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EVALUATING AND MANAGING ROCK FALL RISK FOR STEEP ROCK SLOPES

Summary:

In open cast mines, road and railway cuttings and on access roads to dam sites in mountainous terrain, the excavation of steep rock slopes assists in minimizing excavation costs and maximizing project value. When not adequately considered in the design process, or managed during the construction or implementation phase, rock falls can present a significant hazard. The management of rock fall hazards is particularly vital for steep slopes. Numerical models are often used to assess the effectiveness of benched slope designs and rock fall barriers to minimize risk at the base of the slope. Commonly used numerical simulations include two-dimensional lumped mass impact models (2DLM) and three-dimensional rigid body impact models (3DRB). Both use coefficients of restitution to characterize the amount of energy lost due to the inelastic deformation during the collision of a rock with the slope. Model input parameters used in the design process are rarely calibrated with any site-specific case studies or field test data during the implementation phase. This paper presents approaches that can be used to effectively evaluate rock fall risk for steep rock slopes using calibrated 2DLM and 3DRB numerical simulations to assess the effectiveness of slope design geometries.

*Keywords**:** rock fall, slopes, risk management*

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ПРОЦЕНА И УПРАВЉАЊЕ РИЗИКОМ ОД ОДРОНА КОД СТРМИХ КОСИНА У ЧВРСТИМ СТЕНСКИМ МАСАМА

Резиме:

На површинским коповима, у засецима путева и железничких пруга, као и код приступних путева до брана у планинским подручјима, адекватан ископ косина у чврстим стенским масама смањује цену ископа и повећава вредност пројекта. Када нису адекватно третирани у пројекту, или се њима не управља на адекватан начин у току извођења објекта или у имплементационој фази управљања пројектом, одрони могу да представљају значајан хазард. Управљање хазардима од одрона је нарочито важно за стрме косине. Нумерички модели се често користе за процену ефикасности пројектованих нагиба косина етажа и баријера за одроне у циљу минимизације ризика у дну косине. Често коришћене нумеричке симулације подразумевају дводимензионалне 2DLM и тродимензионалне 3DRB моделе. Оба модела подразумевају коришћење коефицијената реституције за одређивање количине изгубљене енергије услед не-еластичне деформације током судара комада стена и косине. Улазни параметри за моделе који се користе у пројектовању ретко се калибришу са вредностима добијеним посебним студијама случаја или са подацима са терена добијеним у имплементационој фази управљања пројектом. У овом раду представљени су приступи, који могу да се користе за ефикасну процену ризика од одрона за стрме косине у чврстим стенским масама, користећи 2DLM и 3DRB нумеричке симулације за оцену ефикасности пројектованих геометрија косина.

*Кључне речи****:*** *одрон, косина, управљање ризиком*

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1. INTRODUCTION

Rock fall is the movement of rock from a slope that is so steep that the rock continues to move down the slope. This movement may be sliding, rolling, bouncing or free falling (Fig 1). The term ‘rock fall’ is often used to describe various types of falls of ground including individual or multiple rock fall, landslides or other forms of slope collapse (e.g. planar sliding, wedges, toppling, circular, etc). In the context of this paper, the term ‘rock fall’ is used to portray the movement of a single or multiple rocks or boulders moving down a slope.

In both open cast mines and publically-accessible slopes, rock falls can be symptomatic of poor slope construction (e.g. poor blasting and/or scaling practics), or the result of slope degradation from weathering or freeze-thaw action. Mechanical, environmental and biological events such as earthquakes, blast vibrations, pore pressure changes due to rainfall infiltration, erosion of surrounding material during heavy rain storms, root-growth or leverage by roots moving in high winds can also initiate rock falls [1-2]. When inadequately managed during the slope design or construction phases, rock falls can present a major hazard in open cast mines and publically-accessible slopes.

Early rock fall studies in the 1960’s comprised hundreds of rock fall field trajectory tests and lead to the development of empirical ditch design charts for roadways in mountainous terrain [3]. Rock fall trajectory field tests remained a tool-of-choice of engineers until the late 1990’s, when computing power facilitated the use of numerical models to simulate rock falls using simplified impact theories.

