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Influence of bench geometries on rockfall behaviour in open pit mines

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1 INTRODUCTION

Surface mining is generally considered to be more advantageous than underground mining in recovery, grade control, economy, flexibility of operation, safety, and the working environment (Leider *et al,*1968). Many factors govern the size and shape of an open pit. In planning an open pit mine, the key items affecting the pit design are: geology, tonnage and areal extent of ore reserves, topography, grade and localization of the mineralization, mining equipment, property boundaries, production rates, bench heights, types of ores, ore metallurgical characteristics, hydrological conditions, pit slopes, cut-off grade, stripping ratio, road grades, mining costs and marketing considerations.

The slope angle of the pit wall is one of the key elements affecting the size and shape of the pit. After fixing the allowable stripping ratios, the final pit slope must be determined. Slopes need to be as steep as possible to minimize the amount of waste rock mined and hence to minimize mining costs, but economic consequences of failure of slopes due to oversteepening can be disastrous (Stacey, 2003).

Slopes that have failed and deposited rubble on a haulage ramp or on a conveyor belt, for example, result in a major disruption to the business of getting ore out of the ground and into the mill. However, many slope failures are more subtle than this simple case. The gradual deformation of a slope, even when movement is on the order of 4 m/year, does not represent “failure” but rather is regarded as a slope problem that has to be managed. This is in contrast with the civil engineering practice where slope deformations of this magnitude would certainly be considered as failures (Hoek *et al*, 2000).

An adequate slope evaluation will result in slopes that allow the pit walls to remain stable. The pit slope analysis determines the angle to be used between the roads in the pit, as well as the overall pit slope angle (angle from the toe of the bottom bench to the crest of the top bench). The latter will be flatter than the former to accommodate the road system in the ultimate pit (Leider *et al*, 1968 and Kennedy, 1990). The evaluation of stability includes the consideration of the potential for and effects of rockfalls, which can be hazardous to the mining operation. Rockfall analysis is the subject of this research work.

1.1 Description of the origin of rockfalls and methods for containing their effects

Slopes in open pit mines contain benches, and one such bench is the catch bench aimed at preventing the effects of rockfalls. The primary functional requirement in evaluating benched mine slopes, is to maintain adequate catch bench widths while the interramp slope angle is optimized on economic criteria. However, because of the variability in geological structure, for example jointing, producing varying amounts of back break (the horizontal distance between the planned toe and the actual mined crest of the final bench slope) along the bench crest at each mining level, catch bench widths vary considerably

within the slope for any given interramp slope angle (Ryan and Pryor, 2000; Girard and McHugh, 2004).

In the context of slope instability phenomena, the detachment of blocks from steep walls and their subsequent falls are particularly significant (Azzoni *et al*, 1995). Mechanistically, rockfalls occur when destabilizing factors overcome stabilizing factors (Singh *et al*, 2004 and Vick, 2002). The phenomenon of rockfalls involves high risk in open pit mines as well as in rock cuts for highways and railways in mountainous terrain. Once movement of a rock perched on the top of a slope (bench) has been initiated, the most important factor controlling its fall trajectory is the geometry of the slope (bench) (Hoek, 2000).

The benched slope configuration in open pit is a function of the bench height, the bench face angle, and the required catch bench width. Development of criteria for bench width design is necessary because the purpose of the catch bench is to prevent rocks from rolling from upper portions of the pit slope to the working areas, where personnel and equipment are located (Ryan and Pryor, 2000; Girard and McHugh, 2004).

Clean faces of hard unweathered rock are the most dangerous because they do not retard the movement of the falling or rolling rock to any significant degree. On the other hand, surfaces covered in talus material, scree or gravel absorb a considerable amount of the energy of the rockfall and, in many cases, will stop it completely. The coefficient of restitution is the mathematical expression of this retarding capacity. It depends upon the nature of the materials forming the impact surface (Hoek, 2000).

It is particularly important to have the best possible knowledge of rockfall trajectories and energies in order to determine accurate risk zoning and for the design and construction of adequate defence systems near the threatened areas (Azzoni *et al*, 1992; Azzoni *et al*, 1995).

Common methods for containing the effects of rockfalls (Hoek, 2000) are as follows:

Civil engineering slopes

- Rockfall shelter

A rockfall shelter is a reinforced concrete and fail-safe protective measure used on steep slopes above narrow railways or roadways (Kirsten and Miessner, 1977; Steffen and Dorey, 1977). To have an effective shelter, a steeply sloping or impact resistance roof covering a relatively narrow span is required.

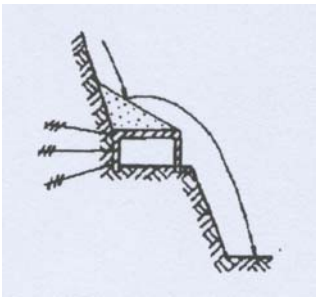


Figure 1.1. Rockfall shelter (Spang, 1987).

- Humps (ditch and fill)

Humps and ditches can be effective in catching rockfalls if there is sufficient room at the toe of the slope to accommodate them.



Figure 1.2a. Ditch (Spang, 1987). **Figure 1.2b. Fill (Spang, 1987).**

- Catch fences or barrier walls

Barriers may be constructed as fabricated walls, or catch fences consisting of vertical steel posts embedded in holes, flexible netting, steel cable support infrastructure and anchorages. They are for protection against rockfalls, relying on dynamic energy absorption, and to ensure safety. The commonly used catch fences are estimated to have an energy absorption capacity of 100 kJ, equivalent to a 500 kg rock moving at about 20 metres per second. Nowadays, catch fences exist with energy absorption capacity of up to 2500kJ (Fatzer, 2001).



Figure 1.3. Catch fence (Spang, 1987).

Open pit mine slopes

- Catch fences

The catch fences used in mining are identical to those used for civil engineering slopes. The cost of installing the fences can be offset against the benefits of safer and often steeper slopes.

- Catch benches

Catch benches are aimed at preventing the effects of rockfalls. They are an effective measure to catch rockfalls, and are usually used on permanent slopes as reported by Hoek (2000). However, they are of limited use in minimizing the risk of rockfalls during construction as they can only be excavated below an existing slope, that is, from the top downwards.

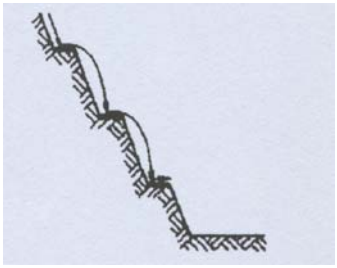


Figure 1.4. Catch benches (Spang, 1987).

- Draped Mesh

The mesh can be draped over the rock face and attached at many locations along the slope. The purpose of the mesh is not to stop rockfalls, but to trap the falling rock between the mesh and the rock face so that workers are protected from the danger of falling rocks (Hoek, 2000; Maccaferi, 2003). This method may be used for civil engineering slopes as well. Hexagonal double-twist mesh is often used, with the steel being heavily galvanized with a zinc coating. One of the great advantages of double-twist technology is that the wire mesh does not unravel when a strand breaks.

In summary, rockfall trajectories and energies are affected by the benched slope configuration, and the coefficient of restitution of the impact surfaces. Alternative methods have been identified that can be used to contain rockfalls, one method being the inclusion of catch benches in the slope geometry.

1.2 Structure of the Research Report

In Chapter 2, previous work on rockfalls and their analysis is reviewed. The aim of the research work is dealt with in Chapter 3, and the main content of the research activity,

namely the analysis of rockfall behaviour associated with a range of open pit slope geometries, is contained in Chapter 4. The conclusions and recommendations arising out of the research work are given in Chapters 5 and 6 respectively.

2 REVIEW OF PREVIOUS WORK ON ROCKFALLS AND THEIR ANALYSIS

In this chapter, a detailed review of previous studies on rockfall analysis is presented. Many reports and papers containing references to cases of rockfall problem have been reviewed. An internet search was also conducted. The literature on rockfall analysis may be divided into two categories:

- Experimental methods involving physical modelling. This usually consists of performance of tests on scale models. Some of this work can be important in the understanding of rockfall phenomena. The results can define criteria for design of protective works such as fences, fill, rockshelters, berms and ditches.
- Computer models: analysis of rockfalls using computer methods may be divided into two types:
  - models considering the falling rock block with its mass concentrated at one point
  - models considering the block as a body with its own shape and volume (Azzoni *et al*, 1995).

These two groups are dealt with in the sections to follow.

2.1 Experimental methods

Ritchie(1963) published his study on rockfall entitled “Evaluation of Rockfall and its control”. The study involved the rolling of hundreds of rocks off highway and state-owned quarry and talus slopes across Washington State. Ritchie measured and recorded the paths and distances the rocks traveled (including production of 16 mm motion pictures). The emphasis of his study was to identify the characteristics of rockfall motion relative to a slope’s configuration and height, and to determine the expected impact distance (where the falling rock first hits the catchment area) of a rockfall from the toe of the slope. He also investigated how to effectively stop a falling rock that had considerable angular momentum once it landed in the catchment area. Based on this work, Ritchie drew several significant conclusions as follows:

- Irrespective of a rock’s shape or size, the rock’s mode of travel down is a function of the slope angle (see Figure 2.1)

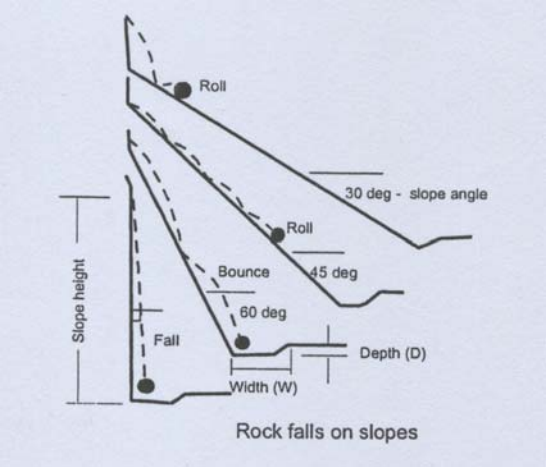


Figure 2.1. Rockfall travel modes (Pierson *et al*, 1994).

- On steeper slopes, even though a rock's initial motion is by rolling, after a short distance the rock starts bouncing and then continues bouncing along the slope or goes into free fall, depending on the slope angle.

- Rocks that fall in trajectory (free fall) seldom give a high bounce after impact. Instead they change their linear momentum into angular momentum.

Some significant limitations of the Ritchie criterion (such as that the Ritchie table always gives the same required catchment area width and height for a given slope height and slope angle; does not provide a means for designing for varying percent rockfall retention levels based on a benefit/cost approach; that the rock rolling was done primarly on "rough" non-presplit highway and quarry slopes and natural slopes, containing numerous launch features, whereas today's highway slopes are predominantly developed using controlled blasting techniques, namely presplit or cushion blasting, and thus are "smoother" with fewer launch features than those in the Ritchie study) led the Oregon Department of Transport (Pierson *et al*, 1994) to develop more current and better-quantified design criteria for sizing rockfall catchment areas. The Oregon Department of Transport research project had three main goals:

- Investigate the nature of rockfall and identify how slope, catchment area and rockfall properties affect the rockfall retention at the base of slopes with various angles (vertical, 4V:1H, 2V:1H, 1.33V:1H, and 1V:1H slopes) for various slope heights (12.2m; 18.3m; 24.4m), and various catchment area geometries (slopes of flat-bottom, 1V:6H and 1V:4H), where V is a unit vertical distance and H a unit horizontal distance.
- Develop improved, more precise design guidelines, including "practitioner-friendly" design charts, to assist with designing new or improved rockfall catchment areas that perform as intended with the minimum economic investment and environmental impact.
- Provide design "flexibility" that allows for the design of catchment areas that will retain percentages of rockfall ranging up to 99%.

Several worthwhile results were realized by the pilot research effort. Rockfall frequency histograms were developed that showed the rockfall retaining ability of catchment areas of a particular width and catchment area slope. General observations and conclusions drawn from the research are as follows:

- A catchment area's slope, whether flat-bottom or inclined, has insignificant influence on where a falling rock will first impact the catchment area.
- Steeper (negative) catchment area slopes dramatically reduce run-out distances
- Cut slope irregularities, commonly referred to as "launch features," when struck by the falling rock strongly influence a rockfall's point of impact in the catchment area.
- Factors such as the presence of launch features and increasing slope height are key to the development of preferred rockfall paths.
- "Launched" rocks tend to have greater impact distances, increasing the spread or dispersion of recorded impacts, compared to rocks that do not strike launch features.
- Launch features change a rock's vertical drop to horizontal displacement. Typically, the higher the rock velocity when it strikes a launch feature, the greater the horizontal displacement.
- Higher slopes and flatter catchment areas produce rockfall rollout distances that are more widely scattered or variable.
- Higher slopes typically produce larger average rollout and impact distances.
- Higher slopes produce impact distances that are more variable.
- Large run-out distances are possible when a falling rock's translational momentum is changed into rotational momentum by impacting the slope, especially if the rock strikes near the base of the cut slope.
- On vertical slopes, falling rocks rarely strike the slope in trajectory. They typically drop undisturbed into the catchment area. Angular momentum is not imparted to the falling rocks, which results in smaller run-out values.
- On flatter slopes where rocks are rolling down the cut slope, the impact distances are lower, with most rocks entering the catchment area very near the base of the slope.
- Rockfalls velocities are a function of cut slope angle and height and the amount of time the rocks are in contact with the slope.
- When in contact with the slope, friction decelerates a rockfall, which lowers the resulting energies.

Based on the paper by Ritchie (1963) on the evaluation of highway shoulders for catching rockfall off excavated and natural slopes, the Modified Ritchie Criteria was evolved by Call and Nicholas, Inc. (Ryan and Pryor, 2000). Ritchie's investigation was limited to a relatively small number of slope angle/slope height geometries and therefore required extrapolation for use in open pit mining. The newer approach employs a Modified Ritchie Criterion as a guide for developing catch bench width criteria. Since slope (bench) height is one of the most important controls on the distance that a rock will travel when detached from the bench, Call and Nicholas, Inc. derived an empirical relationship between the slope and the average, or preferred, catch bench width as follows:

Bench width (m) = 0.2 x bench height + 4.5 m

Ryan and Pryor (2000) have tried to refine the bench width equation for pit slope stability, but they have found that the problem is too complex for any single criterion to be 100 % effective. In field tests, they have been able to demonstrate that the Modified Ritchie Criterion is effective in benched mine slopes, and was very conservative for containing rockfalls in a limestone slope, benched on 12 to 15 m heights for rock blocks anywhere from 30 cm to 2 m in size.

Owing to the complexity of the problem, Ryan and Pryor (2000) have been obliged to approach the rockfall problem from a risk-management perspective. For this purpose, they have increasingly used the reliability-based approach for evaluating benched mine slopes, in which the analysis is structured to evaluate the percentage of the slope area that meets or exceeds a chosen catch bench width criterion. They use a combination of structure modelling, bench face stability analysis, and the Modified Ritchie Criterion to determine the catch bench reliability. This reliability which refers to the percentage of benches having final widths equal to or greater than the Modified Ritchie criterion.

Many case studies have outlined the primary control of three dimensional topography on block kinematics and on the dissipation of kinematic energy at impact or by rolling. The lateral dispersion of trajectories of falling rocks is the most important three dimensional effect. Crosta and Agliardi (2003) conducted a systematic evaluation of the influence of different controlling factors (i.e. mass of falling rock, impact velocity, average terrain slope, micro-topography) on the dispersion of rockfall trajectories due to the effect of the way rockfall dynamics are modeled, countermeasures are designed and rockfall hazards assessed.

The evaluation was performed using three-dimensional parametric modelling. A set of idealized slopes with different geometry (i.e. degree of concavity or convexity) and spatial resolution was used. Results of the analyses are as follows:

- The degree of uncertainty of the restitution and friction coefficients being equal, the dispersion of rockfall trajectories and the related complex scattering of the kinematic parameters are strongly affected by the slope geometry (macro-topography).
- For the same slope geometry, the dispersion is a function of micro-topography.

The above review deals with results of field testing and studies. In addition to the field studies, several rockfall computer simulation programs have been developed that can be run to predict the rockfall trajectories in order to determine the influence of bench geometries on rockfall behaviour. These are dealt with in the following section.

2.2 Computer models

Hoek (1986) wrote a relative crude rockfall simulation program which is capable of producing reasonably accurate predictions of rockfall trajectories. This program has been developed to help in prediction of catchment area requirements.

Other researchers (Pierson *et al*, 1990; Pfeiffer and Bowen, 1989, as reported by Ryan and Pryor, 2000) have developed rock catchment criteria from field tests and from computer simulation methods (Colorado rockfall simulation) as reported by Ryan and Pryor (2000). The figure below shows one of these relationships in addition to the modified Ritchie relationship.

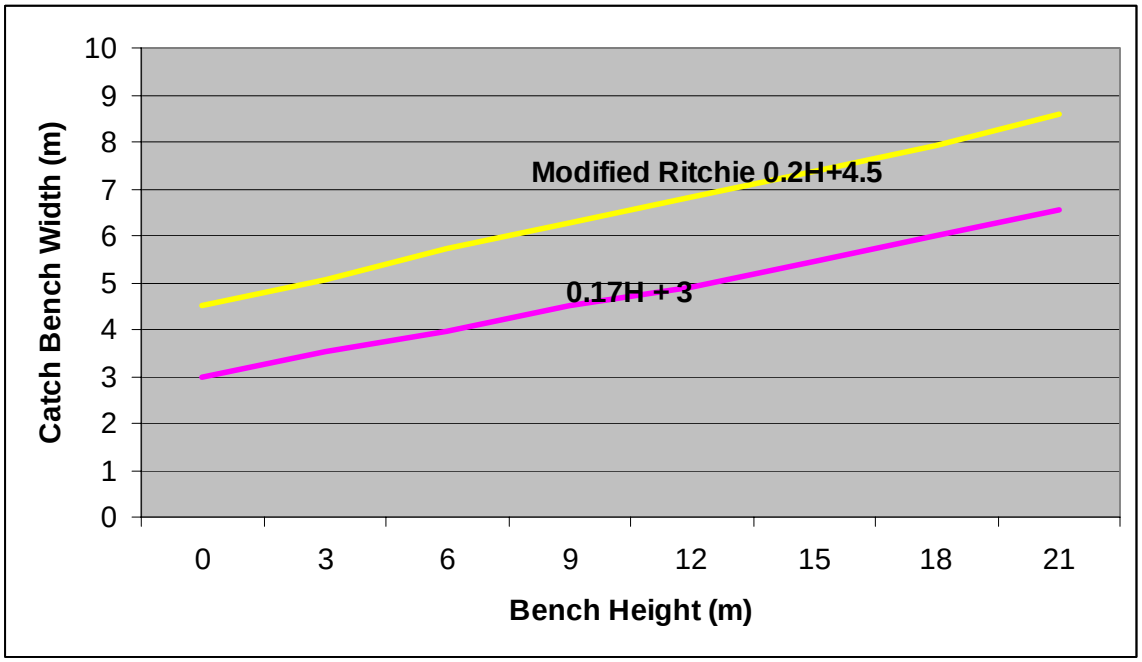
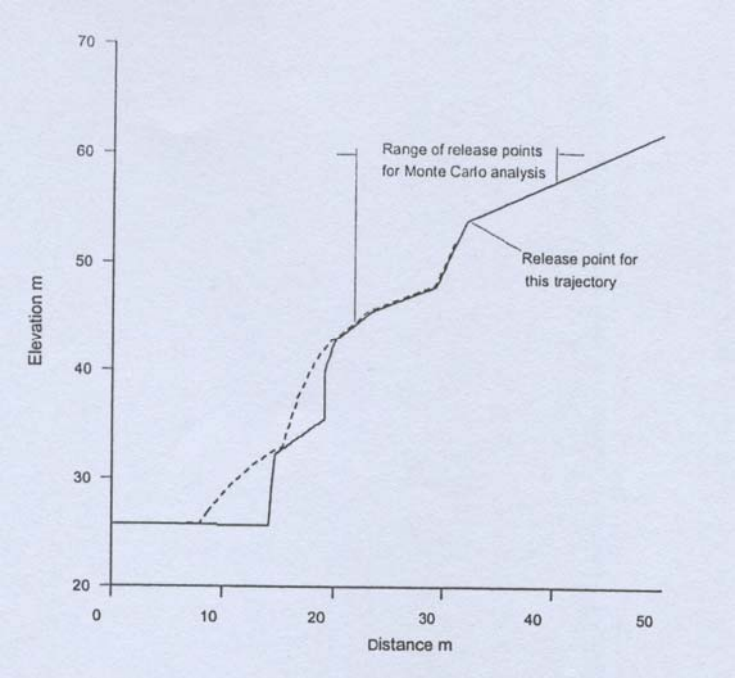
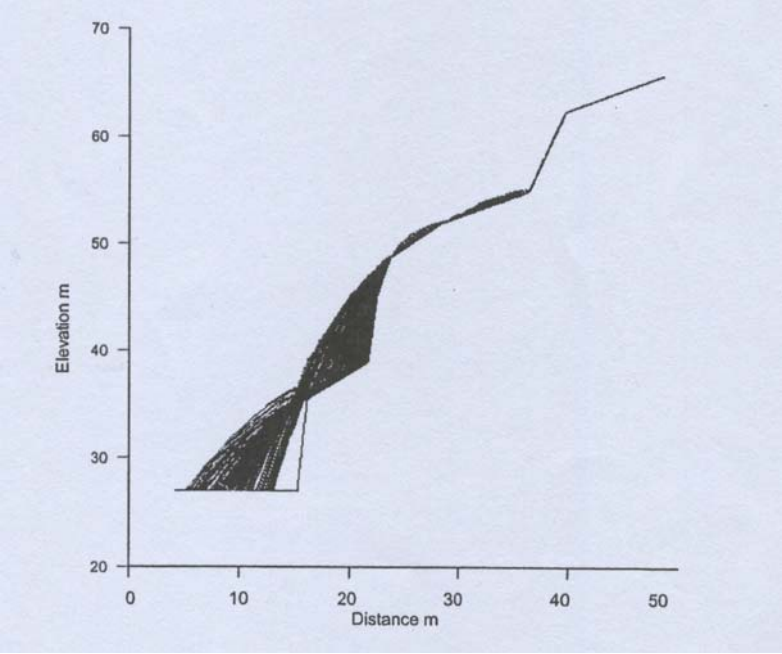


Figure 2.2. Catch bench width criteria for rockfall containment (after Ryan and Pryor, 2000).

Bozzolo et al (1988), Spang and Rautenstrauch (1988), Hungr and Evans (1989), and Azzoni et al (1995), have written more refined rockfall simulation programs producing better results of rockfall trajectories, provided that realistic input information is available. A typical rockfall analysis carried out using the program developed by Hungr as reported by Hoek (2000), is illustrated in figure 2.3.



a) Typical trajectory for a 1000 kg boulder



b) Trajectories for 1000 boulders weighing between 200 and 20,000 kg released within the range shown in a) above.

Figure 2.3. Typical example of a rockfall trajectory for a granite slope (Hoek, 2000).

This program includes a plasticity function that allows the absorption of the impact energy of boulders to be modelled, depending upon their size. The simulation run by this program assumes that large boulders will be damaged or will indent the impact surface while small boulders will bounce off the impact surface with little energy loss.
The impact area was assigned a coefficient of restitution close to zero in the analysis illustrated in Figure 2.3b. Thus, any bounce after the first impact was suppressed. The determination of the spread of first impacts was the purpose of this analysis so that an effective rockfall mitigation measure (catch ditch and barrier fence) could be designed. The study above can be applied in open pit mining by substituting the profile of slope in the figure 2.3 by a benched slope configuration.

Azzoni *et a*l (1995) indicate that a joint research program for the study of rockfall, considering a falling rock block as a body with its own shape and volume was started at the ISMES and ENEL CRIS organisations. The aim of their study was to assess velocity, height of bounce, energies achieved during the fall and maximum run-out distances, in order to determine the areas at risk. They developed a mathematical model, called CADMA which was developed to investigate the principal modes of rockfalls, and at the same time a considerable number of in situ tests were carried out to determine the principal parameters involved in the model. The model is based on rigid body mechanics. The survey for in situ tests was conducted on two different slopes as shown in figure 2.4. The methodology adopted is shown in the flow chart in figure 2.5.

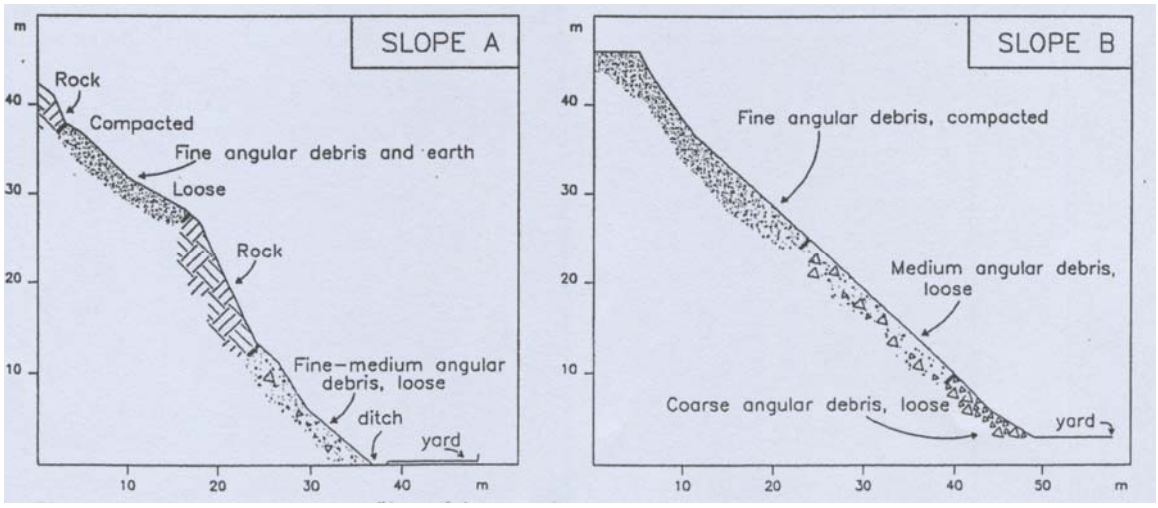


Figure 2.4. Topographical profiles of the test slopes (Azzoni *et a*l, 1995).

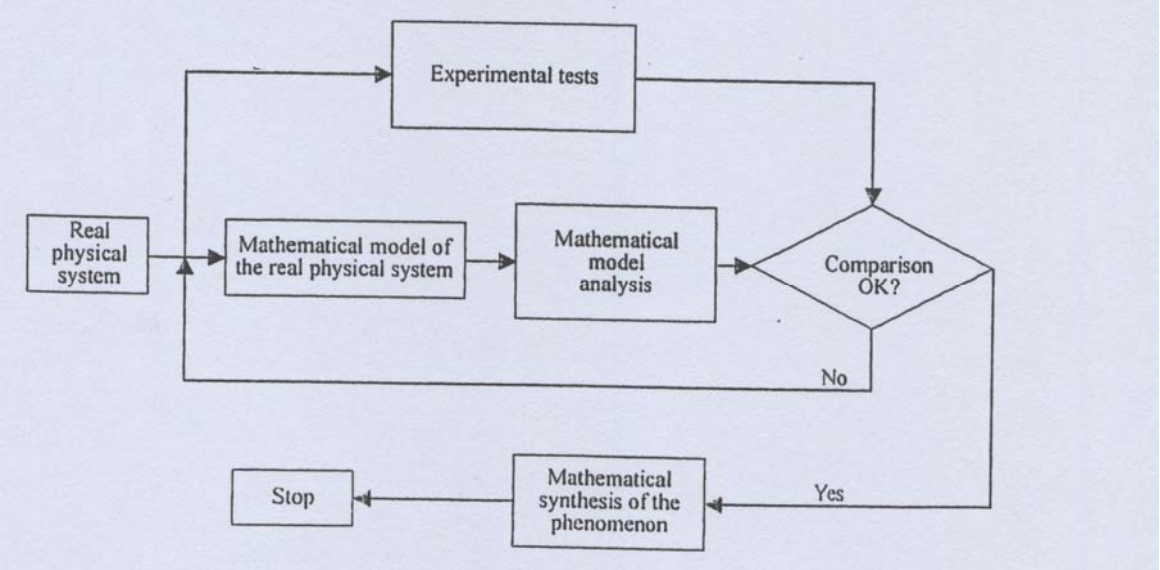


Figure 2.5. Flow-chart showing the steps of the study procedure (Azzoni *et al*, 1995).

In summary, the main characteristics of the mathematical model (techniques and assumptions) and the in situ tests were as follows:

Mathematical model

- Analysis of Rockfalls is carried out in a two-dimensional space
- Rockfall trajectories are established a priori and represented as a sequence of straight segments. Motion kinematics are studied along a vertical plane, defined by rotation on a single plane of all the different vertical planes, including the previously mentioned segments as illustrated in figure 2.6.
- The fall is composed of different phases, each with its own characteristics and assumptions.
- Blocks at the point of impact are modelled as ellipsoidal bodies rotating in a two-dimensional space around the shorter axis (rotation around the other axes is neglected) (figure 2.7).
- Block fracturing is not taken into account. This approach is reasonable for obtaining conservative results.
- Each block falls along a trajectory not affected by those of the other blocks.
- The natural variability of some important parameters (such as the shape of the block, the mechanical characteristics of the slope, local slope angle at impact, detachment area and inclination on the slope of the trajectory after detachment) requires that both description and analysis of the phenomenon be statistical rather than deterministic. For this purpose, the model takes into consideration a large number of falls and adopts random values (chosen within a previously determined

range) for each of the above-mentioned parameters (Azzoni *et al*, 1995).

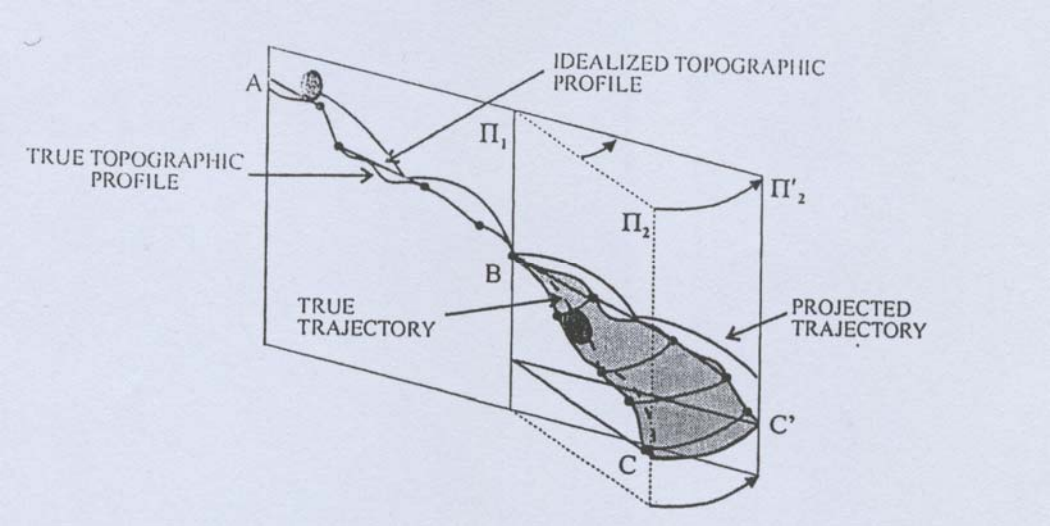


Figure 2.6. The kinematics of the motion is studied in a vertical plane obtained by rotation into a single plane of all different vertical planes (Azzoni *et al*, 1995).

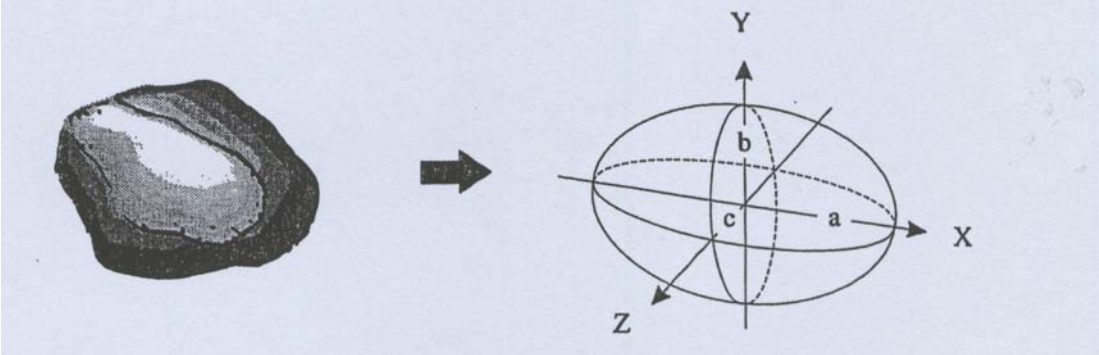


Figure 2.7. Model of the block at the impact (Azzoni *et al*, 1995).

