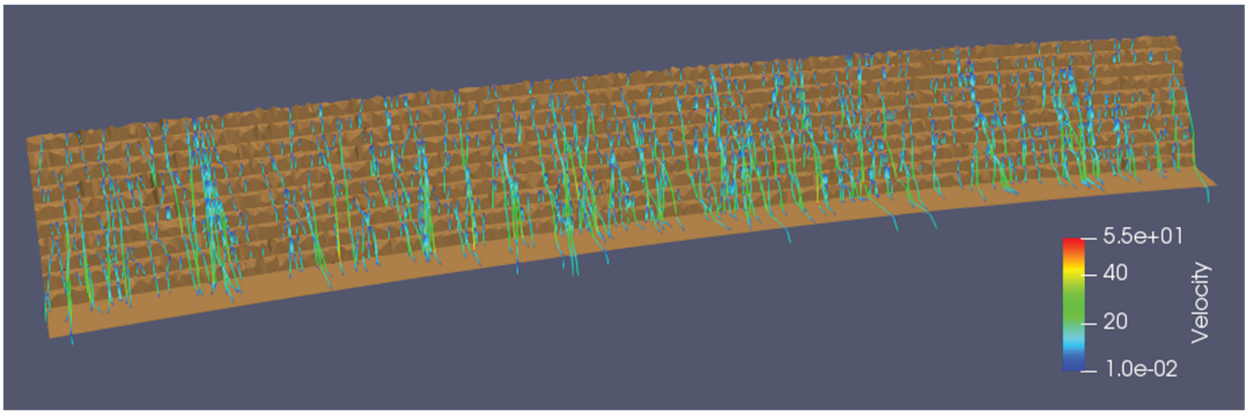


Figure 9 Example of rock trajectories in a single bench geometry

4.2 Results

In what follows, results are shown in terms of berm loss to compare rockfall catchment (bench performance) between the single and double bench. Figure 10 shows the number of rocks that reach the bottom of the bench stack as a percent of the total amount of rocks simulated. As expected, it increases with back-break. Double benches perform slightly better than single benches, arguably due to wider berms.

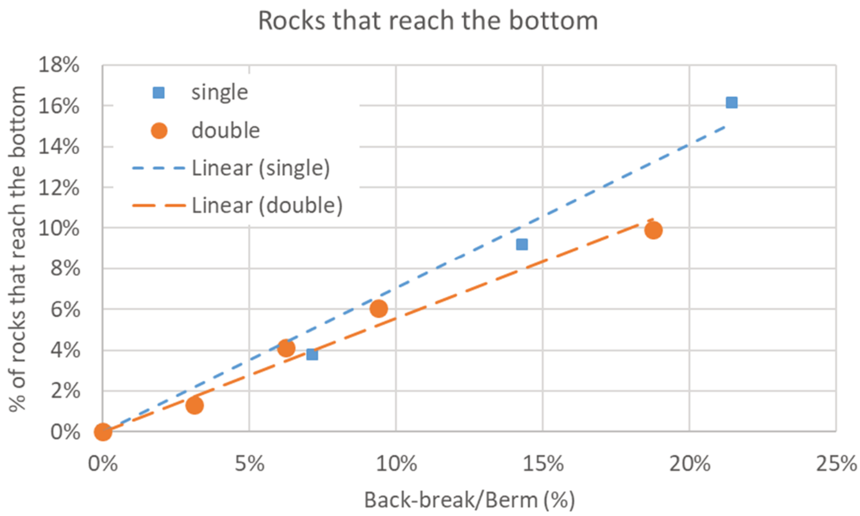


Figure 10 Percent of rocks that reach the bottom of the bench stack

Figure 11 shows the number of rocks with runout exceeding one berm width at the bottom of the wall (i.e. 16 m for double and 7 m for single benches) as a percent of the total number of rocks simulated. The aim of this is to quantify the risk for personnel and equipment that perform drilling for the next bench. Even more than in Figure 10, double benches perform better than single benches, especially with higher berm loss where the risk is doubled with single benches, i.e. for high berm loss, there are double the amount of rocks that go beyond 7 m (single benches) than the rocks that go beyond 16 m (double benches).