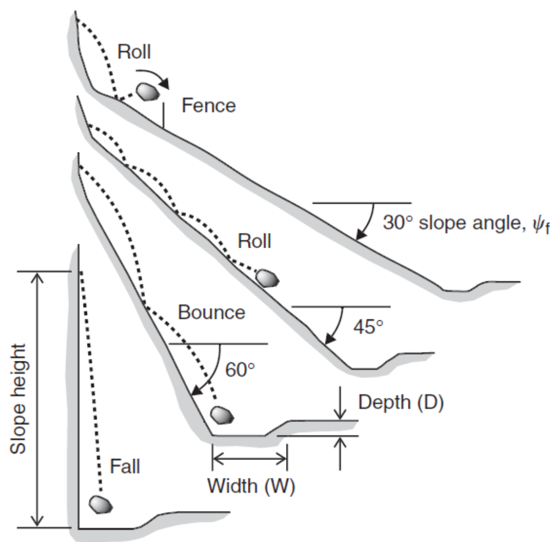


Figure 1. Rockfall modes of travel [3]

Слика 1. Различити начин кретања материјала при одроњавању [3]

The first impact theory used was the lumped-mass (stereomechanical) impact model in two-dimensions (2DLM). It attempted to replicate rebounding velocities of colliding objects or an object colliding with a stationary surface (in the case of rock falls). Improvements in computational power enabled lumped-mass models to be used for probabilistic or statistical rock fall modelling. Software such as *RocFall* of Rocscience Canada enabled most engineers to readily apply the 2DLM impact theory.

During the 1990's several 2DLM model calibration studies were undertaken utilizing rock fall trajectory field tests [4-6]. Model calibration studies became less popular in the 2000's and very rare in the 2010's.

Continuing improvements in computing in recent years enabled the development of software a slighly more complex impact theory [7-9] – the rigid body impact model, in both two and three dimensions. Software such as *Trajec3D* of Basrock Australia can now apply the rigid body impact model in three-dimensions (3DRB).

In recent years, several rock fall publications have considered potential trajectories on slope designs using both 2DLM and 3DRB [10-11]; however, few if any of these have calibrated their model simulations with field testing.

2. ROCK FALL TRAJECTORY FIELD TESTS

Rock fall trajectory field tests were carried out at a large open pit gold mine in Western Australia with the objective of calibrating numerical models to provide realistic simulations of rock fall trajectories rather than merely using input parameters from literature.

A total of 25 individual rock fall trajectory tests were carried out on slope angles of 50°, 60°, 70° and 80° with multiple benches available below for travel paths (examples shown in Fig. 2).

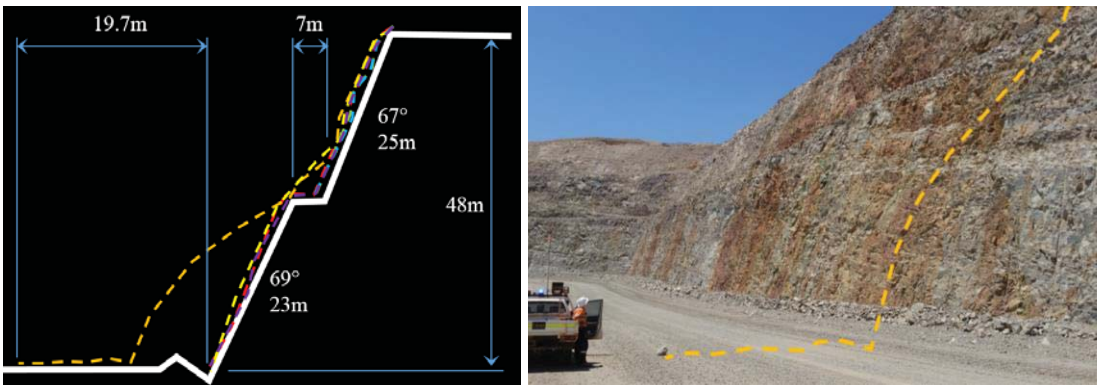


Figure 2. Estimated rock fall trajectory paths (obtained from reviewing field test videos) on a clean, smooth, benched, quartzite slope at a Western Australian gold mine

Слика 2. Процењене трајекторије кретања материјала при одроњавању (конструисане на основу прегледа видео материјала опита in situ) на чистој, глаткој косини у кварцитима на локацији рудника злата у западној Аустралији