Experimental method

The experimental work included the following:

- Assessment of the topographical, geomorphological, geological and mechanical characteristics of the slope and the blocks.
- Rocks were tipped down the slope, depending on their size, by hand, by jacks, or more easily, when the test was carried out in a quarry, by an excavator.

- Recording the rockfalls – three to five fixed video cameras and a lateral moving camera may be used together. These cameras record the movement in a vertical plane parallel to the rock's trajectory. A fixed camera in front of the slope records the lateral displacement of the rock's trajectory.
- Interpretation and analysis of the records are carried out in the following way:

    - Using specific software
    - Measuring the true distance between points on the trajectory since a certain amount of distortion due to non-perpendicularity between the rockfall plane and the direction of view the front camera is practically unavoidable.
    - Calculating translational and rotational velocities, and integrating all data collected from the analysis of all camera records to achieve the best assessment
    - Evaluation of bounce height from analysis of the experimental data.

A comparison between experimental results and computer simulations of height of bounce, velocity and frequency of rotation for two slopes are shown in Figures 2.8 and 2.9.

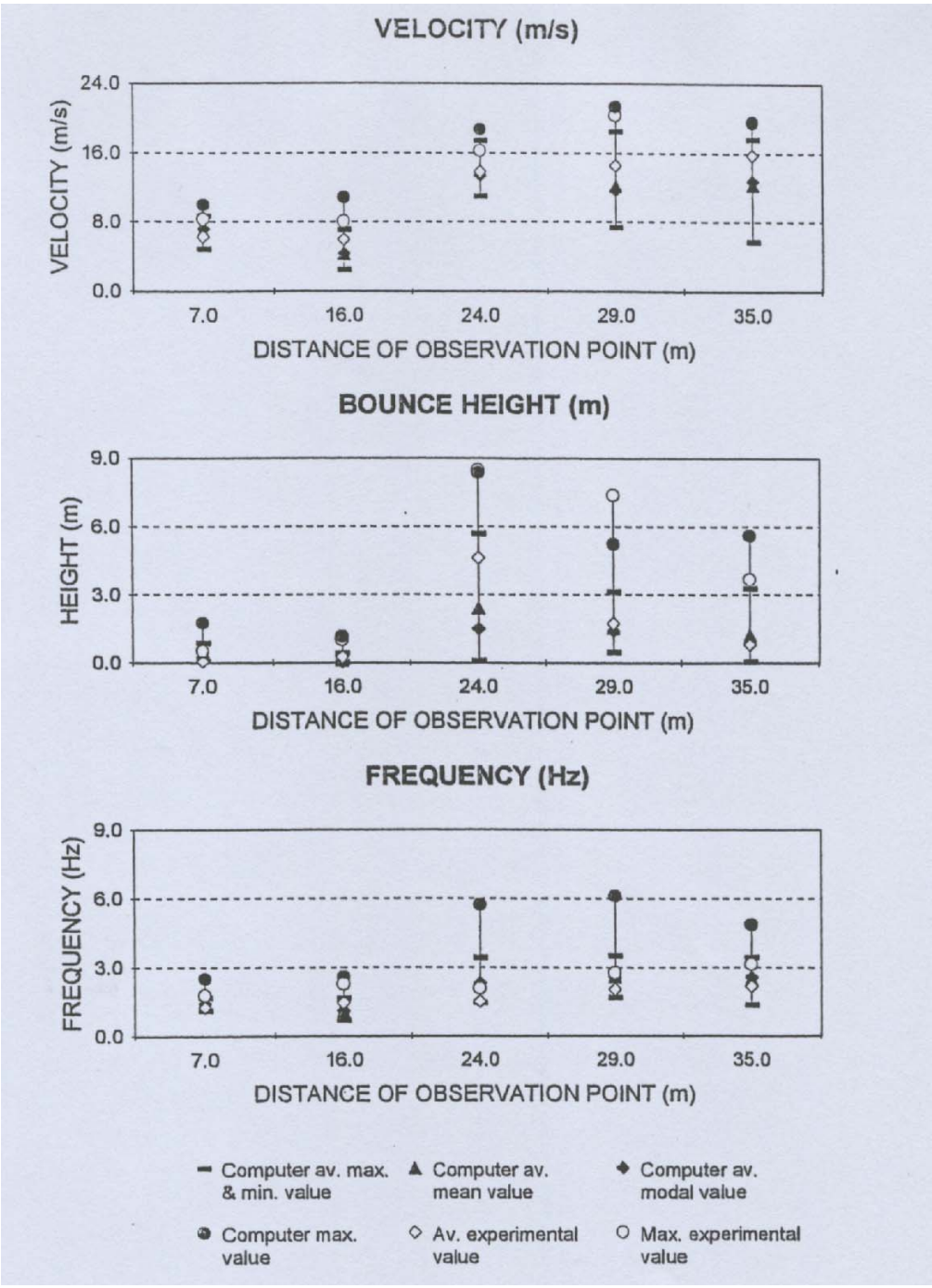


Figure 2.8. Comparison between the computer analysis results and experimental data, for slope A (Azzoni *et al*, 1995).

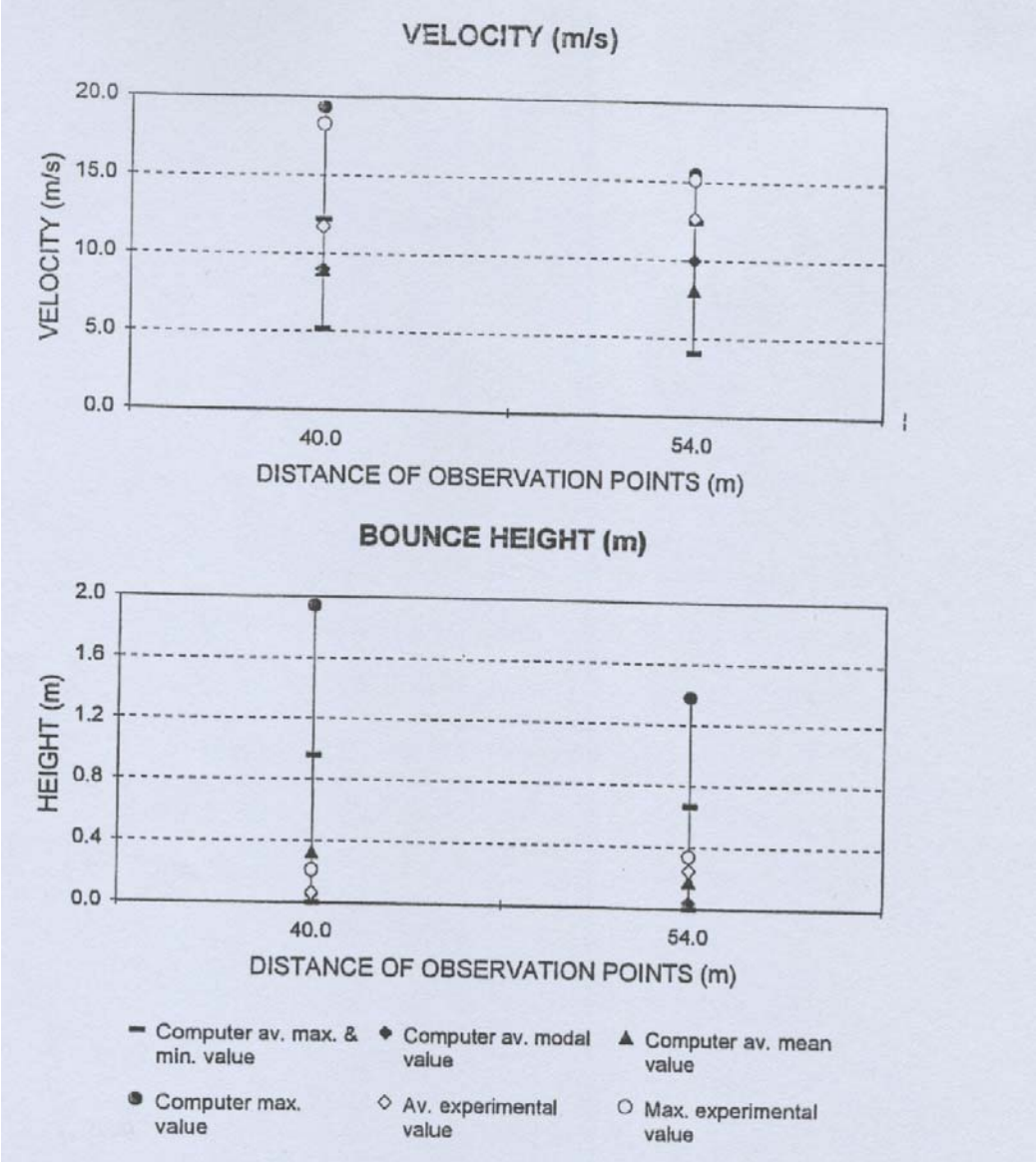


Figure 2.9. Comparison between the computer analysis results and the experimental data, for slope B (Azzoni *et al*, 1995)

The diagrams also show the relation between experimental values and the values provided by the computer analysis. These values were assessed at specific observation points placed at critical positions on the slopes. From these results, the conclusions drawn are as follows:

- Translational and rotational velocity and energy: the program is generally able to make correct (or at least acceptable) predictions of these parameters. In particular, the experimental velocity generally falls within the range of predicted values, and is always described satisfactorily by mean and the modal value.
- Height of bounce: if the topographical input is good, the program is generally

able to find correct results for this parameter. In the sections below steep rock slopes, it tends to underestimate the values, though in this case a possible inaccuracy in the experimental values due to over-estimation should be taken into account.

- Run-out distance (rock endpoints). The program provides acceptable results for this parameter. In particular, the stopping effect of a ditch full of muddy water was also simulated correctly in view of the fact that this ditch stopped over 80% of the falling blocks (Azzoni *et al*, 1995).

Thus, the program CADMA may be used with a high level of confidence to determine the influence of bench geometries on rockfall behaviour in open pit mines.

Krauter and Spang (2003) deal with the application of a commercially available rockfall simulation program ROCFALL 6.0. This program belongs to the rigorous method category, i.e., the size and shape of the blocks are assumed and all the block movements, including those involving block rotation, are considered. The program was used to design rockfall mitigation measures on a slope for the protection of railroads for Japan Railways. The slope extends about 50 m above the railway line and shows an average inclination of 35 degrees. It is topped by a 80 m high nearly vertical rockwall. The results of the application of the program are showed in Table 2.1.

The detachment zone of rockfalls stretched from behind the crest down to the toe of the rock face, so there are different heights of rockfalls. That explains the two columns, in Table 2.1, of minimum and maximum values of different parameters. The minimum values represent the parameters of rockfalls at the lowest height (toe of the rock face) and maximum values at the highest (behind the crest). This is rational because in physics, the velocity and kinetic energy increase with increasing height of fall.

Therefore, the application illustrates the influence of slope geometry, say, height of rockfall detachment on rockfall behaviour, which is expressed in terms of different parameters in Table 2.1.

Table 2.1. Numerical results of ROCKFALL 6.0. (Krauter and Spang, 2003).

No	Parameter	Dimension	Min.	Max.	Mean	Standard deviation
1	Required barrier height	m	0.83	5.77	0.98	0.22
2	Total energy	kJ	31	2.512	253	356
3	Translational kinetic energy	kJ	22	1.958	184	260
4	Rotational kinetic energy	kJ	9	646	69	99
5	Translational velocity	m/s	3	25	6	4
6	Rotational velocity	i/s	3	27	7	5
7	Momentum	tm/s	17	158	41	26
8	Angular momentum	tm^2/s	6	48	13	8
9	Angle against barrier	^{o}	-123	-72	-87	17

2.3 Comparisons and discussions

The experimental approach is based on physical rockfall tests. These might damage the structures to be protected or require the interruption of mining operations (Spang, 1987). Tests on scale models can undoubtedly be considered as an important stage in the understanding of rockfall phenomenology. These physical tests define the leading criteria for the design of protective work such as fences, fill, rockfall shelter, catch benches and ditch. In most cases the number of rocks rolled is not sufficient to obtain statistically reliable results.

In contrast, rockfall simulation is always applicable, quick and reproducible (Krauter and Spang, 2003). However, simulation requires detailed site condition and slope geometry input data and assumptions; therefore accuracy varies, depending on the quality of input data (Pierson *et al*,1994).

From the review of literature, it appears that the only available design criterion for catch benches in open pit mines is the Modified Ritchie Criterion. This is considered to be an unsatisfactory situation since there is a variety of stack configurations, and different types of rock mass have different coefficients of restitution. To investigate the validity of the Modified Ritchie Criterion, in this research project, a range of rockfall simulations will be carried out using Rocscience's ROCFALL version 4 program (Rocscience, 2002). This program analyses the falls in a two-dimensional space and assumes blocks to have their mass concentrated at one point. It was used for rockfall analysis at the ETH organization in 2002. A description of the research project follows in the next section.

3 THE AIM OF THE PROJECT

The aim of this research project is to determine the effect of bench geometries (bench height, bench stack height, bench face angle, catch bench width) on rockfall behaviour. This effect is expressed in terms of:

- The assessment of height of bounce and kinetic energy achieved during the fall on the catch bench, which are parameters necessary for the selection of required energy absorption capacity and required height of rockfall mitigation measures (catch fence).

- The assessment of maximum run-out distances (maximum distance from toe of the bottom bench that falling rocks can roll on the catch bench), in order to determine the areas at risk so that the catch bench width will be designed appropriately.

Different materials will be assumed for the bench in order to determine their impact on the output assessment criteria, as above, for the rockfall analysis. The different materials are represented by different coefficients of restitution. The Rocscience Coefficient of Restitution Table is given in Appendix A.

The rockfall analyses must therefore be performed to determine the impact of all the factors associated with the nature of the material of the bench and stack geometry.

For interpretation of the results, the following output data will be generated for each result:

- The horizontal location of rock endpoints
- Histograms of total kinetic energy and bounce heights.

Quantification of variation of rock endpoints, total kinetic energy and bounce height according to the output results for different values of bench height, bench face angle and catch bench width will be done.

It is important to note that in the philosophy of application of numerical modelling, the obtaining of absolute answers should not be an aim, but it is the trends and the results of comparisons between a range of analyses that are important (Diering and Stacey, 1987; Stacey, 2004). The analyses carried out for this research project are described in Chapter 4.

4 ANALYSIS OF DIFFERENT STACK CONFIGURATIONS

Slopes in open pit mines may be considered to consist of four components. These are, in descending order of importance: overall slope, ramp slope, bench stack and bench. With regard to rockfalls, it is generally the bench stacks and benches that are of relevance. Ramp slopes may be relevant on occasions, and overall slopes are unlikely to be the subject of rockfalls. In this research project, attention is focused on bench and bench stack geometries. The purpose is to determine the influence of bench geometries on rockfall behaviour. As indicated above, this influence will be considered in terms of maximum run-out distance of falling rocks on the catch bench, which will be compared with the value obtained from the application of Modified Ritchie Criterion. As discussed in the review of literature, the Modified Ritchie Criterion is an empirical relationship between the slope height and the average, or preferred, catch bench width. It is as follows (Ryan and Pryor, 2000):

Catch bench width: 0.2 x slope height + 4.5 m

In addition, results obtained will be analysed in order to determine the satisfactory location of a barrier (catch fence) on the catch bench, with the aim of reducing the width of the bench. The factors taken into account in this analysis will be the total kinetic energy, the bounce height and the number of falling rocks reaching it. For the total kinetic energy and catch fence height considerations, the information on capacities of Geobrugg catch fences in Table 4.1 (Fatzer, 2001) will be used.

Table 4.1. System configurations for absorption of energies between 250 and 3000 kJ.

Type	RXI-025	RX-075	RX-150	RX-200	RX-300
Energy absorption	250 kJ	750 kJ	1500 kJ	2000 kJ	3000 kJ
Height of barrier min.	2 m	2 m	3 m	4 m	5 m
Height of barrier max.	5 m	5 m	5 m	6 m	7 m

The Geogrugg catch fences consist of regular steel posts, support wire ropes and the Rocco ring net which was specially designed to absorb kinetic energy. The posts are anchored to the rock either by grouting them into large diameter holes or by using rock anchors. It is important that the rock where the posts are anchored is stable (Fatzer, 2001).

The stack configurations chosen for analysis in this project were based on information gained from a review of literature on open pit mines (Hendricks and Dahlstrand, 1979; Koskiniemi, 1979; Seegmiller, 1979; Bye and Bell, 2001). This has resulted in the selection of three stack configurations for this project, which are shown below:

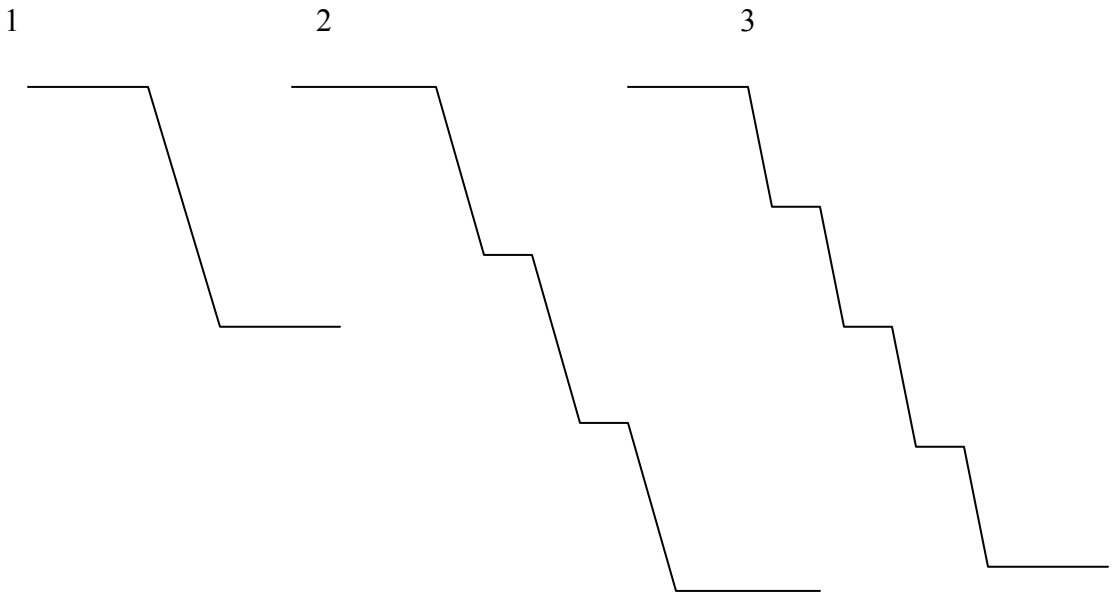


Figure 4.1. Stack configurations.

As seen above, the stack configurations may be described as follows:

- Configuration 1 has 1 bench with a catch bench at the toe;
- Configuration 2 has 3 benches with step outs between 2 consecutives benches and a catch bench at the toe of bottom bench;
- Configuration 3 has 4 benches with step outs between 2 consecutives benches and a catch bench at the toe of bottom bench.

These configurations will be used with different values for bench height, bench face angle and coefficients of restitution as follows:

- Bench height: 8 m, 10 m, 12 m and 15 m as most large mining operations drill and blast on 12 to 15 m intervals;
- Bench face angle: 60^o, 70^o, 80^o and 90^o;
- Coefficients of restitution: the Rocscience Coefficient of Restitution Table (Rocscience, 2003) shows that normal and tangential coefficients of restitution vary between 0 and 1. The rock in open pit mines, especially that of catch benches is usually not clean hard bedrock, but is covered with talus because of blasting, bad weather and passage of trucks and excavators. The selection of adequate coefficients of restitution is important because the results (simulations) are sensitive to the values chosen. Trial simulations run with values from the Rocscience Coefficient of Restitution Table (Appendix A) less than RN (normal coefficient of restitution): 0.487, RT (tangential coefficient of restitution): 0.910 produce results with low values of maximum run-out distance that do not allow satisfactory analysis of the influence of bench geometries on rockfall behaviour. Values more than RN = 0.487 and RT = 0.910 in the same table, are mostly for clean bedrock, concrete and a forested slope. Results to prove the former case are shown in Appendix A.

  As a general rule, harder materials have higher coefficients of restitution than softer materials. Based on values in the Rocscience Coefficient of Restitution Table, by engineering judgment, RN = 0.487 (standard deviation: 0.00), and RT = 0.91 (standard deviation: 0.00) have been selected as softer material, RN = 0.6 (standard deviation: 0.03), RT = 0.6 (standard deviation: 0.03) and RN = 0.75 (standard deviation: 0.00), RT = 0.53 (standard deviation: 0.00) have been assumed as mean and harder materials respectively. Trial simulations run with these coefficients of restitution have provided more realistic paths of rockfalls for the purpose of this project.

Table 4.2. Coefficients of restitution based on the results from Rocscience Coefficient of Restitution Table (Appendix A).

Rock type	Coefficient of normal restitution		Coefficient of tangential restitution	
	Mean	Standard deviation	Mean	Standard deviation
One	0.487	0.000	0.910	0.000
Two	0.600	0.030	0.600	0.030
Three	0.750	0.000	0.530	0.000

For the ROCFALL simulations, initial horizontal velocities of 0.1 m/s and 0.5 m/s were considered, but no realistic paths of rockfalls were obtained for these values, as can be seen from the results in Appendix A. When simulations were run with a horizontal velocity of 1.5 m/s (standard deviation: 0.15), more realistic paths of falling rocks were obtained. Thus, this value is found to be conservative.

Open pit mining operations are usually carried out in hard rocks. The choice of friction angle was based on published information. In an article prepared for RocNews Fall 2003 (Rocscience, 2003), it is pointed out that, given the same material on the slope, and the same material making up the rocks, if the rocks are long flat slabs, then the mode of movement will be sliding, and the friction angle will be higher (much closer to a "standard" friction angle, as can be determined by a tilt test). If the rocks are all spherical, then the mode of movement will tend to be rolling, rather than sliding, and the effective value of the friction angle will be much lower (close to zero).

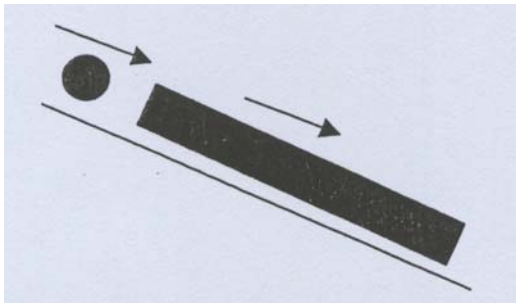


Figure 4.2: Segment of the slope and typical falling rock shape (Rocscience, 2000).

Hoek and Bray (1977) have indicated that the highest friction angle is 50^o and the lowest 7^o. From these findings, an angle of friction of 30^o was selected for an average rock to be used for the numerical modelling in the project. An analysis of the influence of the falling rock shape will be conducted, by considering friction angle of 10^o to represent rocks that are spherically shaped and 40^o to represent rocks that are flat slabs. The results from these analyses will be compared in terms of maximum run-out distance and maximum bounce height with those for a friction angle of 30^o.

Analyses were conducted using 5kg, 10kg and 20kg rocks to determine the appropriate mass of the rock fall. The rock paths resulting from the simulations were almost the same and a 10 kg rock mass was therefore chosen as appropriate for this project. Several analyses will be conducted with greater masses of rock to see their impact on rockfall behaviour. It is noted that Krauter and Spang (2001) used a mass of 6.437 kg.

Figure 4.3 shows the geometry of the bench stack and the parameters used for definition of the geometry. The parameter "x" (which appears in the histograms of total kinetic energy and bounce heights) is the horizontal distance of the barrier on the catch bench from the origin (x = 0 is the x-coordinate of the start point of top bench of the stack configuration). The run-out distance is the difference between the x-coordinate of the toe of the catch bench and final x-coordinate of rocks on the same bench. The maximum run-out distance is the difference between the x-coordinate of the toe of the catch bench and x-coordinate of the furthest final position rock position on the same bench.

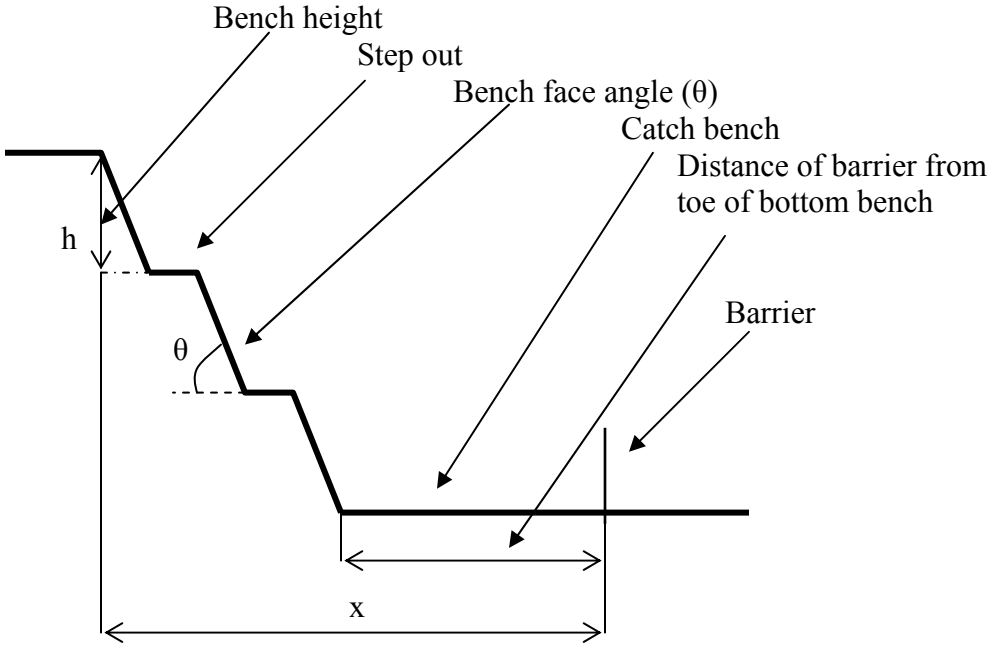


Figure 4.3: Description of a stack configuration.

The computer simulations using ROCFALL generate figures of total kinetic energy and bounce height distribution. For each simulation, the total kinetic energy of rocks at each barrier location is determined. This energy will be determined by considering the highest value on the Total Kinetic Energy Distribution histogram. This total energy is considered to be the energy absorption capacity of barrier.

Very large volumes of output have been generated by simulations carried out for this research project. It is not possible to include all these data in the report, and therefore overall results are summarized, with only representative results being presented as examples. A full set of output data has been written to a CD, which is attached. For each of case of rockfall numerical modelling, the following are contained on the attached CD-

R: histograms of total kinetic energy distribution and bounce height distribution, profiles of rock paths, and rocfall analysis information. For each case of rockfall numerical modeling, the specified file name is “buana” plus a specific number. Details of the files and the means of accessing those files are contained in Appendix A.

In the following sections, results are given for different stack configurations and for the range of different variables in each stack.

4.1 Stack configuration 1

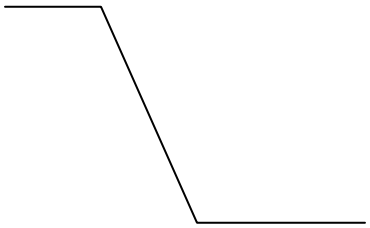


Figure 4.4: Stack configuration 1.

Stack configuration 1 has a single bench. Thus, to be comparable with the bench stack heights for the two other stack geometries (2 and 3), double bench heights will be considered. Therefore, four double bench heights (16 m, 20 m, 24 m and 30 m) will be analysed, each of them with 4 bench face angles (60^o, 70^o, $80^o$and 90^o), and 3 different rock types as indicated above, to determine the optimum location of barrier. The tables below contain the input and output rockfall parameters as follows:

- Bench face angle;
- Maximum-run out distance: difference between the x-coordinate of the toe of the catch bench and the x-coordinate of the furthest final rock position on the same bench;
- Analysed bench width/Modified Ritchie bench width:
  (Maximum run-out distance – Designed bench width)/”Designed” bench width
- x-coordinate of the recommended location of the barrier on the catch bench (x = 0 is the x-coordinate of the crest of top bench of a stack configuration);
- Recommended location of barrier (with characteristics defined above) at a specific distance from the toe of the bottom bench, in order to reduce the bench width;
- Recommended height of barrier;
- Distance of barrier from toe of bottom bench;
- Maximum bounce height of rocks along the catch bench at a specific distance of barrier, taken as catch fence or barrier height;
- Number of rocks: number of falling rocks (within the histogram interval) reaching the maximum bounce height;
- The maximum total kinetic energy out of the 500 kg rockfalls simulated is taken as the required energy absorption capacity of a barrier.

4.1.1 Bench height: 16 m

As the stack configuration has one bench, the slope height is the same as the bench height, namely 16 m. The "designed" bench width, using the Modified Ritchie criterion is determined as:

"Designed" bench width = 0.2 x 16 + 4.5 = 7.7 m

Results of numerical modelling

a) Rock type: One (see Table 4.2)

The results for the four bench face angles are summarized in Table 4.3, and the results compared with the "designed" bench width. The detailed results relating to the choice of barrier location and barrier height are contained in Tables B.1, B.2, and B.3 for 70^o, 80^o and 90^o bench face angles respectively in Appendix B. An example of these results is given in Table 4.4 for a 60^o bench face angle.

Table 4.3. Summary of results for the four bench face angles, stack configuration 1, 16 m bench height, rock type One.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	14.7	13.7	18.1	8.1
Analysed bench width/Modified Ritchie bench width	+91%	+78%	+135%	+5%
Recommended location of barrier (x distance from toe of bottom bench in m)	2.0	2.2	2.8	3.5
Recommended height of barrier (m)	2.0	2.2	2.75	3.9

Table 4.4. Rockfall parameters for stack configuration 1, 16 m bench height, 60^o bench face angle, rock type One (File name on CD-R: buana89).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	10.4	11.2	12	12.8
Distance of barrier from toe of bottom bench (m)	1.1	2	2.8	3.6
Maximum bounce height (m)	1.1	1.56	1.83	1.83
Recommended height of barrier (m)	2.0	2.0	2.0	2.0
Number of rocks	67	33	1	400
Maximum total kinetic energy (kJ)	0.350	0.300	0.300	0.300

b) Rock type: Two (see Table 4.2)

The results for the four bench face angles are summarized in Table 4.5, and the results compared with the "designed" bench width. The detailed results relating to the choice of barrier location and barrier height are contained in Tables B.4, B.5, B.6 and B.7 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix B.

Table 4.5. Summary of results for the four bench face angles, stack configuration 1, 16 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	10.7	8.4	10.8	8.0
Analysed bench width/Modified Ritchie bench width	+39%	+8%	+40%	+4%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.2	1.4	2.8	6.3
Recommended height of barrier (m)	2.0	3.0	4.5	4.0

c) Rock type: Three (see Table 4.2)

The results for the four bench face angles are summarized in Table 4.6. The detailed results relating to the choice of barrier location and barrier height are contained in Tables B.8, B.9, B.10 and B.11 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix B.

Table 4.6. Summary of results for the four bench face angles, stack configuration 1, 16 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	11.6	10.2	10.3	9.3
Analysed bench width/Modified Ritchie bench width	+51%	+33%	+34%	+20%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.2	2.2	4.4	7.7
Recommended height of barrier (m)	2.5	3.6	5	3.1

Comparisons and discussions

In Tables 4.7, 4.8 and 4.9 below, the different rockfall parameters (maximum run-out distance, analysed bench width/Modified Ritchie bench width, and maximum bounce height) relative to 60^o, 70^o, 80^o and 90^o bench face angles in rock type One, Two and Three are compared.

Table 4.7. Summary of results for rock type One, stack configuration 1, 16 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	14.7	91	1.83
70	13.7	78	2.25
80	18.1	135	4
90	8.1	5	3.88

Table 4.8. Summary of results for rock type Two, stack configuration 1, 16 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	10.7	39	2.86
70	8.4	8	2.75
80	10.8	40	6.7
90	8	4	8.5

Table 4.9. Summary of results for rock type Three, stack configuration 1, 16 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	11.6	51	3.46
70	10.2	33	3.6
80	10.3	34	9
90	9.3	20	9.2

From the results above, the following observations can be made:

- For all bench face angles, the maximum run-out distance is longer than the 7.7 m determined using the Modified Ritchie Criterion. In most cases the criterion substantially underestimates the catch bench width required.
- In all cases, the use of a catch fence to reduce the required width of the catch bench is technically feasible.

Consideration of other geometries of falling rocks

As indicated above, different rock block geometries are represented by different angles of friction. Therefore, in addition to the analyses reported above, which were based on a average friction angle of 30^o, analyses have also been carried out for two other friction angles, 10^o and 40^o, representing spherical or rolling rocks and slabby, sliding rocks respectively. The analyses were conducted for the same stack configuration 1 with the same bench height of 16 m. The results of these analyses, tabulated below for each of the three rock types are as follows:

- Rock type: One

Table 4.10. Rockfall parameters relating to the shape of falling rock blocks for rock type One.