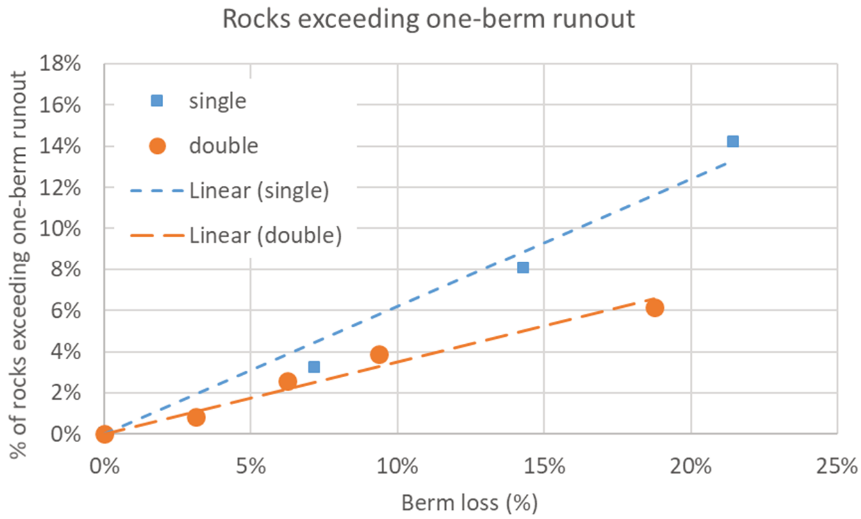


Figure 11 Percent rocks with runout exceeding one berm width (7 m for single benches, 16 m for double benches)

As Figure 12 shows, however, that absolute runout for double and single benches are similar. In other words, the risk of impact for a given standoff distance is almost the same.

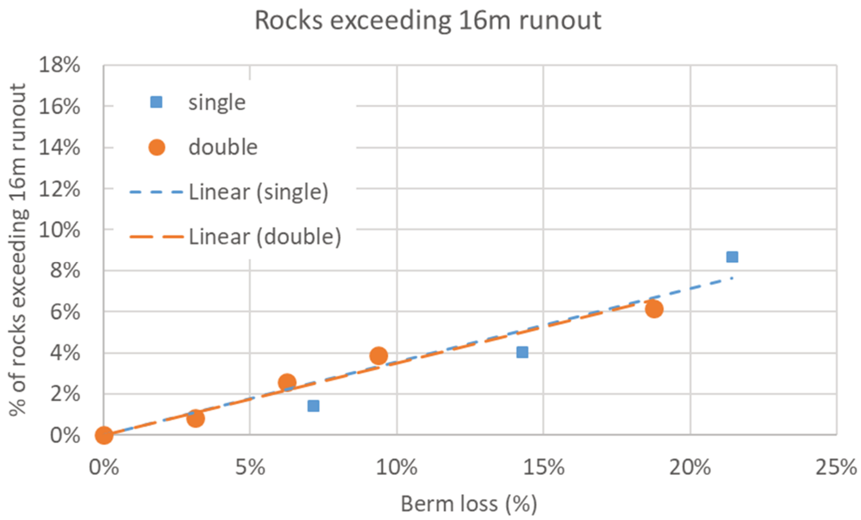


Figure 12 Percent of rocks with runout exceeding 16 m

Moreover, as Figure 13 shows, for the subset of rocks that do reach the bottom, runout tends to be greater for double benches than for single benches. This is possibly because rocks that fall from the lower double bench have a 30 m-high free fall compared with the 15 m-high single bench, i.e. rocks that do reach the bottom have higher energy.