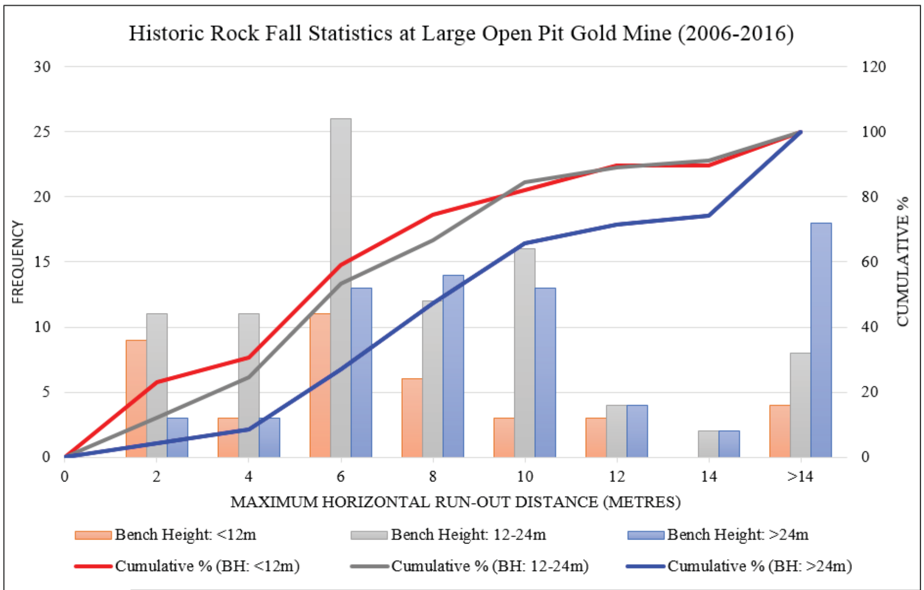
Several considerations were made prior to, and during field testing, including:

- Ensuring no people or equipment were at risk below the test areas.
- Mesuring and photographing rock sizes prior to each test.
- Video recording each of the individual field tests with a slow motion video camera.
- Measuring horizontal run-out distances with a tape measure.
- Describing slope, floor and barrier (if applicable) characteristics, including:

- o Slope face condition (smoothness, rock type, strength, etc);
- o Floor conditions (smoothness, material type, etc);
- o Barriers (bunds, ditches, fences, etc);
- o Estimating slope angle variability using a clinometer or topographic survey.

Rock fall field tests were carried out using the following methods and limitations:

- Rock throw or push for small sized samples (20kg to 40kg) inducing an inital starting velocity of between 1m/s to 2m/s.
- Rock levering using a scaling bar to mobilize medium sized samples (60kg to 300kg). This induced an initial rotataional velocity estimated to be approximately 90° per second from video footage.
- Equipment-assisted rock drops using a telescopic handler for large sized samples (1,000kg to 6,500kg) with zero initial velocity and rotation.
- Limitations of this particular project comprised a relatively low number of test samples and sample size bias to smaller rocks due to limited equipment availability.



	Maximum Horizontal Run-Out Distance (metres)					Bench Face Angles (degrees)					
Bench Height	Mean	Std. Dev.	Minimum	Maximum	No. of Samples	Mode	Median	Mean	Std. Dev.	Minimum	Maximum
<12m	7.00	6.79	0	30	39	65	65	66.47	8.20	40	90
12-24m	7.08	4.42	0	20	90	65	65	65.57	7.87	35	80
>24m	10.99	6.93	0	35	70	65	68	66.90	5.50	50	75

Figure 4. Historic Rock Fall Statistics (2006-2016). For color reproduction, please refer to CD version of the Proceedings.

Слика 4. Преглед забележених одрона у периоду 2006-2016. За интерпретацију различитих боја на слици, потребно је прегледати електронску верзију рада на CD-у.

3. ROCK FALL EVENT CASE STUDIES

Reviewing and recording rock fall events on slopes enables the derivation of rock fall statistics which can supplement field test data and greatly assist in the validation of numerical modelling results. The authors acknowledge that keeping such records is significantly 'easier' in the mining industry where geotechnical engineers usually work for the mining company and have access to all of the data (i.e. a centralized data repository). In civil engineering cases (road and railway cuttings, etc), government boundaries (local, state, etc) and the use of multiple engineering firms who do not necessarily work in partnership with one another can make it very difficult to have a central data repository.