Friction angle (^{o})	Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
10	60	21.8	183	2.42
	70	20.1	161	2.68
	80	22.2	188	4.07
	90	8.4	8	3.88
30	60	14.7	91	1.83
	70	13.7	78	2.25
	80	18.1	135	4
	90	8.1	5	3.88
40	60	12.3	59	1.46
	70	12.9	68	2.05
	80	17.5	127	3.83
	90	8	4	3.83

(Files buana205, 207, 209 and 211 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: 10^o friction angle, and buana206, 208, 210 and 212 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: 40^o friction angle).

- Rock type: Two

Table 4.11. Rockfall parameters relating to the shape of falling rock block for rock type Two.

Friction angle (^{o})	Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
10	60	14.3	86	4.04
	70	8.4	10	3.21
	80	10.9	42	7.5
	90	8	4	7.69
30	60	10.7	39	2.86
	70	8.4	8	2.75
	80	10.8	40	6.7
	90	8	4	8.5
40	60	9.6	24.81	2.3
	70	6.6	-14	2.23
	80	10.4	35	7.12
	90	7.8	1	7.67

(Files buana213, 215, 217 and 219 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: 10^o friction angle, and buana214, 216, 218 and 220 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: 40^o friction angle).

- Rock type: Three

Table 4.12. Rockfall parameters relating to the shape of falling rock block for rock type Three.

Friction angle (^{o})	Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
10	60	15.4	100	4.72
	70	10.2	33	3.64
	80	10.3	34	9
	90	9	17	9.17
30	60	11.6	51	3.46
	70	10.2	33	3.6
	80	10.3	34	9
	90	9.3	20	9.2
40	60	9.3	21	2.67
	70	10.2	33	3.63
	80	10.3	34	9
	90	9.5	23	9.2

(Files buana221, 223, 225 and 227 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: 10^o friction angle, and buana222, 224, 226 and 228 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: 40^o friction angle).

From the results in the above tables, the following observations can be made:

- For a flatter slope, i.e. 60^o bench face angle, as could logically be expected, the maximum run-out distance is greatest for a 10^o friction angle and smallest for a 40^o friction angle. This is due to the fact that on a 60^o bench face angle, the falling rocks roll down the slope most of the time. The 10^o friction angle implies a predominance of round rocks, and these provide essentially no resistance to motion and this results in the largest maximum run-out distance. In contrast, the 40^o friction angle implies a predominance of long flat slabs, and the mode of movement will be sliding, resulting in a smaller maximum run-out distance.
- The maximum run-out distance as function of rock shape (friction shape), for 70^o, 80^o and 90^o bench face angle respectively, reduces as the normal coefficient of restitution increases. This is due to the following:
    - When the bench face angle steepens, there is a trend towards bouncing of rocks on slope and free fall instead of rolling, so the shape effect reduces;
    - The increase in the coefficient of normal restitution has a greater effect in that more kinetic energy is restituted to falling rocks, resulting in almost the same maximum run-out distance whatever the shape (friction angle).

- For all rock types, the maximum bounce height reduces as a function of the friction angle for a 60^o bench face angle. At this angle, the rocks are in contact with the slope during the rockfall. Of course, as the coefficient of normal restitution increases, an increase in the maximum bounce height results.

4.1.2 Bench height: 20 m

The "designed" bench width, using the Modified Ritchie criterion is determined as:

"Designed" bench width is = 0.2 x 20 + 4.5 = 8.5 m

Results of numerical modelling

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.13 below. The detailed results relating to the choice of barrier location and barrier height are contained in Tables B.12, B.13, B.14 and B.15 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix B.

Table 4.13. Summary of results for the four bench face angles, stack configuration 1, 20 m bench height, rock type One.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	17.9	16.6	22.1	9.1
Analysed bench width/Modified Ritchie bench width	+111%	+95%	+160%	+7%
Recommended location of barrier (x distance from toe of bottom bench in m)	2.9	3.1	1.3	4.2
Recommended height of barrier (m)	2.1	2.9	4.7	4.9

b) Rock type: Two

The results for the four bench face angles are summarized in Table 4.14. The detailed results relating to the choice of barrier location and barrier height are contained in Tables B.16, B.17, B.18 and B.19 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix B.

Table 4.14. Summary of results for the four bench face angles, stack configuration 1, 20 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	14.6	9.6	12.7	8.6
Analysed bench width/Modified Ritchie bench width	+72%	+13%	+50%	+2%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.3	1.5	4.5	6.3
Recommended height of barrier (m)	2.5	3.1	4.7	3.9

c) Rock type: Three

The results for the four bench face angles are summarized in Table 4.15. The detailed results relating to the choice of barrier location and barrier height are contained in Tables B.20, B.21, B.22 and B.23 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix B.

Table 4.15. Summary of results for the four bench face angles, stack configuration 1, 20 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	14.8	9.4	12.5	10.5
Analysed bench width/Modified Ritchie bench width	+75%	+11%	+47%	+23%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.3	1.5	5.3	8.4
Recommended height of barrier (m)	2.7	3.8	3.9	4.8

Comparisons and discussions

In Tables 4.16, 4.17 and 4.18 below, the different rockfall parameters (maximum run-out distance, analysed bench width/Modified Ritchie bench width, and maximum bounce height) relative to 60^o, 70^o, 80^o and 90^o bench face angles in rock type One, Two and Three are compared.

Table 4.16. Summary of results for rock type One, stack configuration 1, 20 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	17.9	111	2.3
70	16.6	95	3.01
80	22.1	160	4.9
90	9.1	7	4.88

Table 4.17. Summary of results for rock type Two, stack configuration 1, 20 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	14.6	72	3.84
70	9.6	13	3.7
80	12.7	50	7.82
90	8.6	2	9.7

Table 4.18. Summary of results for rock type Three, stack configuration 1, 20 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	14.8	75	4.5
70	9.4	11	4.14
80	12.5	47	11.12
90	10.5	23	11.6

From the results in the tables above, the following observations can be made:

- For all bench face angles of any rock type, the maximum run-out distance is greater than 8.5 m using the Modified Ritchie criterion. In most cases the criterion substantially underestimates the catch bench width required.
- In all cases, the use of a catch fence to reduce the required width of the catch bench is technically feasible.

4.1.3 Bench height: 24 m

The "designed" bench width, using the Modified Ritchie criterion is determined as

"Designed" bench width = 0.2 x 24 + 4.5 = 9.3 m

Results of numerical modelling

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.19. The detailed results relating to the choice of barrier location and barrier height are contained in Tables B.24, B.25, B.26 and B.27 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix B.

Table 4.19. Summary of results for the four bench face angles, stack configuration 1, 24 m bench height, rock type One.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	20.9	19.5	25.9	9.1
Analysed bench width/Modified Ritchie bench width	+125%	+110%	+179%	-2%
Recommended location of barrier (x distance from toe of bottom bench in m)	2.3	2.1	1.4	-
Recommended height of barrier (m)	2.1	2.6	2.3	-

b) Rock type: Two

The results for the four bench face angles are summarized in Tables 4.20. The detailed results relating to the choice of barrier location and barrier height are contained in Tables B.28, B.29, B.30 and B.31 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix B.

Table 4.20. Summary of results for the four bench face angles, stack configuration 1, 24 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	16.6	13.1	15.5	9.9
Analysed bench width/Modified Ritchie bench width	+79%	+41%	+67%	+7%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.4	1.2	1.4	-
Recommended height of barrier (m)	2.6	3.3	4.2	-

c) Rock type: Three

The results for the four bench face angles are summarized in Table 4.21. The detailed results relating to the choice of barrier location and barrier height are contained in Tables B.32, B.33, B.34 and B.35 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix B.

Table 4.21. Summary of results for the four bench face angles, stack configuration 1, 24 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	18.6	12	14.6	11.3
Analysed bench width/Modified Ritchie bench width	+100%	+29%	+57%	+21%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.4	1.2	6.2	9.6
Recommended height of barrier (m)	3.2	3.9	4	4.7

Comparisons and discussions

In Tables 4.22, 4.23 and 4.24 below, the different parameters (maximum run-out distance, analysed bench width/Modified Ritchie bench width, and maximum bounce height) relative to 60^o, 70^o, 80^o and 90^o bench face angles in rock type One, Two and Three are compared.

Table 4.22. Summary of results for rock type One, stack configuration 1, 24 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	20.9	125	2.77
70	19.5	110	3.6
80	26	179	4.54
90	9.1	-2	5.75

Table 4.23. Summary of results for rock type Two, stack configuration 1, 24 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	16.6	79	4.75
70	13.1	41	5.2
80	15.5	67	8.4
90	9.9	7	11.67

Table 4.24. Summary of results for rock type Three, stack configuration 1, 24 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	18.6	100	5.7
70	12	29	5.5
80	15	37	9.2
90	11.3	21	13.88

From the results in the tables above, the following observations can be made:

- Except for third rock type, the maximum bounce height is as the bench face angle increases.
- For all bench face angles, except 90^o bench face angle in first rock type, the maximum run-out distance is greater than the 9.3 m determined using the Modified Ritchie Criterion. In most cases the criterion substantially underestimates the catch bench width required.
- In all cases, except for the case mentioned above, the use of a catch fence to reduce the required width of the catch bench is technically feasible.

4.1.4 Bench height: 30 m

The "designed" bench width, using the Modified Ritchie criterion is determined as:

"Designed" bench width: 0.2 x 30 + 4.5 = 10.5 m

Results of numerical modelling

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.25. The detailed results relating to the choice of barrier location and barrier height are contained in Tables B.36, B.37, B.38 and B.39 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix B.

Table 4.25. Summary of results for the four bench face angles, stack configuration 1, 30 m bench height, rock type One.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	25.3	23.6	29.6	10.9
Analysed bench width/Modified Ritchie bench width	+141%	+125%	+182%	+4%
Recommended location of barrier (x distance from toe of bottom bench in m)	2.5	1.7	1.9	-
Recommended height of barrier (m)	2.3	2.5	2.9	-

b) Rock type: two

The results for the four bench face angles are summarized in Table 4.26. The detailed results relating to the choice of barrier location and barrier height are contained in Tables B.40, B.41, B.42 and B.43 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix B.

Table 4.26. Summary of results for the four bench face angles, stack configuration 1, 30 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	21.3	16.3	17.6	10.5
Analysed bench width/Modified Ritchie bench width	+103%	+55%	+67%	0%
Recommended location of barrier(x distance from toe of bottom bench in m)	1.6	1.7	1	-
Recommended height of barrier (m)	3.1	4.7	3.9	-

c) Rock type: Three

The results for the four bench face angles are summarized in Table 4.27. The detailed results relating to the choice of barrier location and barrier are contained in Tables B.44,

B.45, B.46 and B.47 for 60°, 70°, 80° and 90° bench face angle respectively in Appendix B.

Table 4.27. Summary of results for the four bench face angles, stack configuration 1, 30 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	23.9	17	17.7	12.6
Analysed bench width/Modified Ritchie bench width	+127%	+61%	+69%	+20%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.6	0.8	1	11.2
Recommended height of barrier (m)	3.9	3.2	4.9	4.4

Comparisons and discussions

In Tables 4.28, 4.29 and 4.30 below, the different rockfall parameters (maximum run-out distance, analysed bench width/Modified Ritchie bench width, and maximum bounce height) relative to 60°, 70°, 80° and 90° bench face angles in rock type One, Two and Three are compared.

Table 4.28. Summary of results for rock type One, stack configuration 1, 30 m bench height.

Bench face angle (°)	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	25.3	141	3.5
70	23.6	125	4.56
80	29.6	162	5.66
90	10.9	4	17.35

Table 4.29. Summary of results for rock type Two, stack configuration 1, 30 m bench height.

Bench face angle (°)	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	21.3	103	6.16
70	16.3	55	7.19
80	17.6	67	8.65
90	10.5	0	13.17

Table 4.30. Summary of results for rock type Three, stack configuration 1, 30 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	23.9	127	7.63
70	17	61	8
80	17.7	69	10.78
90	12.6	20	17.5

Form the results in the tables above, the following observations can be made:

- For all rock types, the maximum bounce height is ascendent as bench face angle increases from 60^o to 90^o
- For all bench face angles, except for 90^o in rock type two, the maximum run-out distance is greater than the 10.5 m determined using the Modified Ritchie Criterion. In most cases the criterion substantially underestimates the catch bench width required.
- In all cases, except for the case mentioned above, the use of a catch fence to reduce the required width of the catch bench is technically feasible.

4.1.5 Discussions

In general, for all rock types the variation of maximum run-out distance compared with Modified Ritchie Criteria is positive at all bench face angles, i.e. all the maximum run-out distances are larger than Modified Ritchie Criteria. In all cases, the use of a catch fence to reduce the required width of the catch bench is technically possible.

For all rock types and bench heights:

- The maximum run-out distance decreases from bench face angle 60^o to 70^o, increases from this latter angle to 80^o and after that starts again to decrease to 90^o.

- The total kinetic energy of falling rocks close to the toe of the bench at bench face angles 60^o and 70^o is less than at 80^o and 90^o. This is due to the fact that when in contact with the bench face, friction decelerates a falling rock which reduces the resulting energies. At the latter angles, there is a trend to free fall, resulting in higher total kinetic energy. Thus at this latter angle, there is proportionally higher energy restituted after impact of falling rocks on catch bench, resulting in higher bounce height. Their linear momentum is changed into angular momentum resulting in lowest maximum run-out distance.

For each rock type and specific bench face angle:

- The maximum run-out distance as a function of bench height (h: 16, 20, 24 and 30 m) increases. Thus applying the linear method of least-squares regression analysis, the maximum run-out distance as function of bench height, which is a polynomial of 1 degree (a_1+a_2h) where the determination of the coefficient a_i is carried out by running the program polfit.exe (Budavari, 2003), is tabulated below.

Table 4.31. Summary of polynomials relative to 60^o, 70^o, 80^o and 90^o bench face angles in rock type One, Two and Three for stack configuration 1.

Rock type	Bench face angle (^{o})	Polynomial (m)
One	60	2.68 + 0.76 h
	70	2.41 +0.71 h
	80	5.35 +0.83 h
	90	5.12 + 0.18 h
Two	60	- 0.77 + 0.74 h
	70	- 1.44 + 0.59 h
	80	3.11 + 0.46 h
	90	5.1 + 0.18 h
Three	60	- 2.62 +0.88 h
	70	0.54 + 0.52 h
	80	1.91 + 0.53 h
	90	5.71 + 0.23 h

- The maximum bounce height as function of bench height (h) increases. Thus applying the linear method of least-squares regression analysis, the following polynomials are obtained.

Table 4.32. Summary of polynomials relative to 60^o, 70^o, 80^o and 90^o bench face angle in rock type One, Two and Three for stack configuration 1.

Rock type	Bench face angle (^{o})	Polynomial (m)
One	60	- 0.08 + 0.12 h
	70	- 0.31 + 0.16 h
	80	2.46 + 0.1 h
	90	- 0.07 + 0.25 h
Two	60	- 2.83 + 0.34 h
	70	- 2.57 + 0.32 h
	80	4.87 + 0.13 h
	90	3.03 + 0.34 h
Three	60	- 1.41 + 0.3 h
	70	- 1.94 + 0.32 h
	80	8.27 +0.08 h
	90	- 0.26 + 0.59 h

4.2 Stack configuration 2

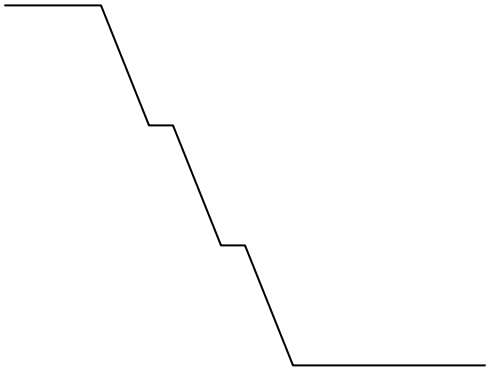


Figure 4.5: Stack configuration 2.

Stack configuration 2 has 3 benches and therefore the stack height is three times the bench height. The following parameters were considered to determine the run-out distances and bounce heights.

- Four bench heights (8, 10, 12 and 15 m)
- Four bench face angles (60^o, 70^o, 80^o and 90^o)
- Three different rock mass types as said above about stack configuration 1.

A survey will be also conducted to determine the influence of falling rock shape and mass on rockfall behaviour. The tables below contain typical rockfall parameters.

4.2.1 Bench height: 8 m

As the stack configuration has 3 benches, so the slope height is: 3 x 8 m =24 m. The "designed" bench width, using the Modified Ritchie criterion is determined as:

"Designed" bench width = 0.2 x 24 + 4.5 = 9.3 m

Results of numerical modelling

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.33. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.1, C.2, C.3 and C.4 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.33. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type One.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	14.6	21.9	19.4	6.1
Analysed bench width/Modified Ritchie bench width	+57%	+135%	+113%	-35%
Recommended location of barrier (x distance from toe of bottom bench in m)	4.7	2.6	7.1	-
Recommended height of barrier (m)	2.7	3.9	2.3	-

b) Type of rock: Two

The results for the four bench face angles are summarized in Table 4.34. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.5, C.6, C.7 and C.8 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.34. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	9.4	11.2	9.8	6.1
Analysed bench width/Modified Ritchie bench width	+0.7%	+20%	+6%	-35%
Recommended location of barrier (x distance from toe of bottom bench in m)	0.97	2.6	2.6	-
Recommended height of barrier (m)	2.8	4.5	4.7	-

c) Type of rock: Three

The results for the four bench face angles are summarized in Tables 4.35. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.9, C.10, C.11 and C.12 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.35. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	11.1	12.2	10.7	7.2
Analysed bench width/Modified Ritchie bench width	+19%	+31%	+15%	-22%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.1	5.3	6.2	-
Recommended height of barrier (m)	2.5	4.7	4.1	-

Comparisons and discussions

In Tables 4.36, 4.37 and 4.38 below, the different rockfall parameters (maximum run-out distance, analysed bench width/Modified Ritchie bench width, and maximum bounce height) relative to 60^o, 70^o, 80^o and 90^o bench face angles in rock type One, Two and Three are compared.

Table 4.36. Summary of results for rock type One, stack configuration 2, 8 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	14.6	57	2.63
70	21.9	135	4.28
80	19.8	113	2.75
90	6.1	-35	2.94

Table 4.37. Summary of results for rock type Two, stack configuration 2, 8 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	9.4	0.7	4.28
70	11.2	20	5.31
80	9.8	6	4.63
90	6.1	-35	7.82

Table 4.38. Summary of results for rock type Three, stack configuration 2, 8 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	11.1	19	3.44
70	12.2	31	7.82
80	10.7	15	7.17
90	7.2	-22	10.19

From the results in the tables above, the following observations can be made:

- In general for each bench face angle, there is an increase trend of maximum bounce height as the normal coefficient of restitution increases.
- For all rock types:
  - For 60^o, 70^o and 80^o, the maximum run-out distance is greater than the 9.3 m determined using the Modified Ritchie Criterion. The criterion substantially underestimates the catch bench width required. Thus, the use of a catch fence to reduce the required width of the catch bench is technically feasible.
  - For 90^o bench face angle, the maximum run-out distance is less than 9.3 m.
  - The maximum bounce height increases from bench face angle 60^o to 70^o, decreases from this latter to 80^o and after that, starts to increase to 90^o to attain the highest value.

Consideration of other geometries of falling rocks

Different rock block geometries are represented by different angles of friction. Consideration of geometries of falling rocks other than a 30^o friction angle will be taken into account to survey the rockfall behaviour. The survey will be conducted considering the same stack configuration 2 with the same bench height (8 m). As said above, a friction angle of 10^o represents rocks that are "spherical" and 40^o represents rocks that are flat slabs. The results of these analyses are tabulated below for each of the three rock types are as follows:

- Rock type: One

Table 4.39. Rockfall parameters relating to the shape of falling rock blocks for rock type One.

Friction angle (^{o})	Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
10	60	29.4	216	2.83
	70	27.3	193	4.15
	80	21.8	135	4.3
	90	6.1	-34	2.9
30	60	14.6	57	2.63
	70	21.9	135	4.28
	80	19.6	111	2.75
	90	6.1	-35	2.94
40	60	13.8	49	2.53
	70	21.1	127	4.31
	80	19.5	110	2.28
	90	6.3	-32	2.94

(Files buana137, 139, 141 and 143 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: friction angle 40^o, and buana138, 140, 142 and 144 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: friction angle 10^o).

- Rock type: Two

Table 4.40. Rockfall parameters relating to the shape of falling rock blocks for rock type Two.

Friction angle (^{o})	Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
10	60	11.9	28	4.5
	70	10.4	12	4.33
	80	10.5	13	5
	90	5.4	-42	6.31
30	60	9.4	0.5	4.28
	70	11.2	20	5.31
	80	9.8	6	4.63
	90	6.1	-35	7.82
40	60	8.7	-6	1.92
	70	11	18	4.9
	80	11	14	4.56
	90	5.6	-40	6.2

(Files buana146, 148, 150 and 152 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: friction angle 10^o, and buana145, 147, 149 and 151 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: friction angle 40^o).

- Rock type: Three

Table 4.41. Rockfall parameters relating to the shape of falling rock blocks for rock type Three.

Friction angle (^{o})	Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
10	60	11.1	19	6.2
	70	12.2	31	7.68
	80	10.8	16	7.19
	90	7	-25	10.19
30	60	11.1	19	3.44
	70	12.2	31	7.82
	80	10.7	15	7.17
	90	7.2	-22	10.19
40	60	10.8	16	3.17
	70	12.1	30	7.7
	80	10.8	16	7.19
	90	7.3	-21	10.19

(Files buana154, 156, 158 and 160 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: friction angle 10^o, and buana153, 155, 157 and 159 respectively for bench face angle 60^o, 70^o, 80^o and 90^o: friction angle 40^o).

From the results in the above tables, the following observations can be made:

- For a flatter slope, i.e. 60^o bench face angle, as could logically be expected, the maximum run-out distance is greatest for 10^o friction angle and smallest for a 40^o friction angle. This is due to the fact that on a 60^o bench face angle, the falling rocks are rolling down the slope most of the time, so 10^o friction angle, implying a predominance of round rocks. These provide essentially no resistance to motion and this results in largest maximum run-out distance. In contrast, the 40^o friction angle implies a predominance of long flat slab rocks, the mode of movement will be sliding, resulting in a smaller maximum run-out distance.
- The maximum run-out distance as function of rock shape (friction angle) for 70^o, 80^o and 90^o bench face angle respectively, reduces as the normal coefficient of restitution increases. This is due to the following:
    - When the bench face angle steepens, there is a trend towards bouncing of rocks on slope and free fall instead of rolling, so the shape effect reduces;
    - The increase in the coefficient of normal restitution has a greater effect in that more kinetic energy is restituted to falling rocks, resulting in almost the same maximum run-out distance whatever the

shape (friction angle);

- For all rock types, the maximum bounce height reduces as function of friction angle for a 60^o bench face angle. At this angle, the rocks are in contact with the slope during the rockfall. At 10^o friction angle, the falling rocks are rolling, so there is no resistance. This fact causes the falling rocks to reach the catch bench with more kinetic energy, so more of this energy is restituted, resulting in higher maximum bounce height. Of course, as the coefficient of normal restitution increases, an increase in maximum bounce height results.

Consideration of other masses of falling rocks

Consideration of masses other than 10 kg falling rock will be taken into account to find out their effect on rockfall behaviour. The masses of falling rock that will be considered for the survey are: 70, 110 and 150 kg. The stack configuration 2 and the bench height of 8 m are considered. The results of numerical modelling for different masses considered are as follows:

- **Mass: 70 kg**

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.42. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.13, C.14, C.15 and C.16 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.42. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type One, 70 kg falling rock mass.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	14.3	21.9	19.7	6.2
Analysed bench width/Modified Ritchie bench width	+53%	+136%	+112%	-33%
Recommended location of barrier (x distance from toe of bottom bench in m)	4.2	2.6	7.1	3.2
Recommended height of barrier (m)	2.2	3.9	2.3	3

b) Rock type: Two

The results for the four bench face angles are summarized in Table 4.43. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.17, C.18, C.19 and C.20 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.43. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type Two, 70 kg falling rock mass.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	9.1	10.4	9.7	5.2
Analysed bench width/Modified Ritchie bench width	-2%	+11%	+4%	-44%
Recommended location of barrier (x distance from toe of bottom bench in m)	2	4.4	2.6	-
Recommended height of barrier (m)	3.4	3.9	4.5	-

c) Rock type: Three

The results for the four bench face angles are summarized in Table 4.44. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.21, C.22, C.23 and C.24 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.44. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type Three, 70 kg falling rock mass.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	11	12.2	10.8	6.9
Analysed bench width/Modified Ritchie bench width	+19%	+31%	+16%	-26%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.1	5.3	6.2	-
Recommended height of barrier (m)	2.6	4.7	4.1	-

Comparisons of rockfall parameters between rock mass 10 kg and 70 kg for rock type One, Two and Three relative to 60^o, 70^o, 80^o and 90^o bench face angle respectively are tabulated below:

a) Rock type: One

• Bench face angle: 60^o

Table 4.45. Rockfall parameters for stack configuration 2, 8 m bench height, 60^o bench face angle, rock type One, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	70	10	70	10	70	10	70
x-coordinate of barrier location (m)	22.5	22	23.4	23.1	24.3	24.2	25.2	25.3
Distance of barrier from toe of bottom bench (m)	4.7	4.2	5.6	5.3	6.5	6.4	7.4	7.5
Maximum bounce height (m)	2.63	2.2	2.63	2.63	2.63	2.63	2.63	2.63
Recommended height of barrier (m)	2.7	2.2	2.7	2.7	2.7	2.7	2.7	2.7
Number of rocks	17	17	333	133	413	444	50	6
Maximum total kinetic energy (kJ)	0.278	2.333	0.167	1.550	0.167	1.167	0.278	2.333

• Bench face angle: 70^{o}

Table 4.46. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, rock type One, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	70	10	70	10	70	10	70
x-coordinate of barrier location (m)	15.3	15.3	16.2	16.2	17.1	17.1	18	18
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	5.3	5.3
Maximum bounce height (m)	3.9	3.88	4.28	4.25	4.28	4.25	4.28	4.25
Recommended height of barrier (m)	3.9	3.9	4.3	4.3	4.3	4.3	4.3	4.3
Number of rocks	89	89	133	122	117	117	267	256
Maximum total kinetic energy (kJ)	0.555	3.875	0.555	3.875	0.463	3.875	0.463	3.200

• Bench face angle: 80^{o}

Table 4.47. Rockfall parameters for stack configuration 2, 8 m bench height, 80^{o} bench face angle, rock type One, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	70	10	70	10	70	10	70
x-coordinate of barrier location (m)	15.3	15.3	16.2	16.2	17.1	17.1	18	18
Distance of barrier from toe of bottom bench (m)	7.1	7.1	8	8	8.9	8.9	9.8	9.8
Maximum bounce height (m)	2.3	2.3	2.75	2.75	2.3	2.3	2.3	2.3
Recommended height of barrier (m)	2.3	2.3	2.8	2.8	2.3	2.3	2.3	2.3
Number of rocks	168	157	18	14	186	279	100	111
Maximum total kinetic energy (kJ)	0.367	2.688	0.275	1.917	0.330	2.333	0.330	2.333

• Bench face 90^{o}

Table 4.48. Rockfall parameters for stack configuration 2, 8 m bench height, 90^{o} bench face angle, rock type One, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier	
Mass of rock (kg)	10	70	10	70	10	70
x-coordinate of barrier location (m)	7.2	7.2	8	8	8.8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	3.2	4	4	4.8	4.8
Maximum bounce height (m)	2.9	2.94	2.3	2.94	1.2	1.15
Recommended height of barrier (m)	2.9	3	2.3	3	1.2	1.2
Number of rocks	33	43	4	5	4	5
Maximum total kinetic energy (kJ)	0.350	2.438	0.263	2.438	0.088	0.600

b) Rock type: Two

• Bench face angle: 60^o

Table 4.49.Rockfall parameters for stack configuration 2, 8 m bench height, 60^o bench face angle, rock type Two, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	70	10	70	10	70	10	70
x-coordinate of barrier location (m)	18.8	18.9	19.6	19.8	20.4	20.7	21.2	21.6
Distance of barrier location (m)	0.97	1.1	1.78	2	2.6	2.9	3.66	3.8
Maximum bounce height (m)	2.78	1.67	3.63	3.33	4.19	3.33	4.19	2.94
Recommended height of barrier (m)	2.8	1.7	3.7	3.4	4.2	3.4	4.2	3
Number of rocks	6	11	6	6	6	6	6	6
Maximum total kinetic energy (kJ)	0.363	2.083	0.228	1.375	0.181	1.375	0.270	1.775

• Bench face angle: 70^{o}

Table 4.50. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, rock type Two, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	70	10	70	10	70	10	70
x-coordinate of barrier location (m)	14.4	14.4	15.3	15.3	16.2	16.2	17.1	17.1
Distance of barrier from toe of bottom bench (m)	1.7	1.7	2.6	2.6	3.5	3.5	4.4	4.4
Maximum bounce height (m)	5.3	4.63	4.5	4.63	4.1	4.25	4.1	4.25
Recommended height of barrier (m)	5.3	4.7	4.5	4.7	4.1	4.3	4.1	4.3
Number of rocks	6	8	8	6	17	6	11	6
Maximum total kinetic energy (kJ)	0.963	7.375	0.455	2.833	0.340	2.833	0.455	2.833

• Bench face angle: 80^{o}

Table 4.51. Rockfall parameters for stack configuration 2, 8 m bench height, 80^{o} bench face angle, rock type Two, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	70	10	70	10	70	10	70
x-coordinate of barrier location (m)	10.8	10.8	11.7	11.7	12.6	12.6	13.5	13.5
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	5.3	5.3
Maximum bounce height (m)	4.63	4.42	4.63	4.9	4.63	4.42	3.69	3.9
Recommended height of barrier (m)	4.7	4.5	4.7	4.9	4.7	4.50	3.7	3.9
Number of rocks	4	18	7	5	4	5	4	4
Maximum total kinetic energy (kJ)	1.000	2.550	0.428	3.300	0.428	3.300	0.370	2.900

• Bench face angle: 90^{o}

Table 4.52. Rockfall parameters for stack configuration 2, 8 m bench height, 90^{o} bench face angle, rock type Two, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier	
Mass of rock (kg)	10	70	10	70	10	70
x-coordinate of barrier location (m)	7.2	7.2	8	8	8.8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	3.2	4	4	4.8	4.8
Maximum bounce height (m)	6.4	5.55	4.28	2.08	2.88	0.69
Recommended height of barrier (m)	5	5	4.3	2.1	2.9	2
Number of rocks	4	9	4	9	4	9
Maximum total kinetic energy (kJ)	0.550	3.850	0.160	1.625	0.080	0.550

c) Rock type: Three

• Bench face angle: 60^o

Table 4.53. Rockfall parameters for stack configuration 2, 8 m bench height, 60^o bench face angle, rock type Three, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	70	10	70	10	70	10	70
x-coordinate of barrier location (m)	18.9	18.9	19.8	19.8	20.7	20.7	21.6	21.6
Distance of barrier from toe of bottom bench (m)	1.1	1.1	2	2	2.9	2.9	3.8	3.8
Maximum bounce height (m)	2.45	2.58	3.44	3.28	3.19	3.05	2.69	2.56
Recommended height of barrier (m)	2.5	2.6	3.5	3.3	3.2	3.1	2.7	2.6
Number of rocks	6	6	6	8	11	8	11	8
Maximum total kinetic energy (kJ)	0.292	2.000	0.194	1.333	0.245	1.333	0.245	1.667

• Bench face angle: 70^{o}

Table 4.54. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, rock mass Three, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	70	10	70	10	70	10	70
x-coordinate of barrier location (m)	10.8	10.8	11.7	11.7	12.6	12.6	13.5	13.5
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	5.3	5.3
Maximum bounce height (m)	6.5	6.2	5.88	5.81	5.46	5.42	4.69	4.65
Recommended height of barrier (m)	5	5	5	5	5	5	4.7	4.7
Number of rocks	21	23	179	181	83	77	29	38
Maximum total kinetic energy (kJ)	0.600	4.163	0.333	2.333	0.600	4.150	0.600	4.150

• Bench face angle: 80^{o}

Table 4.55. Rockfall parameters for stack configuration 2, 8 m bench height, 80^{o} bench face angle, rock type Three, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	70	10	70	10	70	10	70
x-coordinate of barrier location	10.8	10.8	11.7	11.7	12.6	12.6	13.5	13.5
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	5.3	5.3
Maximum bounce height (m)	7.2	7.19	7.2	7.19	6.67	6.67	5.63	5.63
Recommended height of barrier (m)	5	5	5	5	5	5	5	5
Number of rocks	5	7	61	57	136	136	38	14
Maximum total kinetic energy (kJ)	1.150	8.000	0.450	4.000	0.513	3.563	0.700	5.333

• Bench face angle: 90^{o}

Table 4.56. Rockfall parameters for stack configuration 2, 8 m bench height, 90^{o} bench face angle, rock type Three, 10 and 70 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	70	10	70	10	70	10	70
x-coordinate of barrier location (m)	7.2	7.2	8	8	8.8	8.8	9.6	9.6
Distance of barrier from toe of bottom bench (m)	3.2	3.2	4	4	4.8	4.8	5.6	5.6
Maximum bounce height (m)	10.2	10.2	9.38	9.3	6	6	3.4	4.25
Recommended height of barrier (m)	5	5	5	5	5	5	3.4	4.3
Number of rocks	13	25	4	4	8	6	8	4
Maximum total kinetic energy (kJ)	0.875	5.563	0.875	6.667	0.558	3.900	0.480	2.250

Ratios of total kinetic energies for masses of 70 kg compared to 10 kg for rock type One, Two and Three are tabulated below:

- Rock type: One

Table 4.57. Ratios of total kinetic energies for masses of 70 kg compared to 10 kg for rock type One.