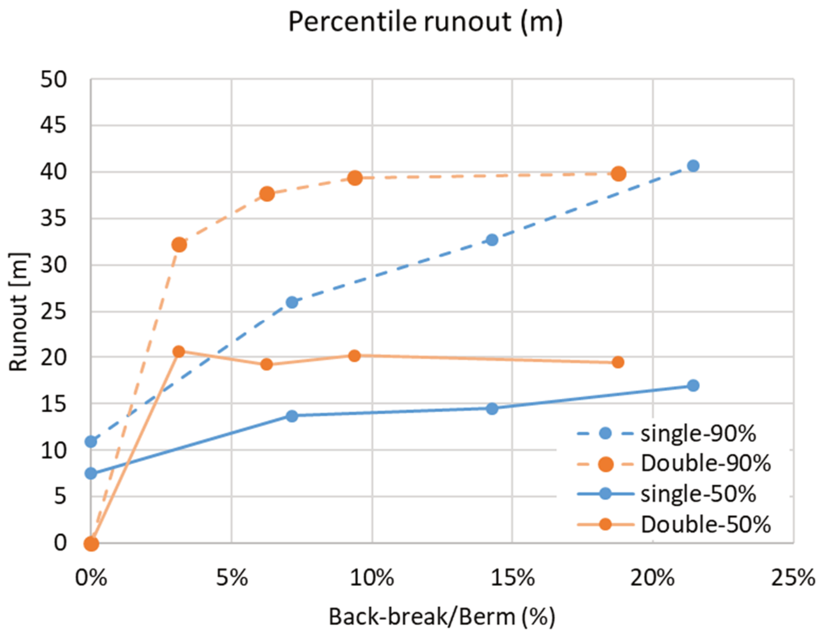


Figure 13 50 and 90% percentile runouts of rocks that reach the bottom

5 Conclusion

A mine in South America intended to implement double benches in order to reduce operational costs while improving drilling techniques in order to reduce rockfall hazards. SRK was retained to assess the effectiveness of pre-split blasting and to evaluate the impact of moving from single to double benches on rockfall hazard.

This paper presents a method to incorporate back-break into the pit design geometry with the aim of performing rockfall analyses and studying its effect on rockfall hazard at the toe and comparing the effectiveness of double versus single benches.

Back-break distributions were taken from measurements carried out at the mine and then applied to the pit design, whereby crests are displaced into the slope, providing a more realistic slope surface for rockfall calculations.

The performance of single benches (15 m high) versus double benches (30 m high) was compared, with a stack height of 150 m and an inter-ramp angle of 55° for both. The mass distributions of falling rocks were adopted from the mine and, according to Basson et al. (2013), both the normal and tangential coefficients of restitution were adopted as having an inverse linear relation with rock weight.

Double and single benches were assessed and compared in terms of rockfall retention:

- Double benches show a slightly lower percentage of unretained rocks.
- Double benches show a lower percentage of rocks that exceed a one berm runout (7 or 16 m).
- Both configurations exhibit the same absolute runout which, as expected, increases with back-break.
- Within the set of unretained rocks, runout tends to be greater for double benches than for single benches, which can be explained by the higher free fall from the lowermost bench (30 versus 15 m).

Considering the results obtained, double benches were recommended, for which the improved blasting practices ensured berm loss was kept to a minimum.

Acknowledgement

The authors thank William Gibson for the assistance provided with RFall_3D software.

References

Basson, FRP, Humphreys, R & Temmu, A 2013, 'Coefficient of restitution for rigid body dynamics modelling from onsite experimental data', *Proceedings of the 2013 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*, Australian Centre for Geomechanics, Perth, pp. 1161–1170.

Gibson W 2018, *Three dimensional rock fall analysis program*, version 3.0, unpublished manual, SRK Consulting.

Langford, JC, Corkum, B & Curran, JH 2014, 'Preliminary selection of optimum bench face angle using uniformly distributed wedges', *Proceedings of the 1st International Conference on Discrete Fracture Network Engineering*, Canadian Rock Mechanics Association, Vancouver, https://www.rocscience.com/assets/resources/learning/papers/Preliminary-selection-of-optimum-bench-face-angle.pdf

Mears, C 2017, *Three-dimensional rockfall modelling using RFall_3D*, MSc Thesis, University of Exeter, Exeter.

Pastine, S, García Mendive, I, Leizerow, T & Gibson, W 2018, 'Cómo romper un diseño: evaluación de desempeño banco-berma con geometrías más realistas' (Breaking a design: bench performance assessment with more realistic geometries), *XXIV Congreso Argentino de Mecánica de Suelos e Ingeniería Geotécnica*, La Sociedad Argentina de Ingeniería Geotécnica, Salta.

Read, JRL & Stacey, P 2009, Guidelines for open pit slope design, CSIRO Publishing, Melbourne.

Rocsience 2019, *Coefficient of Restitution Table*, viewed 2 February 2020, https://www.rocscience.com/help/rocfall/baggage/rn_rt_table.htm

Romer, C, Ferentinou, M & Jermy, C 2015, 'Comparison of 2D and 3D rockfall analysis, based on theoretical and realistic profiles', *Proceedings of the 2015 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*, Southern African Institute of Mining and Metallurgy, Cape Town, pp. 577–590.

Ryan, TM & Pryor, PR 2000, 'Design catch benches and interramp slopes', in WA Hustrild, MK McCarter & DJ Van Zyl (eds), *Slope Stability in Surface Mining*, Society for Mining, Metallurgy & Exploration, Englewood, pp. 27–38.