At the same Western Australian gold mine where the rock fall trajectory field tests were carried out, records of all reported rock fall and other forms of slope collapse had been kept. This mine has been operating for over 30 years and had exposed slopes of up to 400m high. A total of 352 detailed records of rock falls and other forms of slope collapse were made available from between 2006 to 2016. Of these, 199 records contained both general slope geometry and maximum horizontal run-out distance data (Fig. 4). Some of these records included larger forms of slope instabilitiy such as planar or wedge failures – the maximum horizontal run-out distance was measured for these in the same manner as for individual rock falls and was not differentiated in the available data.

4. NUMERICAL MODEL CALIBRATIONS

Rock fall trajectories from the field testing were simulated using two and three dimensional rock fall impact models. In both 2DLM and 3DRB models, observed rock fall trajectory paths were modelled in the software by adjusting relevant input parameters, in particularly, the coefficients of restitution.

4.1. 2D Lumped-Mass Impact Model

Lumped-mass or stereomechanical models consider a falling rock as an infinitesimal particle with a mass (i.e. a falling body is represented as a point mass, ignoring the fall object size and shape which would otherwise affect its trajectory). The fall body mass does not affect the overall body trajectory, but is only used to compute energies. Lumped-mass impact models can only represent sliding motion and mimic rotation with a zero friction angle [8]. Normal and tangential coefficients of restitution (R_n and R_t, respectively) in lumped-mass impact models are used to compensate for the lack of physics captured within the simplified models. The two parameters can depend on the characteristics of the fall body, the slope and the collision point on a fall body shape with a non-spherical shape. The normal coefficient of restitution, R_n, is described as a measure of the degree of energy dissipation in the collision of a falling body in a direction normal to the slope. The tangential coefficient of restitution, R_t, is the measure of the resistance to movement parallel to the slope.

Coefficients of restitution were determined from back calculation of known rock paths and endpoints from the rock fall trajectory field tests. As was expected, harder materials such as bench faces attained higher coefficients of restitution than softer materials such as bench floors (typically rock fill comprising cobbles, gravel and some fines). Table 1 presents the calibrated coefficients of restitution and adopted friction angles for 2D lumped-mass impact models.

Table 1. 2D Lumped-Mass Impact Model – Calibrated Input Parameters

Табела 1. 2D Стереомеханички модел – Калибрисани улазни параметри

Ground Description		Normal Coefficient of Restitution – R_n (mean ± standard deviation)	Tangential Coefficient of Restitution - R_t (mean ± standard deviation)	Friction Angle (°) (based on historic site values)
Bench Floor	Weathered rock	0.240 ± 0.055	0.570 ± 0.110	25
	Fresh rock	0.314 ± 0.050	0.634 ± 0.120	25
	All Data*	0.300 ± 0.058	0.622 ± 0.119	25
Bench Face	Sandstone	0.379 ± 0.061	0.825 ± 0.083	25
	Siltstone	0.440 ± 0.055	0.810 ± 0.055	26
	All Data*	0.404 ± 0.061	0.837 ± 0.073	25

* *All data includes fresh and weathered rock (siltstone, sandstone and quartzite)*
Note: bench faces were generally smooth and free of 'launch features'

4.2. 3D Rigid Body Impact Model

Rigid body impact models use the equations of motion and kinematics to capture the essence of fall body behavior. They assume an instantaneous period of contact, and that the contact region between the colliding bodies is very small. Rigid body impact models consider the fall body shape and size, and various movement types including fall, slide, bounce and roll [8]. Aside from shape, mass and friction angles, only a single coefficient of restitution (C_r) is required in 3DRB. A coefficient of restitution, C_r, of one indicates a perfectly elastic collision with no loss in velocity or energy. In contrast, a coefficient of restitution of zero implies a perfectly plastic collision in which all of the velocity along the line of impact is absorbed. Coefficients of restitution in 3DRB and 2DLM impact models are not interchangeable.

As before, the coefficients of restitution were determined from back calculation of known rock paths and endpoints from the rock fall trajectory field tests. Harder materials such as bench faces attained higher coefficients of restitution than softer materials such as bench floors. Table 2 presents calibrated input parameters for 3D rigid body impact models.