Bench face angle (^{o})	Location of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
60	8.4	9.3	7	8.4
70	7	7	8.4	6.9
80	7.3	7	7.1	7.1
90	7	9.3	6.8	

- Rock type: Two

Table 4.58. Ratios of total kinetic energies for masses of 70 kg compared to 10 kg for rock type Two.

Bench face angle (^{o})	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
60	5.7	6	7.6	6.6
70	7.7	6.2	8.3	6.2
80	3	7.7	7.7	7.8
90	7	10.2	6.9	

- Rock type: Three

Table 4.59. Ratios of total kinetic energies for masses of 70 kg compared to 10 kg for rock type Three.

Bench face angle (^{o})	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
60	6.8	6.9	5.4	6.8
70	6.9	7	5.4	6.9
80	7	8.9	6.9	7.6
90	6.3	7.6	7	4.7

- **Mass: 110 kg**

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.60. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.25, C.26, C.27 and C.28 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.60. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type One, 110 kg falling rock mass.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	14.4	21.8	19.5	6
Analysed bench width/Modified Ritchie bench width	+55%	+135%	+110%	-35%
Recommended location of barrier (x distance from toe of bottom bench in m)	4.7	2.6	7.1	3.2
Recommended height of barrier (m)	2.7	3.9	2.3	2.9

b) Rock type: Two

The results for the four bench face angles are summarized in Table 4.61. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.29, C.30, C.31 and C.32 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.61. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type Two, 110 kg falling rock mass.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	9.5	10.5	10.4	5.6
Analysed bench width/Modified Ritchie bench width	+2%	+12%	+11%	-40%
Recommended location of barrier (x distance from toe of bottom bench in m)	0.6	1.7	3.5	-
Recommended height of barrier (m)	2.1	4.8	4.7	-

c) Rock type: Three

The results for the four bench face angles are summarized in Table 4.62. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.33, C.34, C.35 and C.36 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.62. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type Three, 110 kg falling rock mass.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance(m)	11	12.2	10.8	6.9
Analysed bench width/Modified Ritchie bench width	+19%	+31%	+16%	-28%
Recommended location of barrier (x distance from toe of bottom bench in m)	18.9	5.3	6.2	-
Recommended height of barrier (m)	2.2	4.7	4	-

Comparisons of rockfall parameters between rock mass 10 kg and 110 kg for rock type One, Two and Three relative to 60^o, 70^o, 80^o and 90^o bench face angle respectively are tabulated below:

a) Rock type: One

• Bench face angle: 60^o

Table 4.63. Rockfall parameters for stack configuration 2, 8 m bench height, 60^o bench face angle, rock type One, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	110	10	110	10	110	10	110
x-coordinate of barrier location (m)	22.5	22.5	23.4	23.4	24.3	24.3	25.2	25.2
Distance of barrier from toe of bottom bench (m)	4.7	4.7	5.6	5.6	6.5	6.5	7.4	7.4
Maximum bounce height (m)	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63
Recommended height of barrier (m)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Number of rocks	17	8	333	333	413	444	50	39
Maximum total kinetic energy (kJ)	0.278	3.063	0.167	1.833	0.167	1.833	0.278	3.063

• Bench face angle: 70^{o}

Table 4.64. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, rock type One, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	110	10	110	10	110	10	110
x-coordinate of barrier location (m)	15.3	15.3	16.2	16.2	17.1	17.1	18	18
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	5.3	5.3
Maximum bounce height (m)	3.9	3.88	4.28	4.25	4.28	4.25	4.28	4.25
Recommended height of barrier (m)	3.9	3.9	4.3	4.3	4.3	4.3	4.3	4.3
Number of rocks	89	89	133	122	117	117	267	272
Maximum total kinetic energy (kJ)	0.555	6.100	0.555	6.100	0.463	5.100	0.463	5.100

• Bench face angle: 80^{o}

Table 4.65. Rockfall parameters for stack configuration 2, 8 m bench face angle, 80^{o} bench face angle, rock type One, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	110	10	110	10	110	10	110
x-coordinate of barrier location (m)	15.3	15.3	16.2	16.2	17.1	17.1	18	18
Distance of barrier from toe of bottom bench (m)	7.1	7.1	8	8	8.9	8.9	9.8	9.8
Maximum bounce height (m)	2.3	2.3	2.75	2.75	2.3	2.3	2.3	2.3
Recommended height of barrier (m)	2.3	2.3	2.8	2.8	2.3	2.3	2.3	2.3
Number of rocks	168	185	18	13	186	200	100	100
Maximum total kinetic energy (kJ)	0.367	4.225	0.275	3.625	0.330	3.625	0.330	3.625

• Bench face angle: 90^{o}

Table 4.66. Rockfall parameters for stack configuration 2, 8 m bench height, 90^{o} bench face angle, rock type One, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier	
Mass of rock (kg)	10	110	10	110	10	110
x-coordinate of barrier location (m)	7.2	7.2	8	8	8.8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	3.2	4	4	4.8	4.8
Maximum bounce height (m)	2.9	2.9	2.3	2.3	1.2	1.17
Recommended height of barrier (m)	2.9	2.9	2.3	2.3	2	2
Number of rocks	33	46	4	6	4	7
Maximum total kinetic energy (kJ)	0.350	3.875	0.263	3.875	0.088	1.000

b) Rock type: Two

• Bench face angle: 60^o

Table 4.67. Rockfall parameters for stack configuration 2, 8 m bench height, 60^o bench face angle, rock type Two, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	110	10	110	10	110	10	110
x-coordinate of barrier location (m)	18.8	18.4	19.61	19.2	20.4	20	21.2	20.8
Distance of barrier from toe of bottom bench (m)	0.97	0.6	1.78	1.4	2.6	2.2	3.66	3
Maximum bounce height (m)	2.78	2.04	3.63	3.44	4.19	3.8	4.19	3.5
Recommended height of barrier (m)	2.8	2.1	3.7	3.5	4.2	3.8	4.2	3.5
Number of rocks	6	6	6	6	6	6	6	8
Maximum total kinetic energy (kJ)	0.363	3.300	0.228	2.188	0.181	2.188	0.270	2.750

• Bench face angle: 70^{o}

Table 4.68. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, rock type Two, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock(kg)	10	110	10	110	10	110	10	110
x-coordinate of barrier location (m)	14.4	14.4	15.3	15.3	16.2	16.2	17.1	17.1
Distance of barrier from toe of bottom bench (m)	1.7	1.7	2.6	2.6	3.5	3.5	4.4	4.4
Maximum bounce height (m)	5.3	4.73	4.5	4.3	4.1	4.3	4.1	4.3
Recommended height of barrier (m)	5	4.8	4.5	4.3	4.1	4.3	4.1	4.3
Number of rocks	6	8	8	11	17	6	11	6
Maximum total kinetic energy (kJ)	0.963	10.525	0.455	5.000	0.340	4.350	0.455	4.350

• Bench faced angle: 80^{o}

Table 4.69. Rockfall parameters for stack configuration 2, 8 m bench height, 80^{o} bench face angle, rock type Two, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	110	10	110	10	110	10	110
x-coordinate of barrier location (m)	10.8	10.8	11.7	11.7	12.6	12.6	13.5	13.5
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	5.3	5.3
Maximum bounce height (m)	4.63	4.25	4.63	4.7	4.63	4.25	3.69	4.25
Recommended height of barrier (m)	4.7	4.3	4.7	4.7	4.7	4.3	3.7	4.3
Number of rocks	4	6	7	6	4	22	4	6
Maximum total kinetic energy (kJ)	1.000	11.200	0.428	3.525	0.428	4.750	0.370	4.750

• Bench face angle: 90^{o}

Table 4.70. Rockfall parameters for stack configuration 2, 8 m bench height, 90^{o} bench face angle, rock type Two, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier	
Mass of rock (kg)	10	110	10	110	10	110
x-coordinate of barrier location (m)	7.2	7.2	8	8	8.8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	3.2	4	4	4.8	4.8
Maximum bounce height (m)	6.4	5.17	4.28	3	2.88	1.5
Recommended height of barrier (m)	5	5	4.3	3	2.9	2
Number of rocks	4	9	4	5	4	5
Maximum total kinetic energy (kJ)	0.550	6.050	0.160	2.600	0.080	0.875

c) Rock type: Three

• Bench face angle: 60^o

Table 4.71. Rockfall parameters for stack configuration 2, 8 m bench height, 60^o bench face angle, rock type Three, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	110	10	110	10	110	10	110
x-coordinate of barrier location (m)	18.9	18.9	19.8	19.8	20.7	20.7	21.6	21.6
Distance of barrier from toe of bottom bench (m)	1.1	1.1	2	2	2.9	2.9	3.8	3.8
Maximum bounce height (m)	2.45	4.65	3.44	6.14	3.19	5.52	2.69	2.76
Recommended height of barrier (m)	2.5	4.7	3.5	5	3.2	5	2.7	2.8
Number of rocks	6	6	6	6	11	11	11	8
Maximum total kinetic energy (kJ)	0.292	3.250	0.194	2.167	0.245	2.167	0.245	4.333

• Bench face angle: 70^{o}

Table 4.72. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, rock type Three, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	110	10	110	10	110	10	110
x-coordinate of barrier location (m)	15.3	15.3	16.2	16.2	17.1	17.1	18	18
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	5.3	5.3
Maximum bounce height (m)	6.5	6.3	5.88	5.9	5.46	5.5	4.69	4.7
Recommended height of barrier (m)	5	5	5	5	5	5	4.7	4.7
Number of rocks	21	11	179	143	83	79	29	36
Maximum total kinetic energy (kJ)	0.600	5.917	0.333	4.417	0.600	6.625	0.600	6.625

• Bench face angle: 80^{o}

Table 4.73. Rockfall parameters for stack configuration 2, 8 m bench height, 80^{o} bench face angle, rock type Three, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	110	10	110	10	110	10	110
x-coordinate of barrier location (m)	10.8	10.8	11.7	11.7	12.6	12.6	13.5	13.5
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	5.3	5.3
Maximum bounce height (m)	7.2	7.44	7.2	7.44	6.67	6.83	5.63	5.7
Recommended height of barrier (m) 5	5	5	5	5	5	5	5	5
Number of rocks	5	7	61	58	136	100	38	8
Maximum total kinetic energy (kJ)	1.150	12.550	0.450	7.000	0.513	6.275	0.700	7.667

• Bench face angle: 90^{o}

Table 4.74. Rockfall parameters for stack configuration 2, 8 m bench height, 90^{o} bench face angle, rock type Three, 10 and 110 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier	
Mass of rock (kg)	10	110	10	110	10	110
x-coordinate of barrier location (m)	7.2	7.2	8	8	8.8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	3.2	4	4	4.8	4.8
Maximum bounce height (m)	10.2	10.2	9.38	8.5	6	6
Recommended height of barrier (m)	5	5	5	5	5	5
Number of rocks	13	33	4	6	8	8
Maximum total kinetic energy (kJ)	0.875	8.700	0.875	10.417	0.558	5.250

Ratios of total kinetic energies for masses of 110 kg compared to 10 kg for rock type One, Two and Three are tabulated below:

- Rock type: One

Table 4.75. Ratios of total kinetic energies for masses of 110 kg compared to 10 kg for rock type One.

Bench face angle (^{o})	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 54 of barrier
60	11	11	11	11
70	11	11	11	11
80	11.5	13.2	11	11
90	11.1	14.7	11.4	

- Rock type: Two

Table 4.76. Ratios of total kinetic energies for masses of 110 kg compared to 10 kg for rock type Two.

Bench face angle (^{o})	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
60	9.1	9.6	12.1	10.2
70	10.9	11	12.8	9.6
80	11.2	8.2	11.1	12.8
90	11	16.3	10.9	

- Rock type: Three

Table 4.77. Ratios of total kinetic energies for masses of 110 kg compared to 10 kg for rock type Three.

Bench face angle (^{o})	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
60	11.1	11.2	8.8	17.7
70	9.9	13.3	11	11
80	10.9	15.6	12.2	11
90	9.9	11.9	9.4	

- **Mass: 150 kg**

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.78. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.37, C.38, C.39 and C.40 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.78. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type One, 150 kg falling rock mass.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	14.9	21.8	19.8	5.9
Analysed bench width/Modified Ritchie bench width	+60%	+135%	+113%	-36%
Recommended location of barrier (x distance from toe of bottom bench in m)	4.7	2.6	7.1	3.2
Recommended height of barrier (m)	2.7	3.9	2.5	2.9

b) Rock type: Two

The results for the four bench face angles are summarized in Table 4.79.The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.41, C.42, C.43 and C.44 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.79. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type Two, 150 kg falling rock mass.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	8.9	11	10.3	5.4
Analysed bench width/Modified Ritchie bench width	-5%	18%	10%	-42%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.4	2.6	2.6	-
Recommended height of barrier (m)	2.4	4.7	4.7	-

c) Rock type: Three

The results for the four bench face angles are summarized in Table 4.80. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.45, C.46, C.47 and C.48 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.80. Summary of results for the four bench face angles, stack configuration 2, 8 m bench height, rock type Three, 150 kg falling rock mass.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	11	12.1	10.7	7.1
Analysed bench width/Modified Ritchie bench width	+19%	+30%	+15%	-24%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.1	5.3	6.2	-
Recommended height of barrier (m)	2.4	4.8	4.5	-

Comparisons of rockfall parameters between rock mass 10 kg and 150 kg for rock type One, Two and Three relative to 60^o, 70^o, 80^o and 90^o bench face angle respectively are tabulated below:

a) Rock type: One

• Bench face angle: 60^o

Table 4.81. Rockfall parameters for stack configuration 2, 8 m bench height, 60^o bench face angle, rock type One, 10 and 150 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	150	10	150	10	150	10	150
x-coordinate of barrier location (m)	22.5	22.5	23.4	23.4	24.3	24.3	25.2	25.2
Distance of barrier from toe of bottom bench (m)	4.7	4.7	5.6	5.6	6.5	6.5	7.4	7.4
Maximum bounce height (m)	2.63	2.67	2.63	2.67	2.63	2.67	2.63	2.67
Recommended height of barrier (m)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Number of rocks	17	22	333	333	413	400	50	33
Maximum total kinetic energy (kJ)	0.278	4.167	0.167	2.500	0.167	4.167	0.278	5.000

• Bench face angle: 70^{o}

Table 4.82. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, rock type One, 10 and 150 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	150	10	150	10	150	10	150
x-coordinate of barrier location (m)	15.3	15.3	16.2	16.2	17.1	17.1	18	18
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	5.3	5.3
Maximum bounce height (m)	3.9	3.88	4.28	4.25	4.28	4.25	4.28	4.25
Recommended height of barrier (m)	3.9	3.9	4.3	4.3	4.3	4.3	4.3	4.3
Number of rocks	89	94	133	106	117	89	267	428
Maximum total kinetic energy (kJ)	0.555	8.333	0.555	8.333	0.463	6.900	0.463	6.900

• Bench face angle: 80^{o}

Table 4.83. Rockfall parameters for stack configuration 2, 8 m bench height, 80^{o} bench face angle, rock type One, 10 and 150 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	150	10	150	10	150	10	150
x-coordinate of barrier location (m)	15.3	15.3	16.2	16.2	17.1	17.1	18	18
Distance of barrier from toe of bottom bench (m)	7.1	7.1	8	8	8.9	8.9	9.8	9.8
Maximum bounce height (m)	2.3	4.3	2.75	4.3	2.3	4.3	2.3	3.08
Recommended height of barrier (m)	2.3	4.3	2.8	4.3	2.3	4.3	2.3	3.1
Number of rocks	168	3	18	3	186	3	100	3
Maximum total kinetic energy (kJ)	0.367	5.900	0.275	4.667	0.334	4.667	0.330	5.900

• Bench face angle: 90^o

Table 4.84. Rockfall parameters for stack configuration 2, 8 m bench height, 90^o bench face angle, rock type One, 10 and 150 kg falling rock masses.

	Location 1of barrier		Location 2 of barrier		Location 3 of barrier	
Mass of rock (kg)	10	150	10	150	10	150
x-coordinate of barrier location	7.2	7.2	8	8	8.8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	3.2	4	4	4.8	4.8
Maximum bounce height (m)	2.9	2.9	2.3	2.3	1.2	1.17
Recommended height of barrier (m)	2.9	2.9	2.3	2.3	2	2
Number of rocks	33	46	4	6	4	7
Maximum total kinetic energy (kJ)	0.350	5.250	0.263	5.250	0.088	1.333

b) Rock type: Two

• Bench face angle: 60^o

Table 4.85. Rockfall parameters for stack configuration 2, 8 m bench height, 60^o bench face angle, rock type Two, 10 and 150 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	150	10	150	10	150	10	150
x-coordinate of barrier location (m)	18.8	18.4	19.6	19.2	20.4	20	21.2	20.8
Distance of barrier from toe of bottom bench (m)	0.97	0.6	1.78	1.4	2.6	2.2	3.66	3
Maximum bounce height (m)	2.78	1.08	3.63	2.4	4.19	3.25	4.19	3.25
Recommended height of barrier (m)	2.8	2	3.7	2.4	4.2	3.3	4.2	3.3
Number of rocks	6	11	6	6	6	6	6	6
Maximum total kinetic energy (kJ)	0.363	6.250	0.228	3.100	0.181	2.333	0.270	3.100

• Bench face angle: 70^{o}

Table 4.86. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, rock type Two, 10 and 150 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	150	10	150	10	150	10	150
x-coordinate of barrier location	14.4	14.4	15.3	15.3	16.2	16.2	17.1	17.1
Distance of barrier from toe of bottom bench (m)	1.7	1.7	2.6	2.6	3.5	3.5	4.4	4.4
Maximum bounce height (m)	5.3	5.03	4.5	4.65	4.1	4.31	4.1	4.31
Recommended height of barrier (m)	5	5	4.5	4.7	4.1	4.4	4.1	4.4
Number of rocks	6	6	8	8	17	6	11	6
Maximum total kinetic energy (kJ)	0.963	15.375	0.455	6.833	0.340	6.000	0.455	6.833

• Bench face angle: 80^{o}

Table 4.87. Rockfall parameters for stack configuration 2, 8 m bench height, 80^{o} bench face angle, rock type Two, 10 and 150 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	150	10	150	10	150	10	150
x-coordinate of barrier location (m)	10.8	10.8	11.7	11.7	12.6	12.6	13.5	13.5
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	3.69	5.3
Maximum bounce height (m)	4.63	4.67	4.63	4.67	4.63	4.67	3.69	3.63
Recommended height of barrier (m)	4.7	4.7	4.7	4.7	4.7	4.7	3.7	3.7
Number of rocks	4	4	7	6	4	4	4	6
Maximum total kinetic energy (kJ)	1.000	15.375	0.428	6.000	0.428	6.000	0.370	6.833

• Bench face angle: 90^{o}

Table 4.88. Rockfall parameters for stack configuration 2, 8 m bench height, 90^{o} bench face angle, rock type Two, 10 and 150 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier	
Mass of rock (kg)	10	150	10	150	10	150
x-coordinate of barrier location (m)	7.2	7.2	8	8	8.8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	3.2	4	4	4.8	4.8
Maximum bounce height (m)	6.4	6.05	4.28	2.25	2.88	0.75
Recommended height of barrier (m)	5	5	4.3	2.3	2.9	2
Number of rocks	4	4	4	8	4	13
Maximum total kinetic energy (kJ)	0.550	7.125	0.160	3.550	0.080	1.200

c) Rock type: Three

• Bench face angle: 60^o

Table 4.89. Rockfall parameters for stack configuration 2, 8 m bench height, 60^o bench face angle, rock type Three, 10 and 150 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	150	10	150	10	150	10	150
x-coordinate of barrier location (m)	18.9	18.9	19.8	19.8	20.7	20.7	21.6	21.6
Distance of barrier from toe of bottom bench (m)	1.1	1.1	2	2	2.9	2.9	3.8	3.8
Maximum bounce height (m)	2.45	2.38	3.44	3.25	3.19	3.25	2.69	2.67
Recommended height of barrier (m)	2.5	2.4	3.5	3.3	3.2	3.3	2.7	2.7
Number of rocks	6	6	6	6	11	19	11	19
Maximum total kinetic energy (kJ)	0.292	4.000	0.194	2.667	0.245	2.667	0.245	3.313

• Bench face angle: 70^{o}

Table 4.90. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, rock type Three, 10 and 150 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	150	10	150	10	150	10	150
x-coordinate of barrier location (m)	15.3	15.3	16.2	16.2	17.1	17.1	18	18
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	5.3	5.3
Maximum bounce height (m)	6.5	6.5	5.88	5.9	5.46	5.5	4.69	4.73
Recommended height of barrier (m)	5	5	5	5	5	5	4.7	4.8
Number of rocks	21	4	179	115	83	62	29	23
Maximum total kinetic energy (kJ)	0.600	9.000	0.333	6.000	0.600	9.000	0.600	9.000

• Bench face angle: 80^{o}

Table 4.91. Rockfall parameters for stack configuration 2, 8 m bench height, 80^{o} bench face angle, rock type Three, 10 and 150 kg falling rock masses.

	Location 1 of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	150	10	150	10	150	10	150
x-coordinate of barrier location (m)	10.8	10.8	11.7	11.7	12.6	12.6	13.5	13.5
Distance of barrier from toe of bottom bench (m)	2.6	2.6	3.5	3.5	4.4	4.4	5.3	5.3
Maximum bounce height (m)	7.2	7.25	7.2	7.25	6.67	6.69	5.63	5.63
Recommended height of barrier (m)	5	5	5	5	5	5	5	5
Number of rocks	5	8	61	46	136	154	38	69
Maximum total kinetic energy (kJ)	1.150	17.225	0.450	4.800	0.513	9.550	0.700	10.550

• Bench face angle: 90^{o}

Table 4.92. Rockfall parameters for stack configuration 2, 8 m bench height, 90^{o} bench face angle, rock type Three, 10 and 150 kg falling rock masses.

	Location 1of barrier		Location 2 of barrier		Location 3 of barrier		Location 4 of barrier	
Mass of rock (kg)	10	150	10	150	10	150	10	150
x-coordinate of barrier location (m)	7.2	7.2	8	8	8.8	8.8	9.6	9.6
Distance of barrier from toe of bottom bench (m)	3.2	3.2	4	4	4.8	4.8	5.6	5.6
Maximum bounce height (m)	10.2	10.19	9.38	10.19	6	6	3.4	6
Recommended height of barrier (m)	5	5	5	5	5	5	3.4	5
Number of rocks	13	38	4	4	8	8	8	4
Maximum total kinetic energy (kJ)	0.875	12.600	0.875	14.900	0.558	10.000	0.480	7.500

Ratios of total kinetic energies for masses of 150 kg compared to 10 kg for rock type One, Two and three are tabulated below:

- Rock type: One

Table 4.93. Ratios of total kinetic energies for masses of 150 kg compared to 10 kg for rock type One.

Bench face angle (^{o})	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
60	14.9	15	25	18
70	15	15	14.9	14.9
80	16.1	17	14	17.9
90	15	20	15.1	

- Rock type: Two

Table 4.94. Ratios of total kinetic energies for masses of 150 kg compared to 10 kg for rock type Two.

Bench face angle (^{o})	Location1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
60	17.2	13.6	12.9	11.5
70	16	15	17.6	15
80	15.4	14	14	18.5
90	13	22.2	15	

- Rock type: Three

Table 4.95. Ratios of total kinetic energies for masses 150 kg compared to 10 kg for rock type Three.

Bench face angle (^{o})	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
60	13.7	13.7	10.9	13.5
70	15	18	15	15
80	15	10.7	18.6	15.1
90	14.4	17	18	15.6

From the results in the above tables, the following observations can be made:

The comparisons of rockfall parameters for falling rock mass 10 kg vs 70 kg, 10 kg vs 110 kg and 10 kg vs 150 kg provide the results that are approximately the same except for the total kinetic energy. For this latter parameter, tables of ratios of mass 70, 110 and 150 kg to mass 10 kg total kinetic energy indicate that each simulation of falling rock mass 70, 110 and 150 kg, has a total kinetic energy approximately 7, 11 and 15 times the total kinetic energy respectively of its equivalent simulation of falling rock mass of 10 kg. This is rational. As the formula of kinetic energy is $mv^2/2$ (Serway *et al* 2000:194), when the mass is increased n times, subsequently the kinetic energy is increased n times as well.

4.2.2 Bench height: 10 m

The slope height is: 3 x 10 = 30 m.The "designed" bench width, using the Modified Ritchie criterion is determined as:

"Designed" bench width = 0.2 x 30 + 4.5 = 10.5 m

Results of numerical modelling

a) Type of rock: One

The results for the four bench face angles are summarized in Table 4.96. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.49, C.50, C.51 and C.52 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.96. Summary of results for the four bench face angles, stack configuration 2, 10 m bench height, rock type One.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	27	22.9	24.7	7.1
Analysed bench width/Modified Ritchie bench width	+157%	+118%	+135%	-32%
Recommended location of barrier (x distance from toe of bottom bench in m)	4.6	10.2	13	-
Recommended height of barrier (m)	3.2	5	4.4	-

b) Type of rock: Two

The results for the four bench face angles are summarized in Table 4.97. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.53, C.54, C.55 and C.56 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.97. Summary of results for the four bench face angles, stack configuration 2, 10 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	12.5	12.7	12.4	6.4
Analysed bench width/Modified Ritchie bench width	+19%	+21%	+18%	-38%
Recommended location of barrier (x distance from toe of bottom bench in m)	5.6	5.2	6.6	-
Recommended height of barrier (m)	3.8	4.8	4.5	-

c) Type of rock: Three

The results for the four bench face angles are summarized in Table 4.98. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.57, C.58, C.59 and C.60 for 60^o, 70^o, 80^o and 90^o respectively in Appendix C.

Table 4.98. Summary of results for the four bench face angles, stack configuration 2, 10 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	13.5	14	13.7	8.9
Analysed bench width/Modified Ritchie bench width	+28%	+33%	+30%	-16%
Recommended location of barrier (x distance from toe of bottom bench in m)	1.6	7.2	9	-
Recommended height of barrier (m)	3.2	4.3	4.9	-

Comparisons and discussions

In Tables 4.99, 4.100 and 4.101 below the different rockfall parameters (maximum run-out distance, analysed bench width/Modified Ritchie bench width, and maximum bounce height) relative to 60^o, 70^o, 80^o and 90^o bench face angle in rock type One, Two and Three are compared.

Table 4.99. Summary of results for rock type One, stack configuration 2, 10 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	27	157	3.75
70	22.9	118	5.69
80	24.7	135	5.25
90	7.1	-32	3.69

Table 4.100. Summary of results for rock type Two, stack configuration 2, 10 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	12.5	19	5.34
70	12.7	21	5.83
80	12.4	18	8.13
90	6.4	-38	8

Table 4.101. Summary of results for rock type Three, stack configuration 2, 10 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	13.5	28	7.9
70	14	33	9.7
80	13.7	30	9.69
90	8.9	-16	12.75

From the results in the tables above, the following observations can be made:

- Particularly for rock type One, the maximum bounce height at 90^o bench face angle is not the highest.
- For all bench face angles, there is an increase in maximum bounce height as the normal coefficient of restitution increases.
- For all rock types:
  - For 60^o, 70^o and 80^o bench face angles, the maximum run-out distance is greater than the 10.5 m determined using the Modified Ritchie Criterion. The criterion substantially underestimates the catch bench width required. Thus, the use of a catch fence to reduce the required width of the catch bench is technically feasible.
  - For a 90^o bench face angle, the maximum run-out distance is less than 10.5 m.
- Comparisons between rockfall parameters for bench heights 8 m and 10 m, i.e., table 4.34 vs table 4.99, table 4.35 vs table 4.100 and table 4.36 vs table 4.101, indicate that for an increase in bench height, maximum run-out distance and bounce height also increase . This implies the increase of kinetic energy as well.
- As the normal coefficient of restitution increases, in general for each bench face angle, there is an increase in maximum bounce height.

4.2.3 Bench height: 12 m

The slope height is: 3 x 12 = 36 m. The "designed" bench width, using the Modified Ritchie criterion is determined as:

"Designed" bench width = 0.2 x 36 + 4.5 = 11.7 m

Results of numerical modelling

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.102. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.61, C.62, C.63 and C.64 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 1.102. Summary of results for the four bench face angles, stack configuration 2, 12 m bench height, rock type One.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	32.8	26.4	29.2	7.3
Analysed bench width/Modified Ritchie bench width	+181%	+126%	+149%	-38%
Recommended location of barrier (x distance from toe of bottom bench in m)	2.9	-	-	-
Recommended height of barrier (m)	2.6	-	-	-

b) Type of rock: Two

The results for the four bench face angles are summarized in Table 4.103. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.65, C.66, C.67 and C.68 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.103. Summary of results for the four bench face angles. Stack configuration 2, 12 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	19.2	15.5	14.7	7.2
Analysed bench width/Modified Ritchie bench width	+64%	+32%	+25%	-38%
Recommended location of barrier (x distance from toe of bottom bench in m)	8.9	8	10.1	-
Recommended height of barrier (m)	4.8	4.2	2.3	-

c) Type of rock: Three

The results for the four bench face angles are summarized in Table 4.104. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.69, C.70, C.71 and C.72 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.104. Summary of results for the four bench face angles, stack configuration 2, 12 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	18	16.7	16.2	9.6
Analysed bench width/Modified Ritchie bench width	+54%	+43%	+38%	-18%
Recommended location of barrier (x distance from toe of bottom bench in m)	-	11.6	-	-
Recommended height of barrier (m)	-	4.6	-	-

Comparisons and discussions

In Tables 4.105, 4.106 and 4.107 below, the different rockfall parameters (maximum run-out distance, analysed bench width/Modified Ritchie bench width, and maximum bounce height) relative to 60^o, 70^o, 80^o and 90^o bench face angle in rock type One , Two and Three are compared.

Table 4.105. Summary of results for rock type One, stack configuration 2, 12 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	32.8	181	4.08
70	26.4	126	6.55
80	29.25	149	6.5
90	7.3	-38	8.83

Table 4.106. Summary of results for rock type Two, stack configuration 2, 12 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	19.2	64	6.9
70	15.5	32	6.73
80	14.7	25	12.3
90	7.2	-38	12.63

Table 4.107. Summary of results for rock type Three, stack configuration 2, 12 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	18	54	9.58
70	16.8	43	12.3
80	16.2	38	11.63
90	9.6	-18	20.38

From the results in Tables 105 to 107, the following observations can be made:

- For each bench face angle, there is an increase in maximum bounce height as the normal coefficient of restitution increases.
- For all rock types:
    - For 60^o, 70^o and 80^o bench face angles, the maximum run-out distance is greater than 11.7 m determined using the Modified Ritchie criterion. The criterion substantially underestimates the catch bench width required.

Thus, the use of a catch fence to reduce the required width of the catch bench is technically feasible.

- For a 90^o bench face angle, the maximum run-out distance is less than 11.7 m.

- As the normal coefficient of restitution increases, in general for each bench face angle, there is an increase in maximum bounce height.

4.2.4 Bench height: 15 m

The slope height is: 3 x 15 = 45 m.The "designed" bench width, using the Modified Ritchie criterion is determined as:

"Designed" bench width = 0.2 x 45 + 4.5 = 13.5 m

Results of numerical modelling

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.108. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.73, C.74, C.75 and C.76 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.108. Summary of results for the four bench face angles, stack configuration 2, 15 m bench height, rock type One .

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance	40.5	31.1	35.7	8.2
Analysed bench width/Modified Ritchie bench width	+200%	+130%	+164%	-39%
Recommended location of barrier (x distance from toe of bottom bench in m)	3	12.6	-	-
Recommended height of barrier (m)	2.5	4.5	-	-

b) Rock type: Two

The results for the four bench face angles are summarized in Table 4.109. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.77, C.78, C.79 and C.80 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.109. Summary of results for the four bench face angles, stack configuration 2, 15 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	23.5	17.9	18.9	8.8
Analysed bench width/Modified Ritchie bench width	+74%	+33%	+40%	-35%
Recommended location of barrier (x distance from toe of bottom bench in m)	13.5	9.6	10.7	-
Recommended height of barrier (m)	3.9	4	4.8	-

c) Rock type: Three

The results for the four bench face angles are summarized in Table 4.110. The detailed results relating to the choice of barrier location and barrier height are contained in Tables C.81, C.82, C.83 and C.84 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix C.

Table 4.110. Summary of results for the four bench face angles, stack configuration 2, 15 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	25.5	19.3	20	11.5
Analysed bench width/Modified Ritchie bench width	+89%	+43%	+48%	-15%
Recommended location of barrier (x distance from toe of bottom bench in m)	-	-	-	-
Recommended height of barrier (m)	-	-	-	-

Comparisons and discussions

In Tables 4.111, 4.112 and 4.113 below, the different rockfall parameters (maximum run-out distance, analysed bench width/Modified Ritchie bench width, and maximum bounce height) relative to 60^o, 70^o, 80^o and 90^o bench face angle in rock type One, Two and Three are compared.

Table 4.111. Summary of results for rock type One, stack configuration 2, 15 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	40.5	200	4.88
70	31.1	130	8.13
80	35.7	164	8.69
90	8.2	-39	11.06

Table 4.112. Summary of results for rock type Two, stack configuration 2, 15 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	23.5	74	8.56
70	17.9	33	7.88
80	18.9	40	14.8
90	8.8	-35	20.38

Table 4.113. Summary of results for rock type Three, stack configuration 2, 15 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	25.5	89	11.78
70	19.3	43	14.65
80	20.0	48	19.33
90	11.5	-15	25.48

From the results in the Tables 111 to 113, the following observations can be:

- In general for each bench face angle, there is an increase in maximum bounce height as the normal coefficient of restitution increases.
- For all rock types:
    - For 60^o, 70^o and 80^o bench face angles, the maximum run-out distance is greater than the 13.5 m determined using the Modified Ritchie criterion. The criterion substantially underestimates the catch bench

width required. Thus, the use of a catch fence to reduce the required width of the catch bench is technically feasible.

- For a 90^o bench face angle, the maximum run-out distance is less than 13.5 m.

- Except for rock type Two, the maximum bounce height increases as the bench face angle increases.

4.2.5 Discussions

For all rock types and bench heights, the maximum run-out distance is greater than the value determined using the Modified Ritchie Criterion implying the use of a catch fence to reduce the required width of the catch bench. For a 90^o bench face angle, the maximum run-out distance is less than the Modified Ritchie Criterion.

For each bench height, the general trend of maximum bounce height is to increase when the coefficient of normal restitution increases for a given bench face angle because more energy is restituted to falling rocks after impact on the catch bench.

For a 12 m bench height, there are some bench face angles other than 90^o in rock type One and Three for which there is no position suitable for the location of a barrier. This is due to the fact that the conditions in Table 4.1 (first category) and the Modified Ritchie criterion are not met by the maximum bounce height and distance of barrier from the toe of the bottom bench.

For each rock type and specific bench face angle:

- The maximum run-out distance increases as a function of bench height (h: 8, 10, 12 and 15 m). Applying the linear method of least-squares regression analysis, the following polynomials are obtained and tabulated below.

Table 4.114. Summary of polynomials relative to 60^o, 70^o, 80^o and 90^o bench face angle in rock type One, Two and Three for stack configuration 2.

Rock type	Bench face angle (^{o})	Polynomial (m)
One	60	- 11.34 + 3.56 h
	70	10.17 + 1.37 h
	80	1.66 + 2.28 h
	90	3.97 + 0.28 h
Two	60	- 7.69 + 2.12 h
	70	3.19 + 0.99 h
	80	- 0.51 + 1.28 h
	90	2.61 + 0.48 h
Three	60	- 6.64 + 2.1 h
	70	3.79 + 1.05 h
	80	0.31 + 1.32 h
	90	2.64 + 0.59 h

- The maximum bounce height increases as a function of bench height (h). Applying the linear method of least-squares regression analysis, the following polynomials are obtained.

Table 4.115. Summary of polynomials relative to 60^o, 70^o, 80^o and 90^o bench face angle in rock type One, Two and Three for stack configuration 2.

Rock type	Bench face angle (^{o})	Polynomial (m)
One	60	0.42 + 0.30 h
	70	0.12 + 0.54 h
	80	- 3.44 + 0.82 h
	90	- 7.64 + 1.27 h
Two	60	- 0.75 + 0.62 h
	70	2.21 + 0.38 h
	80	- 6.65 + 1.48 h
	90	- 9.02 + 1.89 h
Three	60	- 4.57 + 1.13 h
	70	- 0.08 + 0.99 h
	80	- 7.30 + 1.71 h
	90	- 8.78 + 2.31 h

4.3 Stack configuration 3

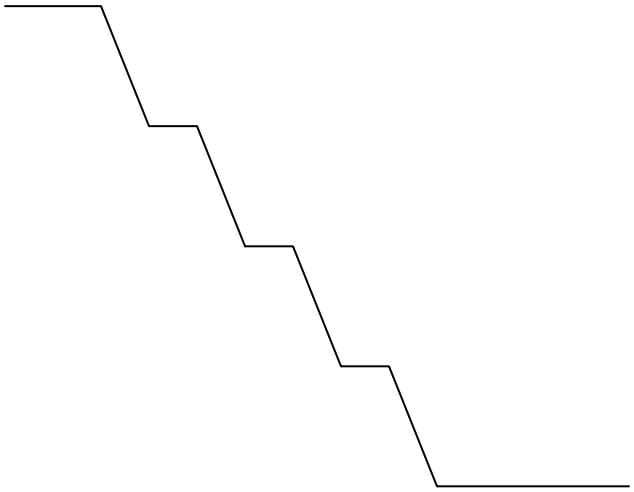


Figure 4.6: Stack configuration 3.

Stack configuration 3 has 4 benches. The following parameters were considered to determine the run-out distances and bounce heights:

- Four bench heights (8, 10, 12 and 15 m);

- Four bench face angles (60^o, 70^o, 80^o and 90^o);
- Three different rock types.

4.3.1 Bench height: 8 m

As the stack configuration has 4 benches, so the slope height is: 4 x 8 m =32 m
The "designed" bench width, using the Modified Ritchie criterion is determined as:

"Designed" bench width = 0.2 x 32 + 4.5 = 10.9 m

Results of numerical modelling

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.116. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.1, D.2, D.3 and D.4 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix D.

Table 4.116. Summary of results for the four bench face angles, stack configuration 3, 8 m bench height, rock type One.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	24.7	31.6	22.3	5.7
Analysed bench width/Modified Ritchie bench width	+126%	+190%	+104%	-48%
Recommended location of barrier (x distance from toe of bottom bench in m)	4.1	9.4	6.4	-
Recommended height of barrier (m)	2.3	4.5	4.3	-

b) Rock type: Two

The results for the four bench face angles are summarized in Table 4.117. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.5, D.6, D.7 and D.8 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix D.

Table 4.117. Summary of results for the four bench face angles, stack configuration 3, 8 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	12.4	13.3	10.6	4.5
Analysed bench width/Modified Ritchie bench width	+14%	+22%	-3%	-59%
Recommended location of barrier (x distance from toe of bottom bench in m)	2.6	4.9	5.2	-
Recommended height of barrier (m)	4.5	4.9	4.6	-

c) Rock type: Three

The results for the four bench face angles are summarized in Table 4.118. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.9, D.10, D.11 and D.12 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix D.

Table 4.118. Summary of results for the four bench face angles, stack configuration 3, 8 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	15.2	15.8	12.1	6.2
Analysed bench width/Modified Ritchie bench width	+39%	+45%	+11%	-43%
Recommended location of barrier (x distance from toe of bottom bench in m)	7.1	9.4	8.8	-
Recommended height of barrier (m)	3.7	2.5	3.8	-

Comparisons and discussions

In Tables 4.119, 4.120 and 4.121 below, the different rockfall parameters (maximum run-out distance, analysed bench width/Modified Ritchie bench width, and maximum bounce height) relative to 60^o, 70^o, 80^o and 90^o bench face angles in rock type One, two and Three are compared.

Table 4.119. Summary of results for rock type One, stack configuration 3, 8 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	24.7	126	2.67
70	31.6	190	4.5
80	22.3	104	6.4
90	5.7	-48	5.23

Table 4.120. Summary of results for rock type Two, stack configuration 3, 8 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	12.4	14	4.5
70	13.3	22	5.4
80	10.6	-3	8.5
90	4.5	-59	10.68

Table 4.121. Summary of results for rock type Three, stack configuration 3, 8 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	15.2	39	6.56
70	15.8	45	8.17
80	12.1	11	11.2
90	6.2	-43	14.7

From the results in the tables above, the following observations can be made:

- Particularly for rock type One, the maximum bounce height at 90^o bench face angle is not the highest.
- For 60^o, 70^o and 80^o bench face angles, the maximum run-out distance is greater than the 10.9 m determined using the Modified Ritchie Criterion, except for 80^o in rock type two. Thus, the use of a catch fence is required to reduce the width of the catch bench.

- For 90^{o} bench face angle, the maximum run-out distance is less than 10.9 m.

4.3.2 Bench height: 10 m

The slope height is: 4 x 10 = 40 m. The "designed" bench width, using the Modified Ritchie criterion is determined as:

"Designed" bench width is: 0.2 x 40 + 4.5 = 12.5 m

Results of numerical modelling

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.122. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.13, D.14, D.15 and D.16 for 60^{o}, 70^{o}, 80^{o} and 90^{o} bench face angles respectively in Appendix D.

Table 4.122. Summary of results for the four bench face angles, stack configuration 3, 10 m bench height, rock type One.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	39.8	37.6	27.7	6.6
Analysed bench width/Modified Ritchie bench width	+218%	+200%	+121%	-47%
Recommended location of barrier (x distance from toe of bottom bench in m)	-	11.1	-	-
Recommended height of barrier (m)	-	4.5	-	-

b) Rock type: Two

The results for the four bench face angles are summarized in Table 4.123. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.17, D.18, D.19 and D.20 for 60^{o}, 70^{o}, 80^{o} and 90^{o} bench face angles respectively in Appendix D.

Table 4.123. Summary of results for the four bench face angles, stack configuration 3, 10 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	19.2	16.2	13.3	5.2.
Analysed bench width/Modified Ritchie bench width	+54%	+30%	+6.2%	-59%
Recommended location of barrier (x distance from toe of bottom bench in m)	5.4	6.6	7.9	-
Recommended height of barrier (m)	5	5	3.6	-

c) Rock type: Three

The results for the four bench face angles are summarized in Table 4.124. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.21, D.22, D.23 and D.24 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix D.

Table 4.124. Summary of results for the four bench face angles, stack configuration 3, 10 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	17.7	20	17	7.1
Analysed bench width/Modified Ritchie bench width	+41%	+61%	+36%	-43%
Recommended location of barrier (x distance from toe of bottom bench in m)	8.4	11.1	10.9	-
Recommended height of barrier (m)	4.6	4.5	5	-

Comparisons and discussions

In Tables 4.125, 4.126 and 4.127 below, the different rockfall parameters (maximum run-out distance, analysed bench width/modified Ritchie bench width, and maximum bounce height) relative to 60^o, 70^o, 80^o and 90^o bench face angle in rock type One, Two and Three are compared.

Table 4.125. Summary of results for rock type One, stack configuration 3, 10 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	39.8	218	3.25
70	37.6	200	7.6
80	27.7	121	7.6
90	6.6	-47	6.5

Table 4.126. Summary of results for rock type Two, stack configuration 3, 10 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	19.2	54	6.8
70	16.2	30	6.25
80	13.3	6.2	9.9
90	5.2	-59	12

Table 4.127. Summary of results for rock type Three, stack configuration 3, 10 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	17.7	41	9.8
70	20	61	10.3
80	17	36	14.1
90	7.1	-43	18.3

From the results in the tables above, the following observations can be made:

- Particularly for rock type One, the maximum bounce height at 90^o bench face angle is not the highest.
- For 60^o, 70^o and 80^o bench face angles, the maximum run-out distance is greater than 12.5 m, determined using the Modified Ritchie criterion. Thus, the use of a catch fence is required to reduce the width of the catch fence.
- For a 90^o bench face angle, the maximum run-out distance is less than 12.5 m.

4.3.3 Bench height: 12 m

The slope height is: 4 x 12 = 48 m. The "designed" bench width, using the Modified Ritchie criterion is determined as:

"Designed" bench width is: 0.2 x 48 + 4.5 = 14.1 m

Results of numerical modelling

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.128. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.25, D.26, D.27 and D.28 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix D.

Table 4.128. Summary of results for the four bench face angles, stack configuration 3, 12 m bench height, rock type One.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	44.6	41.6	33	6.7
Analysed bench width/Modified Ritchie bench width	+216%	+195%	+134%	-53%
Recommended location of barrier (x distance from toe of bottom bench in m)	-	-	-	-
Recommended height of barrier (m)	-	-	-	-

b) Rock type: Two

The results for the four bench face angles are summarized in Table 4.129. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.29, D.30, D.31 and D.32 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix D.

Table 4.129. Summary of results for the four bench face angles, stack configuration 3, 12 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	25.5	18.1	17.9	6.6
Analysed bench width/Modified Ritchie bench width	+81%	+28%	+27%	-53%
Recommended location of barrier (x distance from toe of bottom bench in m)	10.6	8.9	11.1	-
Recommended height of barrier (m)	3.8	4.3	4.5	-

c) Rock type: Three

The results for the four bench face angles are summarized in Table 4.130. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.33, D.34, D.35 and D.36 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in A.

Table 4.130. Summary of results for the four bench face angles, stack configuration 3, 12 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	29.4	23.4	19	7.5
Analysed bench width/Modified Ritchie bench width	+108%	+66%	+35%	-47%
Recommended location of barrier (x distance from toe of bottom bench in m)	14	-	14.1	-
Recommended height of barrier (m)	4.7	-	5	-

Comparisons and discussions

In Tables 4.131, 4.132 and 4.133 below, the different rockfall parameters (maximum run-out distance, analysed bench width/Modified Ritchie bench width, and maximum bounce height) relative to 60^o, 70^o, 80^o and 90^o bench face angle in rock type One, Two and Three are compared.

Table 4.131. Summary of results for rock type One, stack configuration 3, 12 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	44.6	21.6	4
70	41.6	195	9
80	33	134	10
90	6.7	-53	7.1

Table 4.132. Summary of results for rock type Two, stack configuration 3, 12 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	25.5	81	7.6
70	18.1	28	6.55
80	17.9	27	12.38
90	6.6	-53	14.7

Table 4.133. Summary of results for rock type Three, stack configuration 3, 12 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	29.4	108	12.56
70	23.4	66	12.81
80	19	35	18.08
90	7.5	-47	21.67

From the results in the tables above, the observations made for a 10 m bench height (previous case) are also valid for this case (12 m bench height).

4.3.4 Bench height: 15 m

The slope height is: 4 x 15 = 60 m. The "designed" bench width, using the Modified Ritchie criterion is determined as:

"Designed" bench width is: 0.2 x 60 + 4.5 = 16.5 m

Results of numerical modelling

a) Rock type: One

The results for the four bench face angles are summarized in Table 4.134. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.37, D.38, D.39 and D.40 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix D.

Table 4.134. Summary of results for the four bench face angles, stack configuration 3, 15 m bench height, rock type One.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	56.2	49.7	39.7	8.2
Analysed bench width/Modified Ritchie bench width	+240%	+201%	+141%	-51%
Recommended location of barrier (x distance from toe of bottom bench in m)	-	-	-	-
Recommended height of barrier (m)	-	-	-	-

b) Rock type: Two

The results for the four bench face angles are summarized in Table 4.135. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.41, D.42, D.43 and D.44 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix D.

Table 4.135. Summary of results for the four bench face angles, stack configuration 3, 15 m bench height, rock type Two.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	31.8	22.7	24.4	8.2
Analysed bench width/Modified Ritchie bench width	+93%	+38%	+48%	-51%
Recommended location of barrier (x distance from toe of bottom bench in m)	12.3	11.3	15.6	-
Recommended height of barrier (m)	4.5	4.6	4.3	-

c) Rock type: Three

The results for the four bench face angles are summarized in Table 4.136. The detailed results relating to the choice of barrier location and barrier height are contained in Tables D.45, D.46, D.47 and D.48 for 60^o, 70^o, 80^o and 90^o bench face angles respectively in Appendix D.

Table 4.136. Summary of results for the four bench face angles, stack configuration 3, 15 m bench height, rock type Three.

Bench face angle (degrees)	60	70	80	90
Maximum run-out distance (m)	36.4	28.6	24.1	10.1
Analysed bench width/Modified Ritchie bench width	+121%	+73%	+46%	-39%
Recommended location of barrier (x distance from toe of bottom bench in m)	-	-	-	-
Recommended height of barrier (m)	-	-	-	-

Comparisons and discussions

In Tables 4.137, 4.138 and 4.139 below, the different rockfall parameters (maximum run-out distance, analysed bench width/Modified Ritchie bench width, and maximum bounce height) relative to 60^o, 70^o, 80^o and 90^o bench face angles in rock type One, Two and Three are compared.

Table 4.137. Summary of results for rock type One, stack configuration 3, 15 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	56.2	240	4.88
70	49.7	201	11
80	39.7	141	10.5
90	8.2	-51	10

Table 4.138. Summary of results for rock type Two, stack configuration 3, 15 bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	31.8	93	7.67
70	22.7	38	12
80	24.4	48	17.17
90	8.2	-51	16

Table 4.139. Summary of results for rock type Three, stack configuration 3, 15 m bench height.

Bench face angle (^{o})	Maximum run-out distance (m)	Analysed bench width/Modified Ritchie bench width (%)	Maximum bounce height (m)
60	36.4	121	15.5
70	28.6	73	15
80	24.1	46	22.7
90	10.1	-39	24.1

From the results in the tables above, the observations made for the previous case are also valid for the present case, except for rock type Two, for which the maximum bounce height is not the highest at 90^o, as for rock type One.

4.3.5 Discussions

Particularly for rock type One, the maximum bounce height at a 90^o bench face angle is not the highest. For all rock types, the maximum run-out distance at 90^o bench face angle is less than the value determined using the Modified Ritchie Criterion whereas for other bench face angles, it is greater. Thus, the use of a catch fence is required to reduce the width of the catch bench.

For a 10 m bench height, there are some bench face angles other than 90^o in rock type One and Three for which there is no position suitable for the location of a barrier. This is due to the fact that the conditions in Table 4.1 (first category) and the Modified Ritchie criterion are not met by the maximum bounce height and distance of barrier from the toe of the bottom bench.

For each rock type and specific bench face angle:

- The maximum run-out distance increases as a function of bench height (h: 8, 10, 12 and 15 m). Applying the linear method of least-squares regression analysis, the following polynomials are obtained.

Table 4.140. Summary of polynomials relative to 60°, 70°, 80° and 90° bench face angle in rock type One, Two and Three for stack configuration 3.

Rock type	Bench face angle (°)	Polynomial (m)
One	60	- 6.76 + 1.07 h
	70	11.57 + 0.63 h
	80	2.60 + 0.62 h
	90	3.06 + 0.08 h
Two	60	- 8.86 + 2.76 h
	70	2.68 + 1.32 h
	80	- 6.06 + 2.01 h
	90	0.01 + 0.54 h
Three	60	- 11.96 + 3.26 h
	70	1.62 + 1.82 h
	80	- 0.51 + 1.65 h
	90	1.64 + 0.54 h

- The maximum bounce height increases as a function of bench height (h). Thus, applying the linear method of least-squares regression analysis, the following polynomials are obtained.

Table 4.141. Summary of polynomials relative to 60°, 70°, 80° and 90° bench face angle in rock type One, Two and Three for stack configuration 3.

Rock type	Bench face angle (°)	Polynomial (m)
One	60	0.1 + 0.08 h
	70	- 2.02 + 0.22 h
	80	1.65 + 0.15 h
	90	- 0.24 + 0.17 h
Two	60	1.87 + 0.42 h
	70	- 2.77 + 0.92 h
	80	- 2.17 + 1.26 h
	90	4.38 + 0.80 h
Three	60	- 3.18 + 1.27 h
	70	0.45 + 0.99 h
	80	- 2.26 + 1.67 h
	90	4.56 + 1.38 h

5 CONCLUSIONS

The research work in this report has dealt with the effect of bench geometries (bench height, bench stack height, bench face angle, catch bench width) as well as the nature of the material, on rockfall behaviour. The validity of the Modified Ritchie criterion for the design of catch benches in open pit mines has been considered. Considerations of different geometries and masses of falling rocks have been taken into account to observe their effects on rockfall behaviour. From the research work, the following conclusions have been drawn:

- For all stack configurations and rock types, the maximum run-out distance and maximum bounce height increase as functions of bench height at a specific bench face angle. When the height of fall increases, the falling rock has more energy so that, when impacting on the catch bench, proportionally more kinetic energy is restituted, resulting in increasing maximum run-out distance and bounce height.
- A single bench configuration provides a maximum run-out distance of falling rocks larger than the value determined using the Modified Ritchie criterion for all rock types and bench face angles. Multiple bench stack configurations provide maximum run-out distances less than the value determined using the Modified Ritchie criterion only for the 90^o bench face angle in all rock types; those with 60^o, 70^o and 80^o bench face angles provide a larger maximum run-out distance. Therefore, the validity of the Modified Ritchie criterion for the design of catch bench widths in open pit mines must be questioned. If a reduction in the width of the catch bench is required, the use of a catch fence will be necessary in all cases of a simple bench stack configuration. For multiple bench stack configurations, the use of a catch fence will only be required for 60^o, 70^o and 80^o bench face angles.
- According to the Ritchie study (1963), rocks that fall in trajectory (free fall) seldom give high bounces after impact on a catch bench. This project shows that this finding is valid for rocks with low coefficients of normal restitution (i.e. rock type One in this work).
- Rocks with lower coefficients of normal restitution provide larger run-out distances with flatter bench face angles compared with rocks with higher coefficients. In contrast, rocks with higher coefficients provide larger run-out distances than those with lower coefficients for steeper angles (90^o bench face angle).
- For a 90^o bench face angle, all rock types drop undisturbed onto the catch bench. Angular momentum is not imparted to the falling rocks, so smaller maximum run-out distances result.
- The consideration of the influence of geometry (shape) of falling rocks on rockfall behaviour showed the following:

    - For a flatter slope (60^o bench face angle), as could logically be expected, the maximum run-out distance is greatest for rounder rocks (represented by a 10^o friction angle) and smallest for flatter slabby rocks (represented by a 40^o

friction angle). This is due to the fact that on a flatter slope, the mode of falling of rounder rocks is rolling down the slope. This mode provides essentially no resistance to motion, resulting in the largest maximum run-out distance. In contrast, for long flat slabs, the mode of movement will be sliding. This results in a smaller maximum run-out distance.

- The maximum run-out distance as a function of rock shape (friction angle) for 70^o, 80^o and 90^o bench face angles respectively, reduces as the normal coefficient of restitution increases. This is due to the following:

    - When the bench face angle steepens, there is a trend towards bouncing of falling rocks on slopes and free fall instead of rolling, so the shape effect reduces;
    - An increase in the coefficient of normal restitution has a greater effect in that more kinetic energy is restituted to falling rocks, resulting in almost the same maximum run-out distance whatever the shape (friction angle);

- For all rock types, the maximum bounce height reduces as a function of friction angle for a 60^o bench face angle. This is due to the fact at this angle, rocks are in contact with the slope during the rockfall. As the coefficient of normal restitution increases, an increase in the maximum bounce height results.

- The investigation of the influence of the geometry (shape) of falling rocks on rockfall behaviour using stack configurations 1 (simple) and 2 (multiple bench) provided the same trends in rockfall parameters. Comparisons of rockfall parameters for falling rock masses (10 kg vs 70 kg, 10 kg vs 110 kg and 10 kg vs 150 kg) provide results that are approximately the same except for the total kinetic energy. The results show that the total kinetic energies are directly proportional to the mass, which could logically be expected.

6 RECOMMENDATIONS

All the numerical modelling in this project was performed assuming that blocks (falling rocks) had their mass concentrated at one point. However, in reality, each block has its own shape and volume. Models considering blocks with their own characteristics (shape and volume) are therefore more likely to be capable of accurately reproducing the different phases (free falling, impact and bouncing, rolling and sliding) of rockfall phenomena. Therefore, the work contained in this research report could be enhanced by carrying out such analyses, and by extending the analyses to three dimensions.

Values of coefficients of restitution are not always easy to determine. In the Rocscience Coefficient of Restitution Table, values more than 0.487 (coefficient of normal restitution) and 0.910 (coefficient of tangential restitution) are mostly for clean bedrock, concrete and forested slope. Since analysis is sensitive to the values chosen for coefficient of restitution, improved knowledge of restitution coefficients will result in improved findings regarding the influence of bench geometries on rockfall behaviour.

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APPENDIX A

Figures of total kinetic energy distribution, bounce height distribution, profile of rock paths and rockfall analysis information for every case of rockfall simulation modeling, are generated as follows:

- Profile of rock paths is obtained by double clicking on the specific file name.
- Kinetic energy (total, translational, and rotational), bounce height distribution graphs are generated in the following way:
    - Select: Graph → Graph Distribution
    - The graph Distribution dialog, with a drop down list of distribution graphs, will appear
    - select Total Kinetic Energy from the dropdown list and select Create Graph (a thick vertical line on the slope marks the X location of the data sampling. To sample data at other locations, simply click the left mouse button anywhere on the slope. The vertical line will indicate the selected position, and the graph will immediately be updated)
- Rocfall analysis information is obtained as follows: the info viewer option in the file menu and the toolbar, displays a summary of all ROCFALL model parameters in its own view. This includes:

    - Slope geometry
    - Slope materials
    - Seeder properties
    - Simulation parameters

    Barrier and collector properties

Thus for rocfall analysis information, select: File → Info Viewer (Rocscience, 2003).

In the CD-R, there are 2 folders named:

- License containing files buana13 to 42 and buana229 to 236
- License01 containing files buana1 to 12 and buana42 to 228.

Results of rockfall simulations using 3 rock types as follows:

- Document Name: Rock 1

    - Material name: Type Four
    - RN: mean = 0.32 standard deviation = 0.04
    - RT: mean = 0.82 standard deviation = 0.04

RocFall Analysis Information

Document Name

Rock1

Project Settings

Units: Metric
Friction angle: Use friction fngle specified in material editor
Minimum Velocity=0.1
Angular Velocity of the rocks CONSIDERED
Standard Deviations NOT USED when generating slope vertices
Random-number generation: Random

Slope

Segment 1, Material: Type Four
Start Point: X mean=0 std dev=0 Y mean=0 std dev=0
End Point: X mean=4.6 std dev=0 Y mean=-8 std dev=0

Segment 2, Material: Type Four
Start Point: X mean=4.6 std dev=0 Y mean=-8 std dev=0
End Point: X mean=6.6 std dev=0 Y mean=-8 std dev=0

Segment 3, Material: Type Four
Start Point: X mean=6.6 std dev=0 Y mean=-8 std dev=0
End Point: X mean=11.2 std dev=0 Y mean=-16 std dev=0

Segment 4, Material: Type Four
Start Point: X mean=11.2 std dev=0 Y mean=-16 std dev=0
End Point: X mean=13.2 std dev=0 Y mean=-16 std dev=0

Segment 5, Material: Type Four
Start Point: X mean=13.2 std dev=0 Y mean=-16 std dev=0
End Point: X mean=17.8 std dev=0 Y mean=-24 std dev=0

Segment 6, Material: Type Four
Start Point: X mean=17.8 std dev=0 Y mean=-24 std dev=0
End Point: X mean=45 std dev=0 Y mean=-24 std dev=0

Materials

Material name: Type Four
Coefficient of Normal Restitution (RN): mean=0.32 std dev=0
Coefficient of Tangential Restitution (RT): mean=0.82 std dev=0
Friction Angle: mean=30 std dev=0
Roughness: std dev=0

Seeders

Point Seeder
Horizontal Velocity: mean=1.5, std dev=0.15
Vertical Velocity: mean=0, std dev=0

Mass: mean=10, std dev=0
Angular Velocity: mean=0, std dev=0
Location: 0, 0

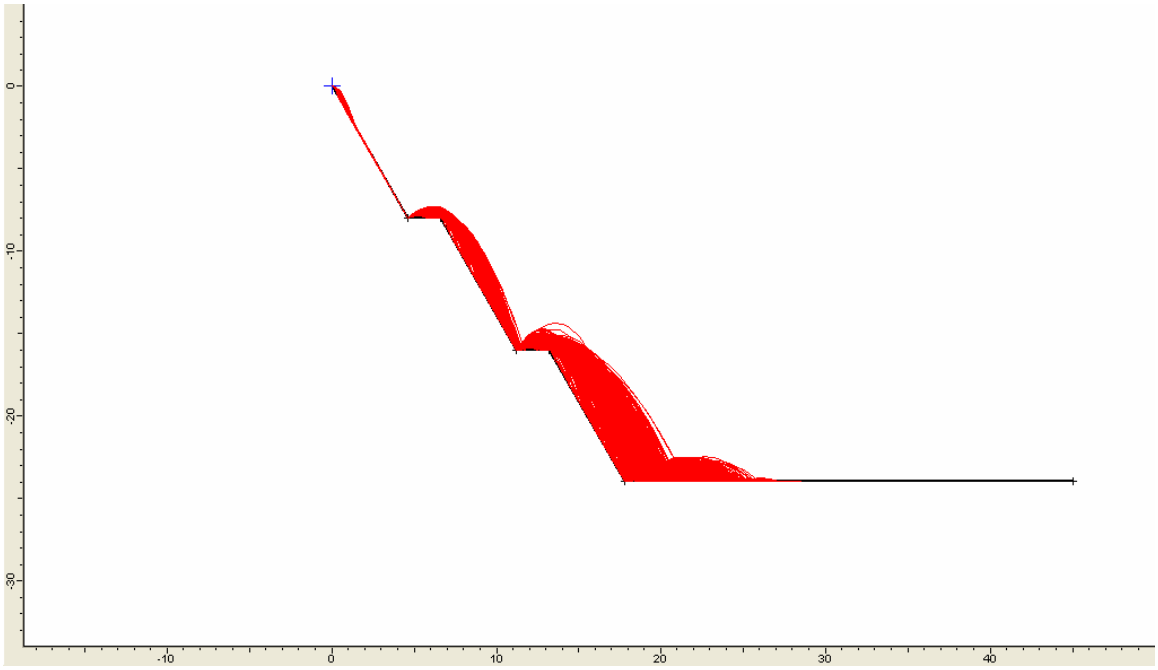


Figure A1. Rockfall paths of rock type Four.

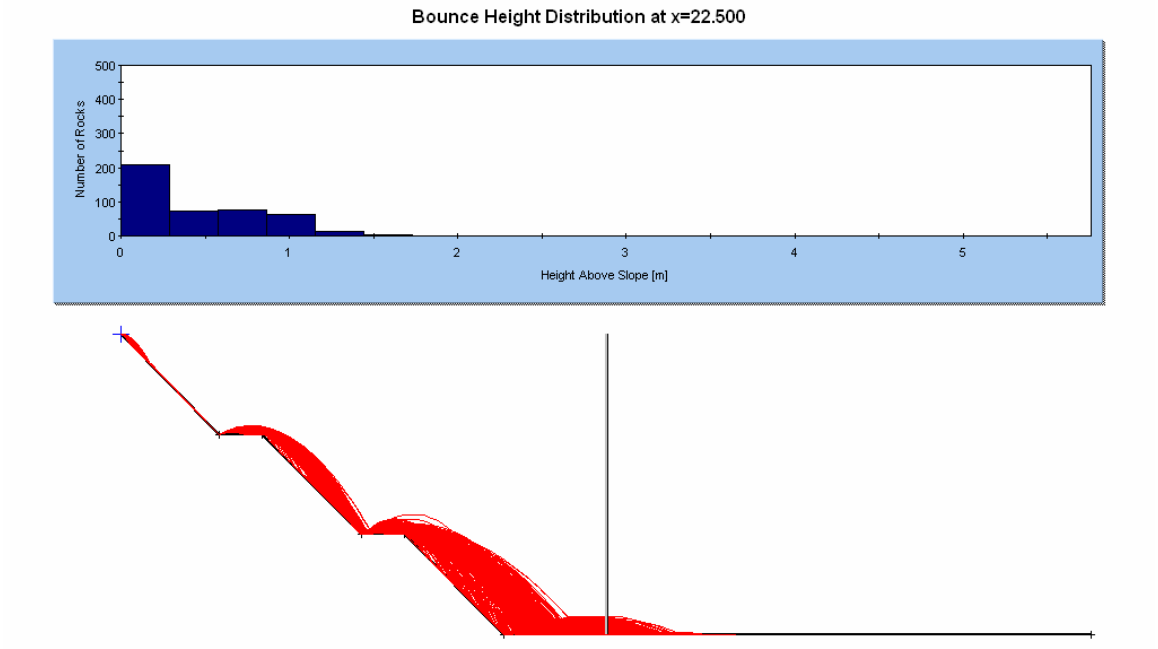


Figure A2. Bounce Height Distribution at x=22.500 and rockfall paths of rock type Four.