Table 2. 3D Rigid Body Impact Model – Calibrated Input Parameters

Табела 2. 3D Модел крутог тела – Калибрисани улазни параметри

Ground Description		Coefficient of Restitution - C_r (mean ± standard deviation)	Static Friction Angle (°)	Dynamic Friction Angle (°)
Floor	Bench	0.037 ± 0.021	65	60
	Haul road	0.074 ± 0.021		
	All Data*	0.049 ± 0.028		
Bench Face	Weathered rock	0.125 ± 0.028	50	40
	Fresh rock	0.164 ± 0.065		
	All Data*	0.155 ± 0.060		

* *All data includes fresh and weathered rock (siltstone, sandstone and quartzite)*
Note: bench faces were generally smooth and free of 'launch features'

5. ASSESSING TYPICAL SLOPE GEOMETRY PROFILES

Standard slope geometry profiles were used to determine likely rock fall trajectories associated with various bench design configurations, comprising:

- Bench face angles of 45°, 60° and 75° which are assumed to be perfectly smooth in 3DRB and have a slope roughness standard deviation of 2° in 2DLM.
- Bench widths of 4m, 5m, 6m, 7m, 8m, 9m and 10m.
- For the purpose of this paper, only bench heights of 20m are discussed. Five stacked benches provided a stack height or inter-ramp slope height of 100m (Fig. 5).

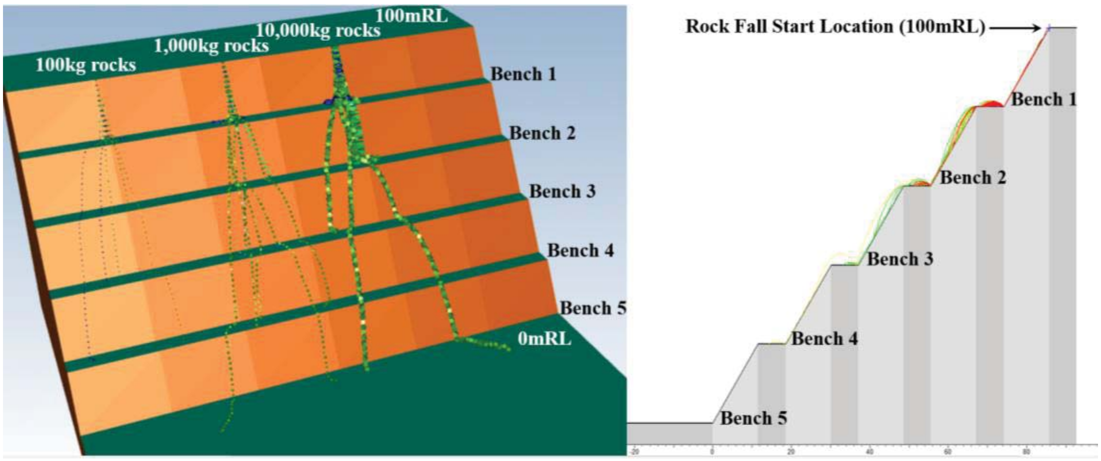


Figure 5. Bench Height = 20m, Bench Face Angle = 60°, Bench Width = 7m. (Left: 3DRB. Right: 2DLM.)

Слика 5. Висина радне етаже = 20m, Нагиб косине радне етаже = 600, Ширина радне етаже = 7m (Лево: 3DRB, Десно: 2DLM)

The standard slope geometry profiles were assessed using the Modified Ritchie Criterion (presented as Eq. 1; Ryan & Pryor 2000), and 2DLM and 3DRB rock fall model simulations.

$$BW = 0.2 x BH + 4.5 \quad (1)$$

where:

BW – bench width (m) and BH – bench height (m)

To allow for variability in trajectory, several simulations tested a number of 100kg, 1,000kg and 10,000kg rocks comprising:

- Infinitesimally small spheres in 2DLM (300 test runs per configuration).
- Appropriately sized cubes, elongated flat boxes and angular ‘smartie’ shapes in 3DRB (90 test runs per configuration).