- Document Name: Rock 2

    - Material Name: Type Five
    - RN: mean = 0.315 standard deviation = 0.064
    - RT: mean = 0.712 standard deviation = 0.116

RocFall Analysis Information

Document Name

Rock2

Project Settings

Units: Metric
Friction angle: Use friction fngle specified in material editor
Minimum Velocity=0.1
Angular Velocity of the rocks CONSIDERED
Standard Deviations NOT USED when generating slope vertices
Random-number generation: Random

Slope

Segment 1, Material: Type Five
Start Point: X mean=0 std dev=0 Y mean=0 std dev=0
End Point: X mean=4.6 std dev=0 Y mean=-8 std dev=0

Segment 2, Material: Type Five
Start Point: X mean=4.6 std dev=0 Y mean=-8 std dev=0
End Point: X mean=6.6 std dev=0 Y mean=-8 std dev=0

Segment 3, Material: Type Five
Start Point: X mean=6.6 std dev=0 Y mean=-8 std dev=0
End Point: X mean=11.2 std dev=0 Y mean=-16 std dev=0

Segment 4, Material: Type Five
Start Point: X mean=11.2 std dev=0 Y mean=-16 std dev=0
End Point: X mean=13.2 std dev=0 Y mean=-16 std dev=0

Segment 5, Material: Type Five
Start Point: X mean=13.2 std dev=0 Y mean=-16 std dev=0
End Point: X mean=17.8 std dev=0 Y mean=-24 std dev=0

Segment 6, Material: Type Five
Start Point: X mean=17.8 std dev=0 Y mean=-24 std dev=0
End Point: X mean=45 std dev=0 Y mean=-24 std dev=0

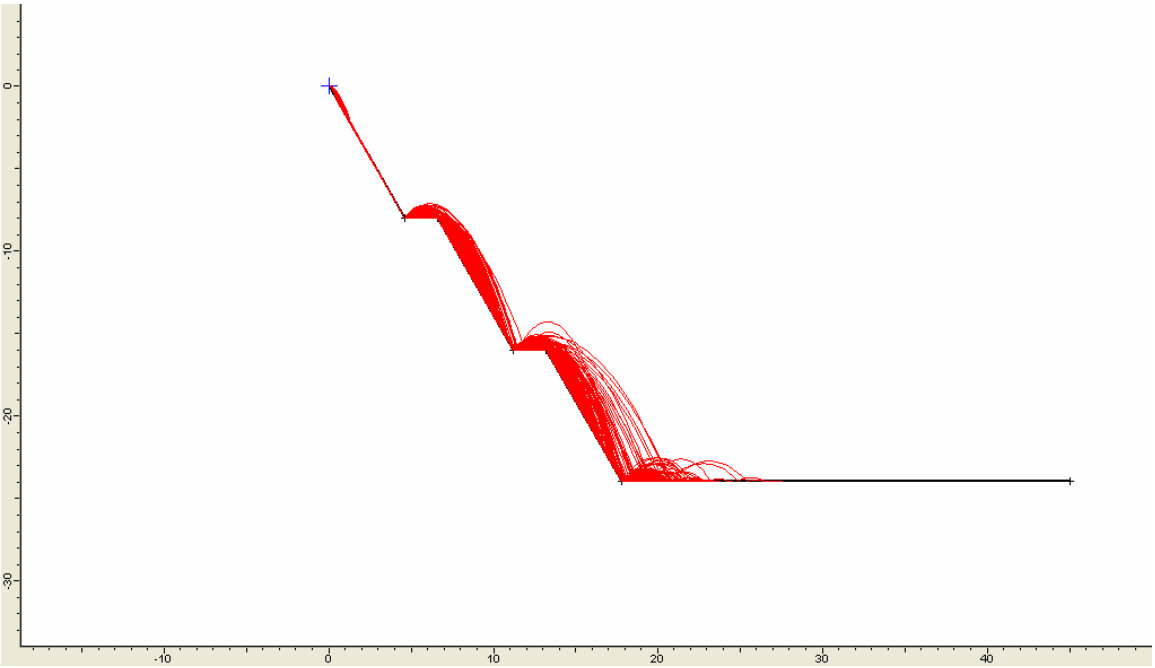
Materials

Material name: Type Five
Coefficient of Normal Restitution (RN): mean=0.315 std dev=0.064

Coefficient of Tangential Restitution (RT): mean=0.712 std dev=0.116
Friction Angle: mean=30 std dev=0
Roughness: std dev=0

Seeders

Point Seeder
Horizontal Velocity: mean=1.5, std dev=0.15
Vertical Velocity: mean=0, std dev=0
Mass: mean=10, std dev=0
Angular Velocity: mean=0, std dev=0
Location: 0, 0



.
Figure A3. Rockfall paths of rock type Five.

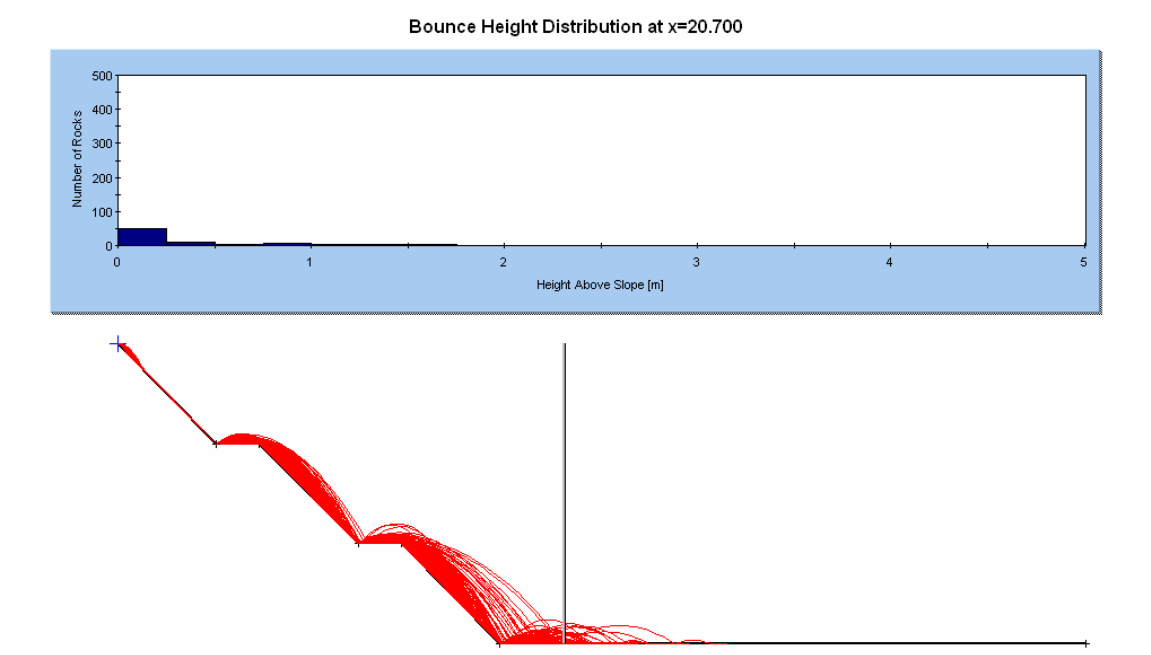


Figure A4. Bounce Height distribution at x=20.700 and rockfall paths of rock type Five.

- Documents Name: Rock 3
    - Material Name: Type Six
    - RN: mean = 0.47 standard deviation = 0
    - RT: mean = 0.55 standard deviation = 0

RocFall Analysis Information

Document Name

Rock3

Project Settings

Units: Metric
Friction angle: Use friction fngle specified in material editor
Minimum Velocity=0.1
Angular Velocity of the rocks CONSIDERED
Standard Deviations NOT USED when generating slope vertices
Random-number generation: Random

Slope

Segment 1, Material: Type Six
Start Point: X mean=0 std dev=0 Y mean=0 std dev=0
End Point: X mean=4.6 std dev=0 Y mean=-8 std dev=0

Segment 2, Material: Type Six
Start Point: X mean=4.6 std dev=0 Y mean=-8 std dev=0
End Point: X mean=6.6 std dev=0 Y mean=-8 std dev=0

Segment 3, Material: Type Six
Start Point: X mean=6.6 std dev=0 Y mean=-8 std dev=0
End Point: X mean=11.2 std dev=0 Y mean=-16 std dev=0

Segment 4, Material: Type Six
Start Point: X mean=11.2 std dev=0 Y mean=-16 std dev=0
End Point: X mean=13.2 std dev=0 Y mean=-16 std dev=0

Segment 5, Material: Type Six
Start Point: X mean=13.2 std dev=0 Y mean=-16 std dev=0
End Point: X mean=17.8 std dev=0 Y mean=-24 std dev=0

Segment 6, Material: Type Six
Start Point: X mean=17.8 std dev=0 Y mean=-24 std dev=0
End Point: X mean=45 std dev=0 Y mean=-24 std dev=0

Materials

Material name: Type Six
Coefficient of Normal Restitution (RN): mean=0.47 std dev=0
Coefficient of Tangential Restitution (RT): mean=0.55 std dev=0
Friction Angle: mean=30 std dev=0
Roughness: std dev=0

Seeders

Point Seeder
Horizontal Velocity: mean=1.5, std dev=0.15
Vertical Velocity: mean=0, std dev=0
Mass: mean=10, std dev=0
Angular Velocity: mean=0, std dev=0
Location: 0, 0

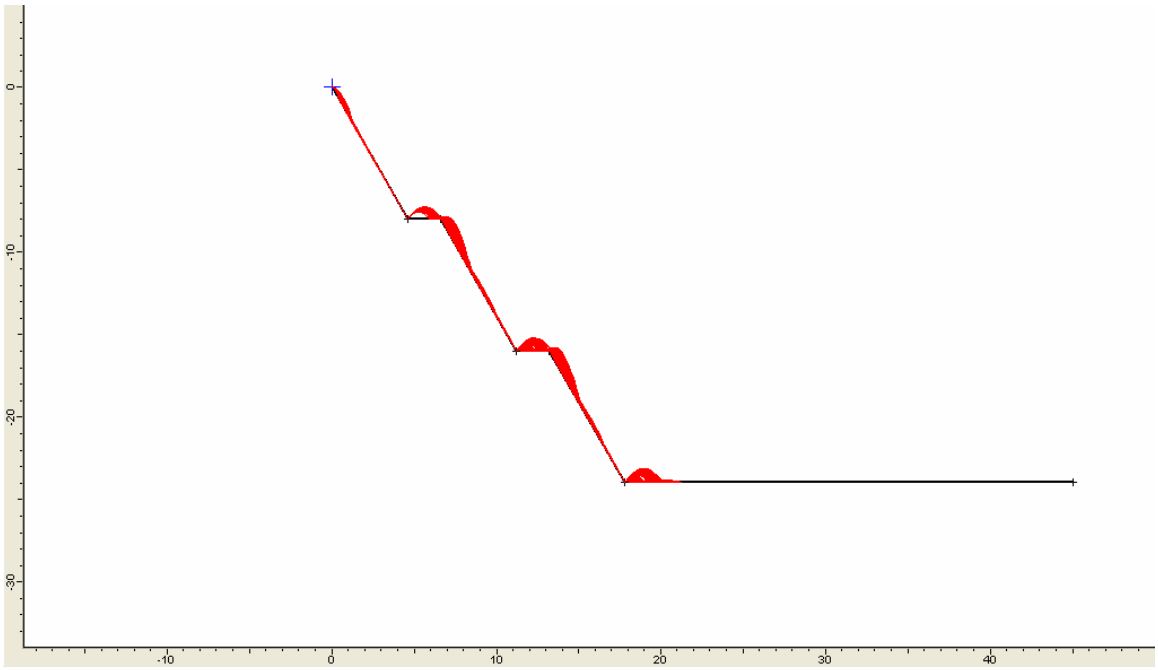


Figure A5. Rockfall paths of rock type Six.

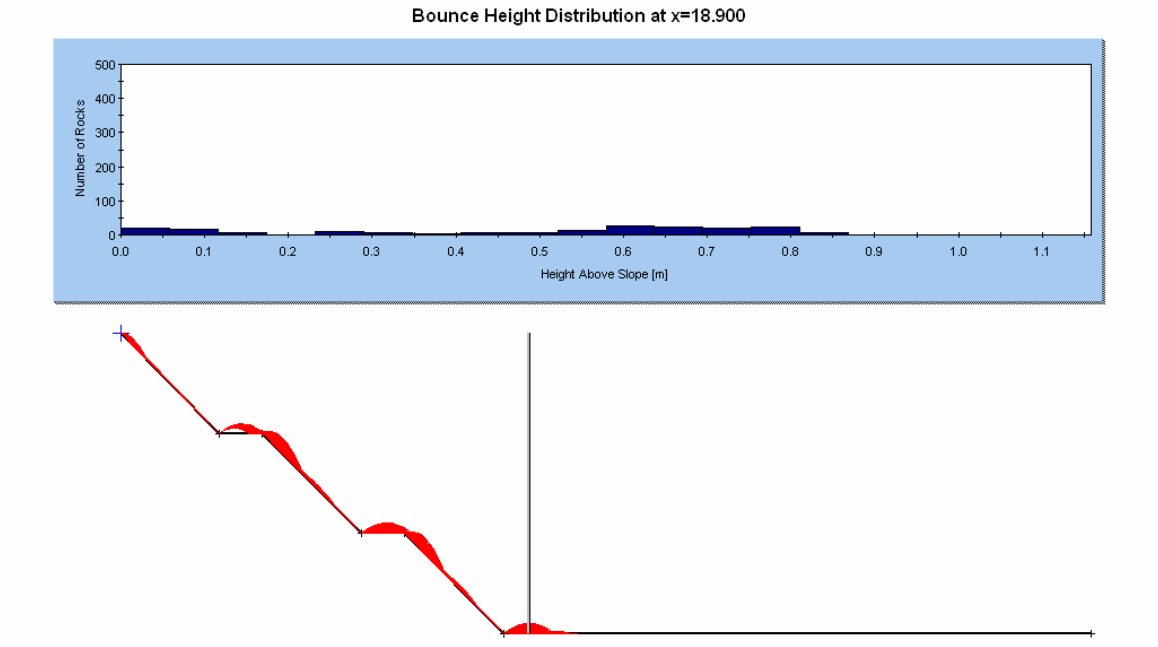


Figure A6. Bounce Height Distribution at x=18.300 and rockfall paths of rock type Six.

Results of rockfall simulations using horizontal velocity 0.1 and 0.5 m/s:

- Document Name: Rock 1

    - Material name: Type One
    - Horizontal velocity: 0.1 m/s standard deviation: 0.01

RocFall Analysis Information

Document Name

Rock1

Project Settings

Units: Metric
Friction angle: Use friction fngle specified in material editor
Minimum Velocity=0.1
Angular Velocity of the rocks CONSIDERED
Standard Deviations NOT USED when generating slope vertices
Random-number generation: Random

Slope

Segment 1, Material: Type One
Start Point: X mean=0 std dev=0 Y mean=0 std dev=0
End Point: X mean=4.6 std dev=0 Y mean=-8 std dev=0

Segment 2, Material: Type One
Start Point: X mean=4.6 std dev=0 Y mean=-8 std dev=0
End Point: X mean=6.6 std dev=0 Y mean=-8 std dev=0

Segment 3, Material: Type One
Start Point: X mean=6.6 std dev=0 Y mean=-8 std dev=0
End Point: X mean=11.2 std dev=0 Y mean=-16 std dev=0

Segment 4, Material: Type One
Start Point: X mean=11.2 std dev=0 Y mean=-16 std dev=0
End Point: X mean=13.2 std dev=0 Y mean=-16 std dev=0

Segment 5, Material: Type One
Start Point: X mean=13.2 std dev=0 Y mean=-16 std dev=0
End Point: X mean=17.8 std dev=0 Y mean=-24 std dev=0

Segment 6, Material: Type One
Start Point: X mean=17.8 std dev=0 Y mean=-24 std dev=0
End Point: X mean=45 std dev=0 Y mean=-24 std dev=0

Materials

Material name: Type One
Coefficient of Normal Restitution (RN): mean=0.487 std dev=0
Coefficient of Tangential Restitution (RT): mean=0.91 std dev=0

Friction Angle: mean=30 std dev=0
Roughness: std dev=0

Seeders

Point Seeder
Horizontal Velocity: mean=0.1, std dev=0.01
Vertical Velocity: mean=0, std dev=0
Mass: mean=10, std dev=0
Angular Velocity: mean=0, std dev=0
Location: 0, 0

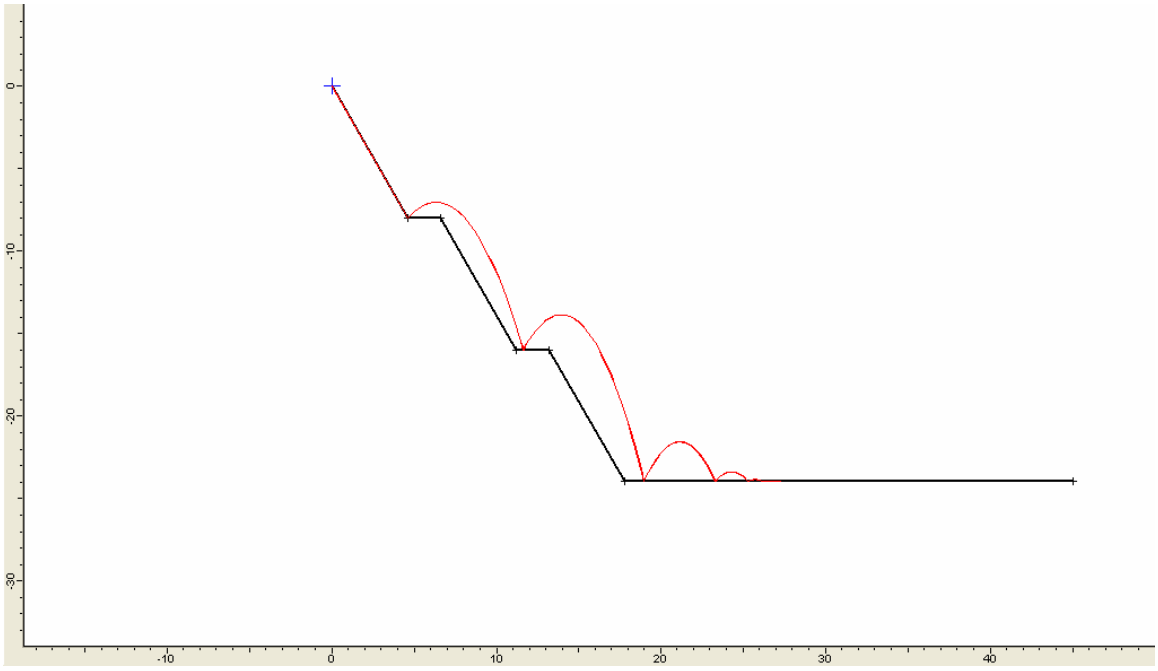


Figure A7. Rockfall paths of rock type One at horizontal velocity of 0.1 m/s with standard deviation of 0.01.

- Document Name: Rock 2
    - Material name: Type One
    - Horizontal velocity: 0.5 m/s standard deviation: 0.05

RocFall Analysis Information

Document Name

Rock2

Project Settings

Units: Metric
Friction angle: Use friction fngle specified in material editor
Minimum Velocity=0.1
Angular Velocity of the rocks CONSIDERED
Standard Deviations NOT USED when generating slope vertices
Random-number generation: Random

Slope

Segment 1, Material: Type one
Start Point: X mean=0 std dev=0 Y mean=0 std dev=0
End Point: X mean=4.6 std dev=0 Y mean=-8 std dev=0

Segment 2, Material: Type one
Start Point: X mean=4.6 std dev=0 Y mean=-8 std dev=0
End Point: X mean=6.6 std dev=0 Y mean=-8 std dev=0

Segment 3, Material: Type one
Start Point: X mean=6.6 std dev=0 Y mean=-8 std dev=0
End Point: X mean=11.2 std dev=0 Y mean=-16 std dev=0

Segment 4, Material: Type one
Start Point: X mean=11.2 std dev=0 Y mean=-16 std dev=0
End Point: X mean=13.2 std dev=0 Y mean=-16 std dev=0

Segment 5, Material: Type one
Start Point: X mean=13.2 std dev=0 Y mean=-16 std dev=0
End Point: X mean=17.8 std dev=0 Y mean=-24 std dev=0

Segment 6, Material: Type one
Start Point: X mean=17.8 std dev=0 Y mean=-24 std dev=0
End Point: X mean=45 std dev=0 Y mean=-24 std dev=0

Materials

Material name: Type one
Coefficient of Normal Restitution (RN): mean=0.487 std dev=0
Coefficient of Tangential Restitution (RT): mean=0.91 std dev=0
Friction Angle: mean=30 std dev=0
Roughness: std dev=0

Seeders

Point Seeder
Horizontal Velocity: mean=0.5, std dev=0.05
Vertical Velocity: mean=0, std dev=0
Mass: mean=10, std dev=0
Angular Velocity: mean=0, std dev=0
Location: 0, 0

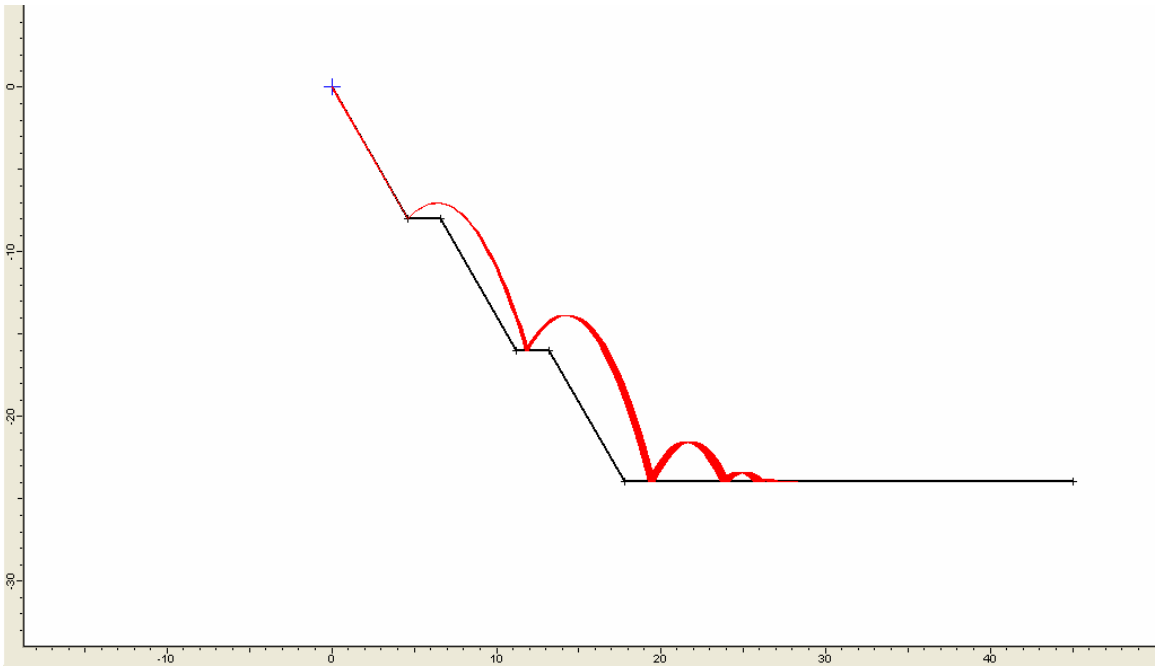


Figure A8. Rockfall paths of rock type One at horizontal velocity of 0.5 m/s with standard deviation of 0.05.

Table A1. Rocscience Coefficient of Restitution Table.

RN (Normal)				*RT (Tangential)*				*Type*
Min	***Max***	***Mean***	***Standard Deviation***	***Min***	***Max***	***Mean***	***Standard Deviation***	
0.370	0.420			0.870	0.920			Hard surface paving
0.330	0.370			0.830	0.870			Bedrock or boulders with little soil or vegetation
0.300	0.330			0.830	0.870			Talus with little vegetation
0.300	0.330			0.800	0.830			Talus with some vegetation
0.280	0.320			0.800	0.830			Soft soil slope with little vegetation
0.280	0.320			0.780	0.820			Vegetated soil slope
		0.315	0.064			0.712	0.112	Limestone face
		0.303	0.080			0.615	0.170	Partially vegetated limestone scree
		0.315	0.064			0.712	0.116	Uncovered limestone blast pile
		0.251	0.029			0.489	0.141	Vegetated covered limestone pile
		0.276	0.079			0.835	0.087	Chalk face
		0.271	0.018			0.596	0.085	Vegetated chalk scree
		0.384	0.133			0.687	0.130	Wood platform slope at 45 degrees was used as a control for the field tests they did.
		0.200				0.530		Dolomitic limestone boulders on rocky surfaces and on talus

								desposits
		0.100				0.200		Remolded pyroclastic from the terraces situated at the base of the cliff
		0.000				0.240		Impacts on detritus of the fans present at the foot of a rock cliff
		0.393				0.567		Soil
		0.453				0.737		Shotcrete
		0.487				0.910		Rock slope
		0.500				0.950		Bedrock
		0.350				0.850		Bedrock covered by large blocks
		0.300				0.700		Debris formed by uniform distributed elements
		0.250				0.550		Soil covered by vegetation
		0.530				0.990		Clean hard bedrock
		0.400				0.900		Asphalt roadway
		0.350				0.850		Bedrock outcrops with hard surface, large boulders
		0.320				0.820		Talus cover
		0.320				0.800		Talus cover with vegetation
		0.300				0.800		Soft soil, some vegetation
0.370	0.420							Smooth hard surfaces and paving
0.330	0.370							Most bedrock and boulder fields
0.300	0.330							Talus and firm soil slopes

0.280	0.300							Soft soil slopes
				0.870	0.920			Smooth hard surfaces such as pavement or smooth bedrock surfaces
				0.830	0.870			Most bedrock surfaces and talus with no vegetation
				0.820	0.850			Most talus slopes with some low vegetation
				0.800	0.830			Vegetated talus slopes and soil slopes with spares vegetation
				0.780	0.820			Brush covered soil slope
		0.530	0.040			0.990	0.040	Clean Hard Bedrock
		0.350	0.040			0.850	0.040	Bedrock outcrop
		0.320	0.040			0.820	0.040	Talus cover
		0.3200	0.040			0.800	0.040	Talus with vegetation
		0.400	0.040			0.900	0.040	Asphalt paving
		0.530	0.040			0.990	0.040	Clean Hard Bedrock
		0.350	0.040			0.850	0.040	Bedrock outcrop
		0.480	0.190			0.530	0.170	Concrete
		0.470	0.300			0.550	0.230	Weathered Rock
		0.480	0.000			0.530	0.000	Concrete
		0.470	0.000			0.550	0.000	Weathered Rock
		0.850	0.000			0.530	0.000	Concrete
		1.000	0.000			0.550	0.000	Weathered Rock
		0.530	0.040			0.990	0.040	Bedrock
		0.500	0.060			0.700	0.060	Blockfield
		0.500	0.060			0.650	0.060	Blockfield with bushes and

								small trees
		0.500	0.060			0.500	0.060	Blockfield with forest
		0.300	0.060			0.800	0.060	Top-soil with vegetation
		0.400	0.040			0.900	0.040	Asphalt paving
		0.350	0.040			0.850	0.040	Gravel road
		0.500				0.800		Sparsely forested slope is covered by a veneer of very fine weathered talus derived from weak schistose units underlying the limestone cap.
		0.500				0.800		Limestone on bare uniform talus slope formed of basalt fragments with a modal size of 5 cm.
		0.700				0.900		Rectangular bolder of metamorphosed tuff on bare rock and a steep snow covered shelf.

File://C:\Program%20Files\Rocscience\Rocscience\RocFall\RN_RT_TABLE.htm

2004/04/13

APPENDIX B

Tables containing typical rockfall parameters for stack configuration (1) and their specified file names in CD-R.

Table B1. Rockfall parameters for stack configuration 1, 16 m bench height, 70^{o} bench face angle, rock type One (File name on CD-R: buana90).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location	7.2	8	8.8	9.6
Distance of barrier from toe of bottom bench (m)	1.4	2.2	3	3.8
Maximum bounce height (m)	1.54	2.01	2.25	2.25
Recommended height of barrier	2.0	2.1	2.3	2.3
Number of rocks	22	28	28	28
Maximum total kinetic energy (kJ)	0.344	0.288	0.288	0.288

Table B2. Rockfall parameters for stack configuration 1, 16 m bench height, 80^{o} bench face angle, rock type One (File name on CD-R: buana91).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	4	4.8	5.6	6.4
Distance of barrier from toe of bottom bench (m)	1.2	2	2.8	3.6
Maximum bounce height (m)	4	4	2.75	2.75
Recommended height of barrier (m)	4	4	2.8	2.8
Number of rocks	143	4	11	82
Maximum total kinetic energy (kJ)	0.460	0.383	0.383	0.383

Table B3. Rockfall parameters for stack configuration1, 16 m bench height, 90^o bench face angle, rock type One (File name on CD-R: buana92).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	3.5	4.2	4.9	5.6
Distance of barrier from toe of bottom bench (m)	3.5	4.2	4.9	5.6
Maximum bounce height (m)	3.88	3.88	3.88	3.88
Recommended height of barrier (m)	3.9	3.9	3.9	3.9
Number of rocks	378	206	11	6
Maximum total kinetic energy (kJ)	0.400	0.400	0.400	0.400

The satisfactory location of barrier for bench face angle:

- 60^o, is location 4 as its maximum bounce height (1.83m) approaches the minimum. barrier height of first category of Table 4.1 and its maximum total kinetic energy is less than 250 kJ. Moreover, more rocks reach the maximum bounce height than at location 3.
- 70^o, is location 2 as its maximum bounce height and maximum total kinetic energy. satisfy the first category of Table 4.1, i.e., 2.01m between height of barrier min. (2 m) and height of barrier max. (5 m), and 0.288 kJ < 250 kJ.
- 80^o, is location 3 (same reason as for 70^o bench face angle).
- 90^o, is location 1 (same reason as for 70^o bench face angle).

Table B4. Rockfall parameters for stack configuration 1, 16 m bench height, 60^o bench face angle, rock type Two (File name on CD-R: buana93).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	10.4	11.2	12	12.8
Distance of barrier from toe of bottom bench (m)	1.2	2	2.8	3.6
Maximum bounce height (m)	2	2.71	2.86	2.71
Recommended height of barrier (m)	2	2.75	2.9	2.75
Number of rocks	11	8	11	8
Maximum total kinetic energy (kJ)	0.219	0.133	0.133	0.219

Table B5. Rockfall parameters for stack configuration 1, 16 m bench height, 70° bench face angle, rock type Two (File name on CD-R: buana94).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8	9.6
Distance of barrier from toe of bottom bench (m)	1.4	2.2	3	3.8
Maximum bounce height (m)	2.75	2.75	1.78	0.8
Recommended height of barrier(m)	2.8	2.8	2.0	2
Number of rocks	6	6	8	33
Maximum total kinetic energy (kJ)	0.130	0.169	0.256	0.300

Table B6. Rockfall parameters for stack configuration 1, 16 m bench height, 80° bench face angle, rock type Two (File name on CD-R: buana95).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	4	4.8	5.6	6.4
Distance of barrier from toe of bottom bench (m)	1.2	2	2.8	3.6
Maximum bounce height (m)	6.7	6.4	4.38	4.03
Recommended height of barrier (m)	5	5	4.4	4.1
Number of rocks	23	7	3	3
Maximum total kinetic energy(kJ)	0.238	0.630	0.550	0.317

Table B7. Rockfall parameters for stack configuration 1, 16 m bench height, 90^o bench face angle, rock type Two (File name on CD-R: buana96).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	3.5	4.2	4.9	5.6	6.3
Distance of barrier from toe of bottom bench (m)	3.5	4.2	4.9	5.6	6.3
Maximum bounce height (m)	6.9	8.5	7.7	5.38	3.08
Recommended height of barrier (m)	5	5	5	5	3.1
Number of rocks	40	5	5	5	10
Maximum total kinetic energy (kJ)	0.713	0.633	0.713	0.713	0.319

The satisfactory location of barrier for bench face angle:
- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle).
- 80^o, is location 3 (same reason as for 60^o bench face angle).
- 90^o, is location 4. As only 5 rocks reach the maximum bounce height (5.38 m) while others have a height less than 3.83 m, a barrier with 3.9 m height will be installed accepting a low risk in rockfall hazard point of view.

Table B8. Rockfall parameters for stack configuration 1, 16 m bench height, 60^o bench face angle, rock Three (File name on CD-R: buana97).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	10.4	11.2	12	12.8
Distance of barrier from toe of bottom bench (m)	1.2	2	2.8	3.6
Maximum bounce height (m)	2.41	3.28	3.46	3.11
Recommended height of barrier (m)	2.5	3.3	3.5	3.2
Number of rocks	28	8	11	8
Maximum total kinetic energy (kJ)	0.188	0.113	0.188	0.268

Table B9. Rockfall parameter for stack configuration 1, 16 m bench height, 70^{o} bench face angle, rock type Three (File name on CD-R: buana98).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8	9.6
Distance of barrier from toe of bottom bench (m)	1.4	2.2	3	3.8
Maximum bounce height (m)	3.08	3.6	3.6	2.69
Recommended height of barrier (m)	3.1	3.6	3.6	2.7
Number of rocks	5	8	5	5
Maximum total kinetic energy (kJ)	0.153	0.153	0.192	0.192

Table B10. Rockfall parameters for stack configuration 1, 16 m bench height, 80^{o} bench face angle, rock type Three (File name on CD-R: buana99).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	6.4	7.2	8	8.8
Distance of barrier from toe of bottom bench (m)	3.6	4.4	5.2	6
Maximum bounce height (m)	5.4	4.95	3.17	3.17
Recommended height of barrier (m)	5	5	3.2	3.2
Number of rocks	17	8	11	11
Maximum total kinetic energy (kJ)	0.470	0.390	0.313	0.160

Table B11. Rockfall parameters for stack configuration 1, 16 m bench height, 90^o bench face angle, rock type Three (File name on CD-R: buana100).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	5.6	6.3	7	7.7
Distance of barrier from toe of bottom bench (m)	5.6	6.3	7	7.7
Maximum bounce height (m)	6.9	5.38	5.38	3.08
Recommended height of barrier (m)	5	5	5	3.1
Number of rocks	8	67	8	8
Maximum total kinetic energy (kJ)	0.869	0.550	0.475	0.550

The satisfactory location of barrier for bench face angle:
- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 2 (same reason as for 60^o bench face angle).
- 80^o, is location 2 (same reason as for 60^o bench face angle).
- 90^o, is location 4 (same reason as for 60^o bench face angle).

Table B12. Rockfall parameters for stack configuration 1, 20 m bench height, 60^o bench face angle, rock type One (File name on CD-R: buana101).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	12.8	13.6	14.4	15.2
Distance of barrier from toe of bottom bench (m)	1.3	2.1	2,9	3.7
Maximum bounce height (m)	1.27	1.73	2.08	2.3
Recommended height of barrier(m)	1.3	1.8	2.1	2.3
Number of rocks	67	400	422	244
Maximum total kinetic energy (kJ)	0.400	0.383	0.383	0.319

Table B13. Rockfall parameters for stack configuration 1, 20 m bench height, 70^{o} bench face angle, rock type One (File name on CD-R: buana102).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	8.8	9.6	10.4	11.2
Distance of barrier from toe of bottom bench (m)	1.5	2.3	3.1	3.9
Maximum bounce height (m)	1.96	2.57	2.88	3.01
Recommended height of barrier (m)	2.0	2.6	2.9	3.1
Number of rocks	6	6	8	8
Maximum total kinetic energy (kJ)	0.367	0.367	0.367	0.367

Table B14. Rockfall parameters for stack configuration 1, 20 m bench height, 80^{o} bench face angle, rock type One (File name on CD-R: buana103).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	4.8	5.6	6.4	7.2
Distance of barrier from toe of bottom bench (m)	1.3	2.1	2.9	3.7
Maximum bounce height (m)	4.65	4.25	3.28	3.6
Recommended height of barrier (m)	4.7	4.3	3.3	3.6
Number of rocks	39	6	67	78
Maximum total kinetic energy (kJ)	0.595	0.495	0.495	0.495

Table B15. Rockfall parameters for stack configuration 1, 20 m bench height, 90^o bench face angle, rock type One (File name on CD-R: buana104).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	4.2	4.9	5.6	6.3
Distance of barrier from toe of bottom bench (m)	4.2	4.9	5.6	6.3
Maximum bounce height (m)	4.88	4.88	4.88	2.9
Recommended height of barrier (m)	4.9	4.9	4.9	2.9
Number of rocks	310	100	10	8
Maximum total kinetic energy (kJ)	0.494	0.494	0.494	0.494

The satisfactory location of barrier for bench face angle:
- 60^o, is location 3 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 3 (same reason as for 60^o bench face angle).
- 80^o, is location 1 (same reason as for 60^o bench face angle).
- 90^o, is location 1 (same reason as for 60^o bench face angle).

Table B16. Rockfall parameters for stack configuration 1, 20 m bench height, 60^o bench face angle, rock type Two (File name on CD-R: buana105).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	12.8	13.6	14.4	15.2
Distance of barrier from toe of bottom bench (m)	1.3	2.1	2.9	3.7
Maximum bounce height (m)	2.5	3,25	3.84	3.84
Recommended height of barrier (m)	2.5	3.3	3.9	3.9
Number of rocks	6	8	8	11
Maximum total kinetic energy (kJ)	0.350	0.230	0.170	0.170

Table B17. Rockfall parameters for stack configuration 1, 20 m bench height, 70^{o} bench face angle, rock type Two (File name on CD-R: buana106).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	8.8	9.6	10.4	11.2
Distance of barrier from toe of bottom bench (m)	1.5	2.3	3.1	3.9
Maximum bounce height (m)	3.1	3.7	3.7	2.9
Recommended height of barrier (m)	3.1	3.7	3.7	2.9
Number of rocks	11	8	6	8
Maximum total kinetic energy (kJ)	0.158	0.158	0.267	0.317

Table B18. Rockfall parameters for stack configuration 1, 20 m bench height, 80^{o} bench face angle, rock type Two (File name on CD-R: buana107).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	6.4	7.2	8	8.8
Distance of barrier from toe of bottom bench (m)	2.9	3.7	4.5	5.3
Maximum bounce height (m)	5.5	5.5	4.69	3.9
Recommended height of barrier (m)	5	5	4.7	3.9
Number of rocks	6	4	4	4
Maximum total kinetic energy (kJ)	0.538	0.267	0.360	0.538

Table B19. Rockfall parameters for stack configuration 1, 20 m bench height, 90^o bench face angle, rock type Two (File name on CD-R: buana108).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	4.2	4.9	5.6	6.3
Distance of barrier from toe of bottom bench (m)	4.2	4.9	5.6	6.3
Maximum bounce height (m)	9.7	8.75	6.8	3.9
Recommended height of barrier (m)	5	5	5	3.9
Number of rocks	8	11	8	17
Maximum total kinetic energy (kJ)	0.690	0.790	0.790	0.790

The satisfactory location of barrier for bench facer angle:
- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle).
- 80^o, is location 3 (same reason as for 60^o bench face angle).
- 90^o, is location 4 (same reason as for 60^o bench face angle).

Table B20. Rockfall parameters for stack configuration 1, 20 m bench height, 60^o bench face angle, rock type Three (File name on CD-R: buana109).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	12.8	13.6	14.4	15.2
Distance of barrier from toe of bottom bench (m)	1.3	2.1	2.9	3.7
Maximum bounce height (m)	2.69	3.83	4.5	4.5
Recommended height of barrier (m)	2.7	3.9	4.5	4.5
Number of rocks	344	56	8	22
Maximum total kinetic energy (kJ)	0.305	0.205	0.153	0.203

Table B21. Rockfall parameters for stack configuration 1, 20 m bench height, 70^{o} bench face angle, rock type Three (File name on CD-R: buana110).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	8.8	9.6	10.4	11.2
Distance of barrier from toe of bottom bench (m)	1.5	2.3	3.1	3.9
Maximum bounce height (m)	3.71	4.14	3.71	2.08
Recommended height of barrier (m)	3.8	4.2	3.8	2.1
Number of rocks	6	6	6	6
Maximum total kinetic energy (kJ)	0.165	0.630	0.538	0.720

Table B22. Rockfall parameters for stack configuration 1, 20 m bench height, 80^{o} bench face angle, rock type Three (File name on CD-R: buana111).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of falling rocks on the catch bench	7.2	8	8.8	9.6
Run-out distance (m)	3.7	4.5	5.3	6.1
Maximum bounce height (m)	6.67	5.56	3.9	1.67
Recommended height of barrier (m)	5	5	3.9	1.7
Number of rocks	69	46	6	108
Maximum total kinetic energy (kJ)	0.180	0.630	0.538	0.720

Table B23. Rockfall parameter for stack configuration 1, 20 m bench height, 90^o bench face angle, rock type Three (File name on CD-R: buana112).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of falling rocks on the catch bench	6.3	7	7.7	8.4
Run-out distance (m)	6.3	7	7.7	8.4
Maximum bounce height (m)	8.75	6.8	6.8	4.8
Recommended height of barrier (m)	5	5	5	4.8
Number of rocks	6	56	11	6
Maximum total kinetic energy (kJ)	1.183	0.990	0.600	0.400

The satisfactory location of barrier for bench face angle:
- 60^o, is location 1 as its maximum bounce height and total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle).
- 80^o, is location 3 (same reason as for 60^o bench face angle).
- 90^o, is location 4 (same reason as for 60^o bench face angle).

Table B24. Rockfall parameters for stack configuration 1, 24 m bench height, 60^o bench face angle, rock type One (File name on CD-R: buana113).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	1.4	2.3	3.2	4.1
Maximum bounce height (m)	1.33	2.08	2.49	2.77
Recommended height of barrier (m)	1.4	2.1	2.5	2.8
Number of rocks	456	8	72	61
Maximum total kinetic energy (kJ)	0.530	0.455	0.455	0.378

Table B25. Rockfall parameters for stack configuration 1, 24 m bench height, 70^o bench face angle, rock type One (File name on CD-R: buana114).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	10.8	11.7	12.6	13.5
Distance of barrier from toe of bottom bench (m)	2.1	3	3.3	4.8
Maximum bounce height (m)	2.51	3.25	3.6	3.6
Recommended height of barrier (m)	2.6	3.3	3.6	3.6
Number of rocks	44	6	8	33
Maximum total kinetic energy (kJ)	0.413	0.413	0.331	0.331

Table B26. Rockfall parameters for stack configuration 1, 24 m bench height, 80^o bench face angle, rock type One (File name on CD-R: buana115).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	5.6	6.4	7.2	8
Distance of barrier from toe of bottom bench (m)	1.4	2.2	3	3.8
Maximum bounce height (m)	2.3	3.17	3.7	4.31
Recommended height of barrier (m)	2.3	3.2	3.7	4.4
Number of rocks	8	17	39	28
Maximum total kinetic energy (kJ)	0.675	0.675	0.560	0.560

Table B27. Rockfall parameters for stack configuration 1, 24 m bench height, 90^o bench face angle, rock type One (File name on CD-R: buana116).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of falling rocks on the catch bench	4	4.8	5.6	6.4
Run-out distance (m)	4	4.8	5.6	6.4
Maximum bounce height (m)	5.75	5.75	5.75	3.5
Number of rocks	289	289	44	6
Total kinetic energy (J)	1500	1500	1500	1500

The satisfactory location of barrier for bench face angle:

- 60^o, is location 2 as its maximum bounce height and maximum total kinetic satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle).
- 80^o, is location 1 (same reason as for 60^o bench face angle).
- 90^o, considering the data in table B.25 and the fact that the maximum run-out distance is less than 9.3 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table B28. Rockfall parameters for stack configuration 1, 24 m bench height, 60^o bench face angle, rock type Two (File name on CD-R: buana117).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	1.4	2.3	3.2	4.1
Maximum bounce height (m)	2.6	3.81	4.5	4.75
Recommended height of barrier (m)	2.6	3.9	4.5	4.8
Number of rocks	22	8	8	6
Maximum total kinetic energy (kJ)	0.419	0.280	0.210	0.210

Table B29. Rockfall parameters for stack configuration 1, 24 m bench height, 70^o bench face angle, rock type Two (File name on CD-R: buana118).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	9.9	10.8	11.7	12.6
Distance of barrier from toe of bottom bench (m)	1.2	2.1	3	3.9
Maximum bounce height (m)	3.3	4.65	5.2	5.2
Recommended height of barrier (m)	3.3	4.7	5.2	5.2
Number of rocks	6	6	6	6
Maximum total kinetic energy (kJ)	0.342	0.205	0.205	0.340

Table B30. Rockfall parameters for stack configuration 1, 24 m bench height, 80^o bench face angle, rock type Two (File name on CD-R: buana119).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of falling rocks on the catch bench	5.6	6.4	7.2	8
Run-out distance (m)	1.4	2.2	3	3.8
Maximum bounce height (m)	8.4	6.56	6.7	7.13
Recommended height of barrier (m)	5	5	5	5
Number of rocks	6	6	6	6
Maximum total kinetic energy (kJ)	0.450	0.338	0.225	0.225

Table B31. Rockfall parameters for stack configuration 1, 24 m bench height, 90^o bench face angle, rock type Two (File name on CD-R: buana120).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	4.8	5.6	6.4	7.2
Distance of barrier from toe of bottom bench (m)	4.8	5.6	6.4	7.2
Maximum bounce height (m)	11.67	10.5	7	4.67
Recommended height of barrier (m)	5	5	5	5
Number of rocks	8	8	6	11
Maximum total kinetic energy (kJ)	0.950	1.183	1.067	0.355

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle)
- 80^o, is location 1. As only 6 rocks reach the maximum bounce height (8.4 m) while others have a height less than 4.2 m, a barrier with this latter height may be installed considering a low risk in rockfall hazard point of view.
- 90^o, considering the data in Table B.31 and the fact that the maximum run-out distance is close to 9.3 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table B32. Rockfall parameters for stack configuration 1, 24 m bench height, 60^{o} bench face angle, rock type Three (File name on CD-R: buana121).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	1.4	2.3	3.2	4.1
Maximum bounce height (m)	3.17	4.6	5.45	5.7
Recommended height of barrier (m)	3.2	4.6	5	5
Number of rocks	344	22	17	28
Maximum total kinetic energy (kJ)	0.390	0.260	0.195	0.195

Table B33. Rockfall parameter for stack configuration 1, 24 m bench height, 70^{o} bench face angle, rock type Three (File name on CD-R: buana122).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	9.9	10.7	11.7	12.6
Distance of barrier from toe of bottom bench (m)	1.2	2.1	3	3.9
Maximum bounce height (m)	3.85	5.23	5.5	4.95
Recommended height of barrier (m)	3.9	5	5	5
Number of rocks	6	6	6	6
Maximum total kinetic energy (kJ)	0.240	0.240	0.288	0.383

Table B34. Rockfall parameters for stack configuration 1, 24 m bench height, 80^{o} bench face angle, rock type Three (File name on CD-R: buana123).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of barrier location	5.6	6.4	7.2	8	8.8	9.6	10.4
Distance of barrier from toe of bottom bench (m)	1.4	2.2	3	3.8	4.6	5.4	6.2
Maximum bounce height (m)	5.9	7.9	9.2	9.2	7.9	5.9	3.95
Recommended height of barrier (m)	5	5	5	5	5	5	4
Number of rocks	21	25	6	6	67	246	263
Maximum total kinetic energy (kJ)	0.450	0.225	0.225	0.225	0.338	0.450	0.680

Table B35. Rockfall parameters for stack configuration 1, 24 m bench height, 90^{o} bench face angle, rock type Three (File name on CD-R: buana124).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8	9.6
Distance of barrier from toe of bottom bench (m)	7.2	8	8.8	9.6
Maximum bounce height (m)	8.13	8.13	8.13	4.63
Recommended height of barrier (m)	5	5	5	4.7
Number of rocks	111	22	6	8
Maximum total kinetic energy (kJ)	1.417	0.710	0.710	0.355

The satisfactory location of barrier for bench face angle:
- 60^o, is location 1 as its maximum bounce height and total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle).
- 80^o, is location 7 (same reason as for 60^o bench face angle).
- 90^o, is location 4 (same reason as for 60^o bench face angle).

Table B36. Rockfall parameters for stack configuration 1, 30 m bench height, 60^o bench face angle, rock type One (File name on CD-R: buana125).

	Location1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	18.9	19.8	20.7	21.6
Distance of barrier from toe of bottom bench (m)	1.6	2.5	3.4	4.3
Maximum bounce height (m)	1.7	2.25	2.9	3.32
Recommended height of barrier (m)	1.7	2.3	2.9	3.4
Number of rocks	11	500	6	44
Maximum total kinetic energy (kJ)	0.680	0.580	0.483	0.483

Table B37. Rockfall parameters for stack configuration 1, 30 m bench height, 70^o bench face angle, rock type One (File name on CD-R: buana126).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	12.6	13.5	14.4	15.3
Distance of barrier from toe of bottom bench (m)	1.7	2.6	3.5	4.4
Maximum bounce height (m)	2.5	3.44	4.1	4.56
Recommended height of barrier (m)	2.5	3.5	4.1	4.6
Number of rocks	8	8	6	6
Maximum total kinetic energy (kJ)	0.555	0.555	0.450	0.450

Table B38. Rockfall parameters for stack configuration 1, 30 m bench height, 80^o bench face angle, rock type One (File name on CD-R: buana127).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	7.2	8.1	9	9.9
Distance of barrier from toe of bottom bench (m)	1.9	2.8	3.7	4.6
Maximum bounce height (m)	2.83	3.9	4.8	5.38
Recommended height of barrier (m)	2.9	3.9	4.8	5.4
Number of rocks	100	39	17	11
Maximum total kinetic energy (kJ)	0.800	0.665	0.665	0.665

Table B39. Rockfall parameters for stack configuration 1, 30 m bench height, 90^o bench face angle, rock type One (File name on CD-R: buana128).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x coordinate of barrier location (m)	5.6	6.4	7.2	8
Distance of barrier from toe of bottom bench (m)	5.6	6.4	7.2	8
Maximum bounce height (m)	7.35	7.35	7.35	3
Recommended height of barrier (m)	5	5	5	3
Number of rocks	200	28	6	33
Maximum total kinetic energy (kJ)	0.670	0.670	0.670	0.600

The satisfactory location of barrier for bench face angle:

- 60^o, is location 2 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle).
- 80^o, is location 1 (same reason as for 60^o bench face angle).
- 90^o, considering the data in Table B.39 and the fact that the maximum run-out distance is close to 10.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table B40. Rockfall parameters for stack configuration 1, 30 m bench height, 60^{o} bench face angle, rock type Two (File name on CD-R: buana129).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	18.9	19.8	20.7	21.6
Distance of barrier from toe of bottom bench (m)	1.6	2.5	3.4	4.3
Maximum bounce height (m)	3.1	4.31	5.25	5.83
Recommended height of barrier	3.1	4.4	5	5
Number of rocks	67	33	28	17
Maximum total kinetic energy (kJ)	0.733	0.550	0.460	0.367

Table B41. Rockfall parameters for stack configuration 1, 30 m bench height, 70^{o} bench face angle, rock type Two (File name on CD-R: buana130).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	12.6	13.5	14.4	15.3
Distance of barrier from toe of bottom bench (m)	1.7	2.6	3.5	4.4
Maximum bounce height (m)	4.67	6.1	7.18	7.18
Recommended height of barrier (m)	4.7	5	5	5
Number of rocks	6	6	6	6
Maximum total kinetic energy (kJ)	0.375	0.283	0.188	0.283

Table B42. Rockfall parameters for stack configuration 1, 30 m bench height, 80^o bench face angle, rock type Two (File name on CD-R: buana131).

	Location 1 of barrier	Location 2 of barrier	Location 2 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	6.3	7.2	8.1	9
Distance of barrier from toe of bottom bench (m)	1	1.9	2.8	3.7
Maximum bounce height (m)	3.9	6.5	8.2	8.64
Recommended height of barrier (m)	4	5	5	5
Number of rocks	5	5	5	5
Maximum total kinetic energy (kJ)	0.613	0.410	0.310	0.310

Table B43. Rockfall parameters for stack configuration 1, 30 m bench height, 90^o bench face angle, rock type Two (File name on CD-R: buana132).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8	9.6
Distance of barrier from toe of bottom bench (m)	7.2	8	8.8	9.6
Maximum bounce height (m)	8.75	5.88	4.4	1.5
Recommended height of barrier (m)	5	5	4.5	2
Number of rocks	8	6	8	33
Maximum total kinetic energy (kJ)	1.140	1.033	0.450	0.150

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle)
- 80^o, is location 1 (same reason as for 60^o bench face angle)
- 90^o, considering the data in Table B.43 and the fact the maximum run-out distance is less than 10.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table B44. Rockfall parameters for stack configuration 1, 30 m bench height, 60^{o} bench face angle, rock type Three (File name on CD-R: buana133).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	18.9	19.8	20.7	21.6
Distance of barrier from toe of bottom bench (m)	1.6	2.5	3.4	4.3
Maximum bounce height (m)	3.85	5.4	6.55	7.33
Recommended height of barrier (m)	3.9	5	5	5
Number of rocks	406	83	33	8
Maximum total kinetic energy (kJ)	0.533	0.450	0.350	0.267

Table B45. Rockfall parameters for stack configuration 1, 30 m bench height, 70^{o} bench face angle, rock type Three (File name on CD-R: buana134).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	11.7	12.6	13.5	14.4
Distance of barrier from toe of bottom bench (m)	0.8	1.7	2.6	3.5
Maximum bounce height (m)	3.2	5.6	7.19	8
Recommended height of barrier (m)	3.2	5	5	5
Number of rocks	8	8	6	6
Maximum total kinetic energy(kJ)	0.630	0.392	0.317	0.392

Table B46. Rockfall parameters for stack configuration 1, 30 m bench height, 80° bench face angle, rock type Three (File name on CD-R: buana135).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	6.3	7.2	8.1	9
Distance of barrier from toe of bottom bench (m)	1	1.9	2.8	3.7
Maximum bounce height (m)	4.85	8.1	10.25	10.75
Recommended height of barrier (m)	4.9	5	5	5
Number of rocks	56	34	19	91
Maximum total kinetic energy (kJ)	0.800	0.500	0.300	0.200

Table B47. Rockfall parameters for stack configuration 1, 30 m bench height, 90° bench face angle, rock type Three (File name on CD-R: buana136).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	8.8	9.6	10.4	11.2
Distance of barrier from toe of bottom bench (m)	8.8	9.6	10.4	11.2
Maximum bounce height (m)	10.2	10.2	5.83	4.4
Recommended height of barrier (m)	5	5	5	4.4
Number of rocks	56	34	19	91
Maximum total kinetic energy (kJ)	1.033	0.888	0.888	0.600

The satisfactory location of barrier for bench face angle:
- 60°, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1
- 70°, is location 1 (same reason as for 60° bench face angle).
- 80°, is location 1 (same reason as for 60° bench face angle).
- 90°, is location 4 (same reason as for 60° bench face angle).

APPENDIX C

Tables containing typical rockfall parameters for stack configuration (2) and their specified file names in CD-R.

Table C1. Rockfall parameters for stack configuration 2, 8 m bench height, 60^o bench face angle, rock type One (File name on CD-R: buana1).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	22.5	23.4	24.3	25.2
Distance of barrier from toe of bottom bench (m)	4.7	5.6	6.5	7.4
Maximum bounce height (m)	2.63	2.63	2.63	2.63
Recommended height of barrier (m)	2.7	2.7	2.7	2.7
Number of rocks	17	333	413	50
Maximum total kinetic energy (kJ)	0.278	0.167	0.167	0.278

Table C2. Rockfall parameters for stack configuration 2, 8 m bench height, 70^o bench face angle, rock type One (File name on CD-R: buana2).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	5.3
Maximum bounce height (m)	3.9	4.28	4,28	4.28
Recommended height of barrier (m)	3.9	4.3	4.3	4.3
Number of rocks	89	133	117	267
Maximum total kinetic energy (kJ)	0.555	0.555	0.463	0.463

Table C3. Rockfall parameters for stack configuration 2, 8 m bench height, 80^o bench face angle, rock type One (File name on CD-R: buana3).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	7.1	8	8.9	9.8
Maximum bounce height (m)	2.3	2.75	2.3	2.3
Recommended height of barrier (m)	2.3	2.8	2.3	2.3
Number of rocks	168	18	186	100
Maximum total kinetic energy (kJ)	0.367	0.275	0.330	0.330

Table C4. Rockfall parameters for stack configuration 2, 8 m bench height, 90^o bench face angle, rock type One (File name on CD-R: buana4).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	4	4.8
Maximum bounce height (m)	2.9	2.3	1.2
Recommended height of barrier (m)	2.9	2.3	2
Number of rocks	33	4	4
Maximum total kinetic energy (kJ)	0.350	0.263	0.088

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle).
- 80^o, is location 1 (same reason as for 60^o bench face angle).
- 90^o, considering the data in Table C.4 and the fact that the maximum run-out distance is less than 9.3 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C5. Rockfall parameters for stack configuration 2, 8 m bench height, 60^{o} bench face angle, rock type Two (File name on CD-R: buana5).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	18.77	19.58	20.4	21.22
Distance of barrier from toe of bottom bench (m)	0.97	1.78	2.6	3.66
Maximum bounce height (m)	2.78	3.63	4.19	4.19
Recommended height of barrier (m)	2.8	3.7	4.2	4.2
Number of rocks	6	6	6	6
Maximum total kinetic energy (kJ)	0.363	0.228	0.181	0.270

Table C6. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, rock type Two (File name on CD-R: buana6).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	14.4	15.3	16.2	17.1
Distance of barrier from toe of bottom bench (m)	1.7	2.6	3.5	4.4
Maximum bounce height (m)	5.3	4.5	4.1	4.1
Recommended height of barrier (m)	5.3	4.5	4.1	4.1
Number of rocks	6	8	17	11
Maximum total kinetic energy (kJ)	0.963	0.455	0.340	0.455

Table C7. Rockfall parameters for stack configuration 2, 8 m bench height, 80^o bench face angle, rock type Two (File name on CD-R: buana7).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	10.8	11.7	12.6	13.5
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	3.69
Maximum bounce height (m)	4.63	4.63	4.63	3.69
Recommended height of barrier (m)	4.7	4.7	4.7	3.7
Number of rocks	4	7	4	4
Maximum total kinetic energy (kJ)	1.000	0.428	0.428	0.370

Table C8. Rockfall parameters for stack configuration 2, 8 m bench height, 90^o bench face angle, rock type Two(File name on CD-R: buana8).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of falling rocks on the catch bench	7.2	8	8.8
Run-out distance (m)	3.2	4	4.8
Maximum bounce height (m)	6.4	4.28	2.88
Recommended height of barrier (m)	5	4.3	2.9
Number of rocks	4	4	4
Maximum total kinetic energy (kJ)	0.550	0.160	0.080

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 2 (same reason as for 60^o bench face angle)
- 80^o, is location 1 (same reason as for 60^o bench face angle)
- 90^o, considering the data in the Table C.8 and more than that, the maximum run-out distance is less than 9.3 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C9. Rockfall parameters for stack configuration 2, 8 m bench height, 60^{o} bench face angle, rock type Three (File name on CD-R: buana9).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	18.9	19.8	20.7	21.6
Distance of barrier from toe of bottom bench (m)	1.1	2	2.9	3.8
Maximum bounce height (m)	2.45	3.44	3.19	2.69
Recommended height of barrier (m)	2.5	3.5	3.2	2.7
Number of rocks	6	6	11	11
Maximum total kinetic energy (kJ)	0.292	0.194	0.245	0.245

Table C10. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, rock type Three (File name on CD-R: buana10).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	5.3
Maximum bounce height (m)	6.5	5.88	5.46	4.69
Recommended height of barrier (m)	5	5	5	4.7
Number of rocks	21	179	83	29
Maximum total kinetic energy (kJ)	0.600	0.333	0.600	0.600

Table C11. Rockfall parameters for stack configuration 2, 8 m bench height, 80^o bench face angle, rock type Three (File name on CD-R: buana11).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	10.8	11.7	12.6	13.5	14.4
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	5.3	6.2
Maximum bounce height (m)	7.2	7.2	6.67	5.63	4.1
Recommended height of barrier (m)	5	5	5	5	4.1
Number of rocks	5	61	136	38	50
Maximum total kinetic energy (kJ)	1.150	0.450	0.513	0.700	0.700

Table C12. Rockfall parameters for stack configuration 2, 8 m bench height, 90^o bench face angle, rock type Three (File name on CD-R: buana12).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8	9.6
Distance of barrier from toe of bottom bench (m)	3.2	4	4.8	5.6
Maximum bounce height (m)	10.2	9.38	6	3.4
Recommended height of barrier (m)	5	5	5	3.4
Number of rocks	13	4	8	8
Maximum total kinetic energy (kJ)	0.875	0.875	0.558	0.480

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 4 (same reason as for 60^o bench face angle).
- 80^o, is location 5 (same reason as for 60^o bench face angle.
- 90^o, considering the data in Table C.12 and the fact that the maximum run-out distance is less than 9.3 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C13. Rockfall parameters for stack configuration 2, 8 m bench height, 60^{o} bench face angle, 70 kg falling rock mass, rock type One (File name on CD-R: buana161).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	22	23.1	24.2	25.3
Distance of barrier from toe of bottom bench (m)	4.2	5.3	6.4	7.5
Maximum bounce height (m)	2.2	2.63	2.63	2.63
Recommended height of barrier (m)	2.2	2.7	2.7	2.7
Number of rocks	17	133	444	6
Maximum total kinetic energy (kJ)	2.333	1.550	1.167	2.333

Table C14. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, 70 kg falling rock mass, rock type One (File name on CD-R: buana162).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	5.3
Maximum bounce height (m)	3.88	4,25	4.25	4.25
Recommended height of barrier (m)				
Number of rocks	89	122	117	256
Maximum total kinetic energy (kJ)	3.875	3.875	3.875	3.200

Table C15. Rockfall parameters for stack configuration 2, 8 m bench height, 80^o bench face angle, 70 kg falling rock mass, rock type One (File name on CD-R: buana163).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	7.1	8	8.9	9.8
Maximum bounce height (m)	2.3	2.75	2.3	2.3
Recommended height of barrier (m)	2.3	2.8	2.3	2.3
Number of rocks	157	14	279	111
Maximum total kinetic energy (kJ)	2.688	1.917	2.333	2.333

Table C16. Rockfall parameters for stack configuration 2, 8 m bench height, 90^o bench face angle, 70 kg falling rock mass, rock type One (File name on CD-R: buana164).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	4	4.8
Maximum bounce height (m)	2.94	2.94	1.15
Recommended height of barrier (m)	3	3	1.2
Number of rocks	43	5	5
Maximum total kinetic energy (kJ)	2.438	2.438	0.600

The satisfactory location of barrier for the bench face angle:
- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1(same reason as for bench face 60^o).
- 80^o, is location 1 (same reason as for bench face angle 60^o).
- 90^o, is location 1(same reason as for bench face angle 60^o).

Table C17. Rockfall parameters for stack configuration 2, 8 m bench height, 60^{o} bench face angle, 70 kg falling rock mass, rock type Two (File name on CD-R: buana165).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location	18.9	19.8	20.7	21.6
Distance of barrier from toe of bottom bench (m)	1.1	2	2.9	3.8
Maximum bounce height (m)	1.67	3.33	3.33	2.94
Recommended height of barrier	1.7	3.4	3.4	3
Number of rocks	11	6	6	6
Maximum total kinetic energy (kJ)	2.083	1.375	1.375	1.775

Table C18. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, 70 kg falling rock mass, rock type Two (File name on CD-R: buana166).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	14.4	15.3	16.2	17.1
Distance of barrier from toe of bottom bench (m)	1.7	2.6	3.5	4.4
Maximum bounce height (m)	4.63	4.63	4.25	4.25
Recommended height of barrier (m)	4.7	4.7	4.3	4.3
Number of rocks	8	6	6	6
Maximum total kinetic energy (kJ)	7.375	2.833	2.833	2.833

Table C19. Rockfall parameters for stack configuration 2, 8 m bench height, 80^o bench face angle, 70 kg falling rock mass, rock type Two (File name on CD-R: buana167).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	10.8	11.7	12.6	13.5
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	5
Maximum bounce height (m)	4.42	4.9	4.42	3.9
Recommended height of barrier (m)	4.5	4.9	4.5	3.9
Number of rocks	18	5	5	4
Maximum total kinetic energy (kJ)	2.550	3.300	3.300	2.900

Table C20. Rockfall parameters for stack configuration 2, 8 m bench height, 90^o bench face angle, 70 kg falling rock mass, rock type Two (File name on CD-R: buana168).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	4	4.8
Maximum bounce height (m)	5.55	2.08	0.69
Recommended height of barrier (m)	5	2.1	2
Number of rocks	9	9	9
Maximum total kinetic energy (kJ)	3.850	1.625	0.550

The satisfactory location of barrier for bench face angle:

- 60^o, is location 2. As only 6 rocks reach the maximum bounce height (3.33 m) while others have a height less than 2.72 m, so accepting a low risk in rockfall hazard point of view, a barrier with 2.8 m height will be installed (refer to the first category of Table 4.11 as well).
- 70^o, is location 4. As only 6 rocks reach the maximum bounce height (4.63 m) while others have a height less than 3.88 m, so accepting a low risk in rockfall hazard point of view, a barrier with 3.9 m height will be installed.
- 80^o, is location 1 as its maximum bounce height and maximum total kinetic energy

satisfy the first category of Table 4.1.