The percentage of rocks captured on benches using 2DLM and 3DRB model simulations are presented in Figure 6. Both models illustrate that narrower bench widths are likely to capture less rocks than wider benches. The 2DLM model simulations suggest a higher ‘certainty’ for capturing rocks on ‘wider’ benches compared with the 3DRB models. This is more clearly evident in Figure 7, which compares the percentage of rocks captured on the first bench between the 2DLM and 3DRB model simulations, the Modified Ritchie Criterion and historic data.

In Figure 7, smooth, almost variability-free curves are obtained from 2DLM model simulations. Re-running these simulations would yield near-identical results. Conversely, in the 3DRB model simulations, a high degree of variability can be observed in the results (i.e. non-smooth curves). When re-running these simulations, identical results are not obtained, but usually vary in the order of 5-10%.

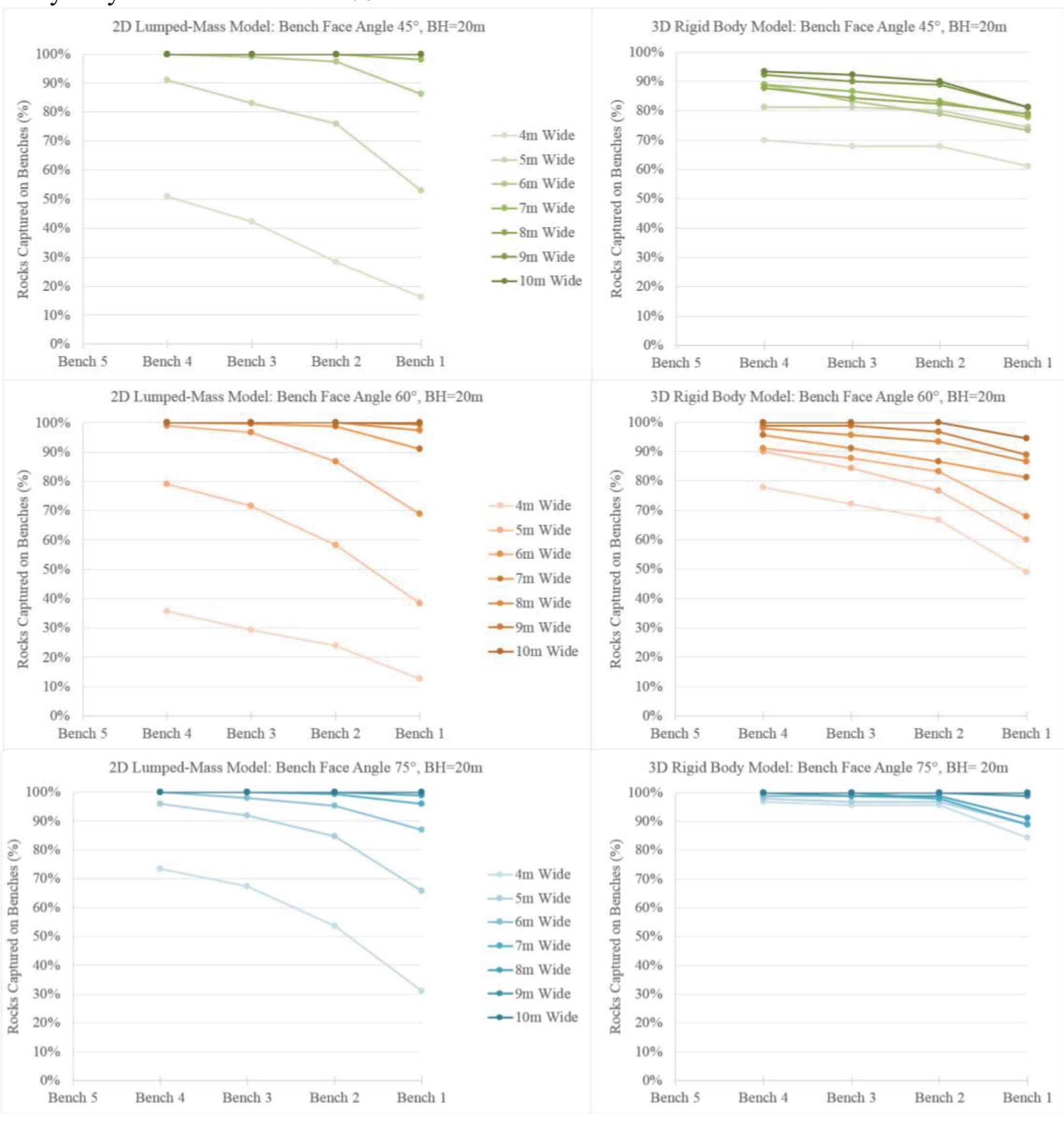


Figure 6. Model Simulation Results: Percentage of Rocks Captured on Benches (Left: 2DLM. Right: 3DRB.). For color reproduction, please refer to CD version of the Proceedings.

Слика 6. Резултати симулације модел: Проценат комада стена који су заостали на етажама (Лево: 3DRB, Десно: 2DLM). За интерпретацију различитих боја на слици, потребно је прегледати електронску верзију рада на CD-у.

The 2DLM results suggest the Modified Ritchie Criterion [12] remains admissible for 20m high benches. As illustrated by both Figures 6 and 7, steeper bench face angles generally result in shorter rock fall trajectories.

The 3DRB results correlate reasonably well with the historic rock fall and other form of slope collapse case studies (2006-2016). It is likely that if only individual rock fall events were used in this historic dataset, the correlation would be even better.

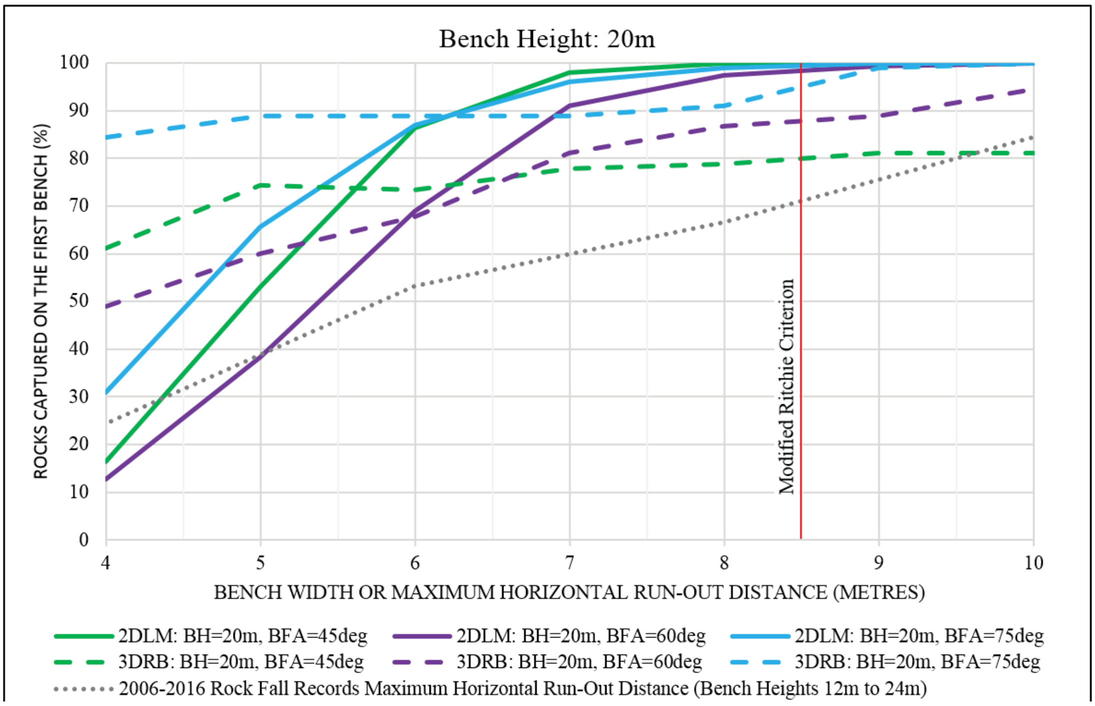


Figure 7. Percentage of rocks captured on the first bench from 2DLM and 3DRB compared to the Modified Ritchie Criterion and Historic Rock Fall Statistics. For color reproduction, please refer to CD version of the Proceedings.

Слика 7. Проценат комада стена који су заостали на првој етажи из 2DLM и 3DRB модела у поређењу са модификованим критеријумом Ричија и до сада забележеним одронима у периоду 2006-2016. За интерпретацију различитих боја на слици, потребно је прегледати електронску верзију рада на CD-у.

5. CONCLUSION

Key findings from the rock fall trajectory field tests and model simulations include:

- Steep bench face angles predominantly result in a ‘fall’ motion and generally reduce horizontal rock fall trajectories. Conversely shallower bench face angles can promote ‘rolling’ and ‘bouncing’, which increase horizontal trajectory.
- Smooth bench faces reduce the likelihood of launch features contributing to horizontal trajectories.
- While not included within the results of this paper, greater bench heights increase the velocity of rock falls and as such, the trajectories (e.g. a 30m high bench has significantly higher potential for increased trajectories than a 20m high bench).
- Minor changes in coefficients of restitution can yield significantly different results As such, models without calibration seldom add significant value to a project.

The 2DLM model simulations often exhibit ‘ellipsoidal’ trajectories, which were not observed in field testing. The 3DRB model simulations provided more realistic rock fall trajectories, which were greatly influenced by the fall body shape and size. This caused significantly more variability in the modelling results than the 2DLM model simulations. Based on the writers’ experience, this better reflects the actual variability of rock fall trajectories that may be observed in the field.

The 3DRB model simulations are believed to add significant value as they illustrate that it is difficult to definitively model rock fall trajectory paths. However, the information is very useful in determining the likely endpoints of rock fall trajectories which can be used in design.

The rock fall trajectory field tests and model simulations assisted in the evaluation of steep slope designs, identify areas of elevated risk, and in refining procedural controls to manage rock fall risk. In a civil engineering project, the calibrated models would likely be used to design appropriate barriers (e.g. ditches, bunds or fences) to minimize risk to the public.

REFERENCES

1. Hoek, E. 2007. Practical Rock Engineering, 2007 Edition, Vancouver, Canada, viewed on 31 May 2016, https://www.rocscience.com/learning/hoek-s-corner.
2. Read, J., Stacey, P. 2009. Guidelines for Open Pit Slope Design. CSIRO Publishing, Australia.
3. Ritchie, A.M. 1963. *Evaluation of rock fall and its control*, Highway Research Record 17, Highway Research Board, Washington, Unitied States of America, 13-28.
4. Budetta, P. Santo, A. 1994, *Morphostructural evolution and related kinematics of rockfalls in Campania (South Italy)*, Engineering Geology, Volume 36, 197-210.
5. Chau, K.T., Wong, R.H.C., Lee, C.F. 1996. *Rockfall problems in Hong Kong and some new experimental results for coefficients of restitution.* International Journal of Rock Mechanics, Mining Sciences and Geomechanics, Volume 35, 662-663.
6. Robotham, M.E., Wang, H., Walton, G. 1995, *Assessment of risk from rockfall from active and abandoned quarry slopes*, Institution of Mining and Metallurgy Section A, Vol 10, A25-A33.
7. Ashayer, P. 2007. *Application of rigid body impact mechanics and discrete element modelling to rockfall simulation*, PhD Thesis, University of Toronto, Canada.
8. Basson, F.R.P. 2012. Rigid body dynamics for rock fall trajectory simulation. Proceedings of the 46th US Rock Mechanics & Geomechanics Symposium, Chicago, United States of America.
9. Basson, F.R.P., Humphries, R., Temmu, A. 2013. Coefficient of resitution for rigid body dynamics modelling from onsite experimental data. Proceedings of Slope Stability 2013 International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering, Brisbane, Australia.

10. Bosman, J.D., Kotze, G. 2015, Verification of catch berm effectiveness through the application of 3D fall body dynamics. Proceedings of Slope Stability 2013 International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering, Cape Town, South Africa.
11. Dadashzadeh, N., Duzgun, H.S.B., Yesiloglu-Gultekin, N., Bilgin, A. 2014. Comparison of Lumped Mass and Rigid Body Rockfall Simulation Models for Mardin Castle, Turkey. Proceedings of the 48th US Rock Mechanics & Geomechanics Symposium, Minneapolis, United States of America.
12. Ryan, T.M., Pryor, P.R. 2000. *Designing catch benches and interramp slopes*, Slope Stability in Surface Mining (editors: W.A. Hastrulid, M.K. McCarter & D.J.A. Van Zyl), SME, Colorado, United States of America, 27-38.