- 90°, considering the data in theTable 4.20 and as the maximum run-out distance is less than 9.3 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C21. Rockfall parameters for stack configuration 2, 8 m bench height, 60° bench face angle, 70 kg falling rock mass, rock type Three (File name on CD-R: buana169).

	Location 1 of barrier	Location 2 of barrier	Location 4 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	18.9	19.8	20.7	21.6
Distance of barrier from toe of bottom bench (m)	1.1	2	2.9	3.8
Maximum bounce height (m)	2.58	3.28	3.05	2.56
Recommended height of barrier (m)	2.6	3.3	3.1	2.6
Number of rocks	6	8	8	8
Maximum total kinetic energy (kJ)	2.000	1.333	1.333	1.667

Table C22. Rockfall parameters for stack configuration 2, 8 m bench height, 70° bench face angle, 70 kg falling rock mass, rock type Three (File name on CD-R: buana170).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	14.4	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	1.7	2.6	3.5	4.4	5.3
Maximum bounce height (m)	7.77	6.2	5.81	5.42	4.65
Recommended height of barrier (m)	5	5	5	5	4.7
Number of rocks	15	23	181	77	38
Maximum total kinetic energy (kJ)	6.938	4.167	2.333	4.150	4.150

Table C23. Rockkfall parameters for stack configuration 2, 8 m bench height, 80^{o} bench face angle, 70 kg falling rock mass, rock type Three (File name on CD-R: buana171).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of barrier location (m)	10.8	11.7	12.6	13.5	14.4	15.3	16.2
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	5.3	6.2	7.1	8
Maximum bounce height (m)	7.19	7.19	6.67	5.63	4.1	4.1	3.1
Recommended height of barrier (m)	5	5	5	5	4.1	4.1	3.1
Number of rocks	7	57	136	14	55	36	21
Maximum total kinetic energy (kJ)	8.000	4.000	3.563	5.333	4.875	3.125	2.667

Table C24. Rockfall parameters for stack configuration 2, 8 m bench height, 90^{o} bench face angle, 70 kg falling rock mass, rock type Three (File name on CD-R: buana172).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8	9.6
Distance of barrier from toe of bottom bench (m)	3.2	4	4.4	5.6
Maximum bounce height (m)	10.2	9.3	6	4.25
Recommended height of barrier (m)	5	5	5	4.3
Number of rocks	25	4	6	4
Maximum total kinetic energy (kJ)	5.563	6.667	3.900	2.250

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 5 (same reason as for 60^o bench face angle).
- 80^o, is location 5 (same reason as for 60^o bench face angle).
- 90^o, considering the data in Table C.24 and as the maximum run-out distance is less than 9.3 m, the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C25. Rockfall parameters for stack configuration 2, 8 m bench height, 60^o bench face angle, 110 kg falling rock mass, rock type One (File name on CD-R: buana173).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	22.5	23.4	24.3	25.2
Distance of barrier from toe of bottom bench (m)	4.7	5.6	6.5	7.4
Maximum bounce height (m)	2.63	2.63	2.63	2.63
Recommended height of barrier (m)	2.7	2.7	2.7	2.7
Number of rocks	8	333	444	39
Maximum total kinetic energy (kJ)	3.063	1.833	1.833	3.063

Table C26. Rockfall parameters for stack configuration 2, 8 m bench height, 70^o bench face angle, 110 kg falling rock mass, rock type One (File name on CD-R: buana175).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	5.3
Maximum bounce height (m)	3.88	4,25	4.25	4.25
Recommended height of barrier (m)	3.9	4.3	4.3	4.3
Number of rocks	89	122	117	272
Maximum total kinetic energy (kJ)	6.100	6.100	5.100	5.100

Table C27. Rockfall parameters for stack configuration 2, 8 m bench height, 80^o bench face angle, 110 kg falling rock mass, rock type One (File name on CD-R: buana177).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	7.1	8	8.9	9.8
Maximum bounce height (m)	2.3	2.75	2.3	2.3
Recommended height of barrier (m)	2.3	2.8	2.3	2.3
Number of rocks	185	13	200	100
Maximum total kinetic energy (kJ)	4.225	3.625	3.625	3.625

Table C28. Rockfall parameters for stack configuration 2, 8 m bench height, 90^o bench face angle, 110 kg falling rock mass, rock type One (File name on CD-R: buana179).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier (m)	7.2	8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	4	4.8
Maximum bounce height (m)	2.9	2.3	1.17
Recommended height of barrier (m)	2.9	2.3	1.2
Number of rocks	46	6	7
Maximum total kinetic energy (kJ)	3.875	3.875	1.000

The satisfactory location of barrier for bench face angle:
- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle).
- 80^o, is location 1 (same reason as for 60^o bench face angle).
- 90^o, is location 1 (same reason as for 60^o bench face angle).

Table C29. Rockfall parameters for stack configuration 2, 8 m bench height, 60^{o} bench face angle, 110 kg falling rock mass, rock type Two (File name on CD-R: buana181).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	18.4	19.2	20	20.8
Distance of barrier from toe of bottom bench (m)	0.6	1.4	2.2	3
Maximum bounce height (m)	2.04	3.44	3.8	3.5
Recommended height of barrier	2.1	3.5	3.8	3.5
Number of rocks	6	6	6	8
Maximum total kinetic energy (kJ)	3.300	2.188	2.188	2.750

Table C30. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, 110 kg falling rock mass, rock type Two (File name on CD-R: buana183).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	14.4	15.3	16.2	17.1
Distance of barrier from toe of bottom bench (m)	1.7	2.6	3.5	4.4
Maximum bounce height (m)	4.73	4.3	4.3	4.3
Recommended height of barrier (m)	4.8	4.3	4.3	4.3
Number of rocks	8	11	6	6
Maximum total kinetic energy (kJ)	10.525	5.000	4.350	4.350

Table C31. Rockfall parameters for stack configuration 2, 8 m bench height, 80^o bench face angle, 110 kg falling rock mass, rock type Two (File name on CD-R: buana185).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	11.7	12.6	13.5	14.4
Distance of barrier from toe of bottom bench (m)	3.5	4.4	5.3	6.2
Maximum bounce height (m)	4.7	4.25	4.25	2.83
Recommended height of barrier (m)	4.7	4.3	4.3	2.9
Number of rocks	6	22	6	6
Maximum total kinetic energy (kJ)	3.525	4.750	4.750	4.750

Table C32. Rockfall parameters for stack configuration 2, 8 m bench height, 90^o bench face angle, 110 kg falling rock mass, rock type Two (File name on CD-R: buana187).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	4	4.8
Maximum bounce height (m)	5.17	3	1.5
Recommended height of barrier (m)	5	3	1.5
Number of rocks	9	5	5
Maximum total kinetic energy (kJ)	6.050	2.600	0.875

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle).
- 80^o, is location 1 (same reason as for 60^o bench face angle).
- 90^o, considering the data in Table C.32 and the fact that the maximum run-out distance is less than 9.3 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C33. Rockfall parameters for stack configuration 2, 8 m bench height, 60^{o} bench face angle, 110 kg falling rock mass, rock type Three (File name on CD-R: buana189).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	18.9	19.8	20.7	21.6
Distance of barrier from toe of bottom bench (m)	18.9	19.8	20.7	21.6
Maximum bounce height (m)	4.65	6.14	5.52	2.76
Recommended height of barrier	4.7	5	5	2.8
Number of rocks	6	6	11	8
Maximum total kinetic energy (kJ)	3.250	2.167	2.167	4.333

Table C34. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, 110 kg falling rock mass, rock type Three (File name on CD-R: buana191).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier
x-coordinate of barrier location (m)	14.4	15.3	16.2	17.1	18	18.9
Distance of barrier from toe of bottom bench (m)	1.7	2.6	3.5	4.4	5.3	6.2
Maximum bounce height (m)	7.85	6.3	5.9	5.5	4.7	3.5
Recommended height of barrier (m)	5	5	5	5	4.7	3.5
Number of rocks	21	11	143	79	36	21
Maximum total kinetic energy (kJ)	11.063	5.917	4.417	6.625	6.625	5.167

Table C35. Rockfall parameters for stack configuration 2, 8 m bench height, 80^o bench face angle, 110 kg falling rock mass, rock type Three (File name on CD-R: buana192).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	10.8	11.7	12.6	13.5	14.4
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	5.3	6.2
Maximum bounce height (m)	7.44	7.44	6.83	5.7	4
Recommended height of barrier (m)	5	5	5	5	4
Number of rocks	7	58	100	8	81
Maximum total kinetic energy (kJ)	12.550	7.000	6.275	7.667	7.000

Table C36. Rockfall parameter for stack configuration 2, 8 m bench height, 90^o bench face angle, 110 kg falling rock mass, rock type Three (File name on CD-R: buana195).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	6.4	7.2	8	8.8	9.6
Distance of barrier from toe of bottom bench (m)	2.4	3.2	4	4.8	5.6
Maximum bounce height (m)	10.2	10.2	8.5	6	3.38
Recommended height of barrier (m)	5	5	5	5	3.4
Number of rocks	25	33	6	8	8
Maximum total kinetic energy (kJ)	17.500	8.700	10.417	5.250	3.500

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1. As only 6 rocks reach the maximum bounce height while others have a height less than 2.17 m, a barrier with 2.2 m height will be installed considering a low risk in rockfall hazard point of view.
- 70^o, is location 5 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.

- 80°, is location 5 (same reason as for 70° bench face angle)
- 90°, considering the data in Table C.36 and the fact that the maximum run-out distance is less than 9.3 m, the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C37. Rockfall parameters for stack configuration 2, 8 m bench height, 60° bench face angle, 150 kg falling rock mass, rock type One (File name on CD-R: buana174).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of falling rocks on the catch bench	22.5	23.4	24.3	25.2
Run-out distance (m)	4.7	5.6	6.5	7.4
Maximum bounce height (m)	2.67	2.67	2.67	2.67
Number of rocks	22	333	400	33
Total kinetic energy (J)	10066.7	3416.7	10066.7	14691.7

Table C38. Rockfall parameters for stack configuration 2, 8 m bench height, 70° bench face angle, 150 kg falling rock mass, rock type One (File name on CD-R: buana176).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	5.3
Maximum bounce height (m)	3.88	4.25	4.25	4.25
Recommended height of barrier (m)	3.9	4.3	4.3	4.3
Number of rocks	94	106	89	428
Maximum total kinetic energy (kJ)	8.333	8.333	6.900	6.900

Table C39. Rockfall parameters for stack configuration 2, 8 m bench height, 80^o bench face angle, 150 kg falling rock mass, rock type One (File name on CD-R: buana178).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	7.1	8	8.9	9.8
Maximum bounce height (m)	4.3	4.3	4.3	3.08
Recommended height of barrier (m)	4.3	4.3	4.3	3.1
Number of rocks	3	3	3	3
Maximum total kinetic energy (kJ)	5.900	4.667	4.667	5.900

Table C40. Rockfall parameters for stack configuration 2, 8 m bench height, 90^o bench face angle, 150 kg falling rock mass, rock type One (File name on CD-R: buana180).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	4	4.8
Maximum bounce height (m)	2.9	2.3	1.17
Recommended height of barrier(m)	2.9	2.3	1.2
Number of rocks	58	4	4
Maximum total kinetic energy (kJ)	5.250	5.250	1.333

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 1 (same reason as for 60^o bench face angle).
- 80^o, is location 1. As only 3 rocks reach the maximum bounce height (4.3 m) while others have a height less than 2.45 m, accepting a low risk in rockfall point of view, a barrier with 2.5 m height will be installed.
- 90^o, is location 1 (same reason as for 60^o bench face angle).

Table C41. Rockfall parameter for stack configuration 2, 8 m bench height, 60^{o} bench face angle, 150 kg falling rock mass, rock type Two (File name on CD-R: buana182).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of Barrier
x-coordinate of barrier location (m)	18.4	19.2	20	20.8
Distance of barrier from toe of bottom bench (m)	0.6	1.4	2.2	3
Maximum bounce height (m)	1.08	2.4	3.25	3.25
Recommended height of barrier (m)	2	2.4	3.3	3.3
Number of rocks	11	6	6	6
Maximum total kinetic energy (kJ)	6.250	3.100	2.333	3.100

Table C42. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, 150 kg falling rock mass, rock type Two (File name on CD-R: buana184).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	14.4	15.3	16.2	17.1
Distance of barrier from toe of bottom bench (m)	1.7	2.6	3.5	4.4
Maximum bounce height (m)	5.03	4.65	4.31	4.31
Recommended height of barrier	5	4.7	4.4	4.4
Number of rocks	6	8	6	6
Maximum total kinetic energy (kJ)	15.375	6.833	6.000	6.833

Table C43. Rockfall parameters for stack configuration 2, 8 m bench height, 80° bench face angle, 150 kg falling rock mass, rock type Two (File name on CD-R: buana186).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	10.8	11.7	12.6	13.5	14.4
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	5.3	6.2
Maximum bounce height (m)	4.67	4.67	4.67	3.63	2.6
Recommended height of barrier (m)	4.7	4.7	4.7	3.7	2.6
Number of rocks	4	6	4	6	6
Maximum total kinetic energy (kJ)	15.375	6.000	6.000	6.833	6.000

Table C44. Rockfall parameters for stack configuration 2, 8 m bench height, 90° bench face angle, 150 kg falling rock mass , rock type Two (File name on CD-R: buana188).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	4	4.8
Maximum bounce height (m)	6.05	2.25	0.75
Recommended height of barrier (m)	5	2.3	2
Number of rocks	4	8	13
Maximum total kinetic energy (kJ)	7.125	3.550	1.200

The satisfactory location of barrier for bench face angle:

- 60°, is location 2 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70°, is location 2 (same reason as for 60° bench face angle).
- 80°, is location 1 (same reason as for 60° bench face angle).
- 90°, considering the data in Table C.44 and the fact that the maximum run-out distance is less than 9.3 m, the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C45. Rockfall parameter for stack configuration 2, 8 m bench height, 60^{o} bench face angle, 150 kg falling rock mass, rock type Three (File name on CD-R: buana190).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	18.9	19.8	20.7	21.6
Distance of barrier from toe of bottom bench (m)	1.1	2	2.9	3.8
Maximum bounce height (m)	2.38	3.25	3.25	2.67
Recommended height of barrier (m)	2.4	3.3	3.3	2.7
Number of rocks	6	6	19	19
Maximum total kinetic energy (kJ)	4.000	2.667	2.667	3.313

Table C46. Rockfall parameters for stack configuration 2, 8 m bench height, 70^{o} bench face angle, 150 kg falling rock mass, rock type Three (File name on CD-R: buana192).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	14.4	15.3	16.2	17.1	18
Distance of barrier from toe of bottom bench (m)	1.7	2.6	3.5	4.4	5.3
Maximum bounce height (m)	7.89	6.3	5.9	5.5	4.73
Recommended height of barrier (m)	5	5	5	5	4.8
Number of rocks	15	4	115	62	23
Maximum total kinetic energy (kJ)	14.950	9.000	6.000	9.000	9.000

Table C47. Rockfall parameters for stack configuration 2, 8 m bench height, 80^o bench face angle, 150 kg falling rock mass, rock type Three (File name on CD-R: buana194).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	10.8	11.7	12.6	13.5	14.4
Distance of barrier from toe of bottom bench (m)	2.6	3.5	4.4	5.3	6.2
Maximum bounce height (m)	7.25	72.5	6.69	5.6	4.48
Recommended height of barrier (m)	5	5	5	5	4.9
Number of rocks	8	46	154	69	8
Maximum total kinetic energy (kJ)	17.225	4.800	9.550	10.550	10.550

Table C48. Rockfall parameters for stack configuration 2, 8 m bench height, 90^o bench face angle, 150 kg falling rock mass, rock type Three (File name on CD-R: buana196).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8	9.6
Distance of barrier from toe of bottom bench (m)	3.2	4	4.8	5.6
Maximum bounce height (m)	10.19	10.19	6	6
Recommended height of barrier (m)	5	5	5	5
Number of rocks	38	4	8	4
Maximum total kinetic energy (kJ)	12.600	14.900	10.000	7.500

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 5 (same reason as for 60^o bench face angle).
- 80^o, is location 5 (same reason as for 60^o bench face angle).
- 90^o, considering the data in Table C.48 and the fact that the maximum run-out distance is less than 9.3 m Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C49. Rockfall parameters for stack configuration 2, 10 m bench height, 60^o bench face angle, rock type One (File name on CD-R: buana13).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	26	27	28	29
Distance of barrier from toe of bottom bench (m)	4.6	5.6	6.6	7.6
Maximum bounce height (m)	3.2	3.75	3.75	3.75
Recommended height of barrier (m)	3.2	3.8	3.8	3.8
Number of rocks	67	28	67	56
Maximum total kinetic energy (kJ)	0.675	0.675	0.675	0.675

Table C50. Rockfall parameters for stack configuration 2, 10 m bench height, 70^o bench face angle, rock type One (File name on CD-R: buana14).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of barrier (m)	19	20	21	22	23	24	25
Distance of barrier from toe of bottom bench (m)	4.2	5.2	6.2	7.2	8.2	9.2	10.2
Maximum bounce height (m)	5.69	5.69	5.69	5.69	5.69	5.69	5
Recommended height of barrier (m)	5	5	5	5	5	5	5
Number of rocks	8	22	6	111	72	8	11
Maximum total kinetic energy (kJ)	0.690	0.460	0.350	0.460	0.690	0.690	0.575

Table C51. Rockfall parameters for stack configuration 2, 10 m bench height, 80^{o} bench face angle, rock type One (File name on CD-R: buana15).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of barrier location (m)	17.6	18.4	19.2	20	20.8	21.6	22.4
Distance of barrier from toe of bottom bench (m)	8.2	9	9.8	10.6	11.4	12.2	13
Maximum bounce height (m)	5.25	5.25	5.25	5.25	5.25	5.25	5.25
Recommended height of barrier (m)	5	5	5	5	5	5	5
Number of rocks	8	22	33	33	33	22	6
Maximum total kinetic energy (kJ)	1.367	0.719	0.455	0.455	0.455	0.573	0.573

Table C52. Rockfall parameters for stack configuration 2, 10 m bench height, 90^{o} bench face angle, rock type One (File name on CD-R: buana16).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location	8	8.8	9.6	10.4
Distance of barrier from toe of bottom bench (m)	4	4.8	5.6	6.4
Maximum bounce height (m)	3.69	2.19	1.5	0.75
Recommended height of barrier (m)	3.7	2.2	2	2
Number of rocks	32	7	7	16
Maximum total kinetic energy (kJ)	0.440	0.330	0.110	0.110

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 7 (same reason as for bench face angle 60^o).
- 80^o, is location 7. As only 6 rocks reach the maximum bounce height (5.25 m) while others have a height less than 4.33 m, so accepting a low risk in rockfall hazard point of view, a barrier with 4.4 m height will be installed.
- 90^o, considering the data in Table C.52 and the fact that the maximum run-out distance is less than 10.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C53. Rockfall parameters for stack configuration 2, 10 m bench height, 60^o bench face angle, rock type Two (File name on CD-R: buana17).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	24	25	26	27
Distance of barrier from toe of bottom bench (m)	2.6	3.6	4.6	5.6
Maximum bounce height (m)	5.34	5.34	5.34	4.63
Recommended height of barrier (m)	5	5	5	4.7
Number of rocks	6	6	6	6
Maximum total kinetic energy (kJ)	0.400	0.263	0.463	0.530

Table C54. Rockfall parameters for stack configuration 2, 10 m bench height, 70^o bench face angle, rock type Two (File name on CD-R: buana18).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	17	18	19	20	21
Distance of barrier from toe of bottom bench (m)	2.2	3.2	4.2	5.2	6.2
Maximum bounce height (m)	5.83	5.83	5.31	4.8	4.5
Recommended height of barrier (m)	5	5	5	4.8	4.5
Number of rocks	11	6	6	8	6
Maximum total kinetic energy (kJ)	1.263	0.590	0.520	0.450	0.520

Table C55. Rockfall parameters for stack configuration 2, 10 m bench height, 80^o bench face angle, rock type Two (File name on CD-R: buana19).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	12.8	13.6	14.4	15.2	16
Distance of barrier from toe of bottom bench (m)	3.4	4.2	5	5.8	6.6
Maximum bounce height (m)	7.38	8.13	8.13	7.4	5.9
Recommended height of barrier (m)	5	5	5	5	5
Number of rocks	8	5	5	5	5
Maximum total kinetic energy (kJ)	1.380	0.530	0.638	0.530	0.530

Table C56. Rockfall parameters for stack configuration 2, 10 m bench height, 90^o bench face angle, rock type Two (File name on CD-R: buana20).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8
Distance of barrier from toe of bottom bench (m)	3.2	4	5.6
Maximum bounce height (m)	8	8	4
Recommended height of barrier (m)	5	5	4
Number of rocks	10	5	5
Maximum total kinetic energy (kJ)	0.690	0.690	0.590

The satisfactory location of barrier for bench face angle:

- 60^o, is location 4. As only 6 rocks reach the maximum bounce height (4.63 m) while others have a height less than 3.78 m, so accepting a low risk in rockfall hazard point of view, a barrier with 3.8 m height will be installed.
- 70^o, is location 4 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 80^o, is location 5. As only 5 rocks reach the maximum bounce height (5.9 m) while others have a height less than 4.42 m, so accepting a low risk in rockfall hazard point of view, a barrier with 4.5 m height will be installed considering that the first category of Table 4.1 is satisfied.

• 90^{o}, considering the data in Table C.56 and the fact that the maximum run-out distance is less than 10.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C57. Rockfall parameters for stack configuration 2, 10 m bench height, 60^{o} bench face angle, rock type Three (File name on CD-R: buana21).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	23	24	25	26	27
Distance of barrier from toe of bottom bench (m)	1.6	2.6	3.6	4.6	5.6
Maximum bounce height (m)	5.09	7.44	7.9	7.44	2.75
Recommended height of barrier (m)	5	5	5	5	5
Number of rocks	6	6	8	6	6
Maximum total kinetic energy (kJ)	0.550	0.206	0.275	0.350	0.623

Table C58. Rockfall parameters for stack configuration 2, 10 m bench height, 70^{o} bench face angle, rock type Three (File name on CD-R: buana22).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier
x-coordinate of barrier location (m)	17	18	19	20	21	22
Distance of barrier from toe of bottom bench (m)	2.2	3.2	4.2	5.2	6.2	7.2
Maximum bounce height (m)	9.7	8.1	7.6	7	5.9	4.3
Recommended height of barrier (m)	5	5	5	5	5	4.3
Number of rocks	6	11	33	33	33	33
Maximum total kinetic energy (kJ)	1.235	0.920	0.617	0.617	0.770	0.692

Table C59. Rockfall parameters for stack configuration 2, 10 m bench height, 80^{o} bench face angle, rock type Three (File name on CD-R: buana23).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier	Location 8 of barrier
x-coordinate of barrier location (m)	12.8	13.6	14.4	15.2	16	16.8	17.6	18.4
Distance of barrier from toe of bottom bench (m)	3.4	4.2	5	5.8	6.6	7.4	8.2	9
Maximum bounce height (m)	8.88	9.69	8.88	8.88	7.3	5.65	5.65	4.88
Recommended height of barrier (m)	5	5	5	5	5	5	5	4.9
Number of rocks	4	42	117	92	150	79	21	117
Maximum total kinetic energy (kJ)	1.486	0.500	0.500	0.910	0.910	0.910	0.828	0.500

Table C60. Rockfall parameters for stack configuration 2, 10 m bench height, 90^{o} bench face angle, rock type Three (File name on CD-R: buana24).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier
x-coordinate of barrier location (m)	7.2	8	8.8	9.6	10.4	11.2
Distance of barrier from toe of bottom bench (m)	3.2	4	4.8	5.6	6.4	7.2
Maximum bounce height (m)	12.75	12.75	11.69	7.45	6.38	3.2
Recommended height of barrier (m)	5	5	5	5	5	3.2
Number of rocks	64	21	4	7	5	4
Maximum total kinetic energy (kJ)	1.983	1.275	1.275	1.000	0.710	0.283

The satisfactory location of barrier for bench face angle:

- 60^o, is location 1.As only 6 rocks reach the maximum bounce height (5.09 m) while others have a height less than 3.13 m, so accepting a low risk in rockfall hazard point of view, a barrier with 3.2 m height will be installed considering that the first category of table 4.1 is satisfied.
- 70^o, is location 6 as its maximum bounce height and maximum total kinetic energy satisfied the first category of Table 4.1.
- 80^o, is location 8 (same reason as for 70^o bench face angle).
- 90^o, considering the data in Table 4.60 and the fact that the maximum run-out distance is less than 10.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C61. Rockfall parameters for stack configuration 2, 12 m bench height, 60^o bench face angle, rock type One (File name on CD-R: buana25).

	Location of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	26.4	27.6	28.8	30
Distance of barrier from toe of bottom bench (m)	1.7	2.9	4.1	5.3
Maximum bounce height (m)	1.88	2.6	3.33	3.7
Recommended height of barrier (m)	2	2.6	3.4	3.7
Number of rocks	11	61	33	105
Maximum total kinetic energy (kJ)	0.920	0.920	0.810	0.810

Table C62. Rockfall parameters for stack configuration 2, 12 m bench height, 70^{o} bench face angle, rock type One (File name on CD-R: buana26).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of barrier location (m)	24	25.2	26.4	27.6	28.8	30	31.2
Distance of barrier from toe of bottom bench (m)	6.8	8	9.2	10.4	11.6	12.8	14
Maximum bounce height (m)	6.55	6.55	6.55	6.55	5.81	5.08	2.85
Recommended height of barrier (m)	5	5	5	5	5	5	2.9
Number of rocks	161	39	72	28	17	6	11
Maximum total kinetic energy (kJ)	0.413	0.550	0.683	0.825	0.550	0.850	0.850

Table C63. Rockfall parameters for stack configuration 2, 12 m bench height, 80^o bench face angle, rock type One (File name on CD-R: buana27).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of barrier location (m)	20.4	21.6	22.1	24	25.2	26.4	27.6
Distance of barrier from toe of bottom bench (m)	10.1	11.3	12.5	13.7	14.9	16.1	17.3
Maximum bounce height (m)	6.5	6.5	6.5	6.5	6.5	5.45	4.3
Recommended height of barrier (m)	5	5	5	5	5	5	4.3
Number of rocks	7	36	82	73	41	36	27
Maximum total kinetic energy (kJ)	1.633	0.550	0.550	0.550	0.817	0.680	0.817

Table C64. Rockfall parameters for stack configuration 2, 12 m bench height, 90^o bench face angle, rock type One (File name on CD-R: buana28).

	Location 1 of barrier	Location 2 of barrier
x-coordinate of barrier location (m)	8.4	9.6
Distance of barrier from toe of bottom bench (m)	4.4	5.6
Maximum bounce height (m)	4.44	2.67
Recommended height of barrier (m)	4.5	2.7
Number of rocks	113	6
Maximum total kinetic energy (kJ)	0.844	0.500

The satisfactory location for bench face angle:

- 60^o, is location 2 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, no position is suitable because any location of barrier does not satisfy both the 11.7 m (Modified Ritchie criterion) and Table 4.1.
- 80^o, the same as for 60^o bench face angle.
- 90^o, considering the data in the Table C.64 and the fact that the maximum run-out

distance is less than 11.7 m (Modified Ritchie Criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C65. Rockfall parameters for stack configuration 2, 12 m bench height, 60^{o} bench face angle, rock type Two (File name on CD-R: buana29).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier
x-coordinate of barrier location (m)	28.8	30	31.2	32.6	33.6	34.8
Distance of barrier from toe of bottom bench (m)	4.1	5.3	6.5	7.7	8.9	10.1
Maximum bounce height (m)	6.9	6.9	6.9	6.38	5.8	2.67
Recommended height of barrier (m)	5	5	5	5	5	2.7
Number of rocks	6	6	6	8	6	17
Maximum total kinetic energy (kJ)	0.633	0.475	0.633	0.633	0.633	0.633

Table C66. Rockfall parameters for stack configuration 2, 12 m bench height, 70^{o} bench face angle, rock type Two (File name on CD-R: buana30).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	20.4	21.6	22.8	24	25.2
Distance of barrier from toe of bottom bench (m)	3.2	4.4	5.6	6.8	8
Maximum bounce height (m)	6.2	6.2	6.2	6.2	4.17
Recommended height of barrier (m)	5	5	5	5	4.2
Number of rocks	8	8	6	6	6
Maximum total kinetic energy (kJ)	0.590	0.590	0.590	0.510	0.510

Table C67. Rockfall parameters for stack configuration 2, 12 m bench height, 80^o bench face angle, rock type Two (File name on CD-R: buana31).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier
x-coordinate of barrier location (m)	14.4	15.6	16.8	18	19.2	20.4
Distance of barrier from toe of bottom bench (m)	4.1	5.3	6.5	7.7	8.9	10.1
Maximum bounce height (m)	12.3	9.88	6.8	6.1	5.3	2.3
Recommended height of barrier (m)	5	5	5	5	5	2.3
Number of rocks	3	6	6	6	3	22
Maximum total kinetic energy (kJ)	1.650	0.883	1.050	1.050	0.633	0.633

Table C68. Rockfall parameters for stack configuration 2, 12 m bench height, 90^o bench face angle, rock type two (File name on CD-R: buana32).

	Location 1 of barrier	Location 2 of barrier	Location 3of barrier
x-coordinate of barrier location (m)	8.4	9.6	10.8
Distance of barrier from toe of bottom bench (m)	4.4	5.6	6.8
Maximum bounce height (m)	9.19	4.63	1.17
Recommended height of barrier (m)	5	4.7	2
Number of rocks	7	7	21
Maximum total kinetic energy (kJ)	1.184	0.333	0.167

The satisfactory location of barrier for bench face angle:

- 60^o, is location 5. As only 6 rocks reach the maximum bounce height (5.8 m) and others have a bounce height less than 4.8 m, so accepting a low risk in rockfall hazard point of view, a barrier with this latter height may be installed.
- 70^o, is location 5 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 80^o, is location 6 (same reason as for bench face angle 80^o).
- 90^o, considering the data in the Table C.68 and the fact that the maximum run-out distance is less than 11.7 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C69. Rockfall parameters for stack configuration 2, 12 m bench height, 60^{o} bench face angle, rock type Three (File name on CD-R: buana33).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of falling rocks on the catch bench	30	31.2	32.4	33.6	34.8	36	37.2
Run-out distance (m)	5.3	6.5	7.7	8.9	10.1	11.3	12.5
Maximum bounce height (m)	9.58	9	8.5	5.3	5.3	5.3	4.75
Number of rocks	28	17	6	33	28	11	6
Total kinetic energy (J)	667.5	3391.7	6028.4	4431.7	2385	2045	1505

Table C70. Rockfall parameters for stack configuration 2, 12 m bench height, 70^{o} bench face angle, rock type Three (File name on CD-R: buana34).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of falling rocks on the catch bench	21.6	22.8	24	25.2	26.4	27.6	28.8
Run-out distance (m)	4.4	5.6	6.8	8	9.2	10.4	11.6
Maximum bounce height (m)	9.06	9.06	7.75	5.19	5.19	5.19	4.56
Number of rocks	78	100	33	50	56	28	17
Total kinetic energy (J)	1680	4680	4680	4680	2385	1160	1355

Table C71. Rockfall parameters for stack configuration 2, 12 m bench height, 80^o bench face angle, rock type Three (File name on CD-R: buana35).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of falling rocks on the catch bench	15.6	16.8	18	19.2	20.4	21.6	22.8
Run-out distance (m)	5.3	6.5	7.7	8.9	10.1	11.3	12.5
Maximum bounce height (m)	11.63	10.63	9.69	6.7	5.83	5.83	3.88
Number of rocks	33	167	120	87	180	77	83
Total kinetic energy (J)	2279.6	1673.3	6687	5617	3340.8	1673.3	1673.3

Table C72. Rockfall parameters for stack configuration 2, 12 m bench height, 90^o bench face angle, rock type Three (File name on CD-R: buana36).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of falling rocks on the catch bench	7.2	8.4	9.6	10.8	12
Run-out distance (m)	3.2	4.4	5.6	6.8	8
Maximum bounce height (m)	20.38	15.3	11.5	10.2	7.7
Number of rocks	14	26	7	4	4
Total kinetic energy (J)	18864	6831	6831	3055.5	345.5

The satisfactory location of barrier for bench face angle:

- 60^o, no position is suitable because any location of barrier does not satisfy both the 11.7 m (Modified Ritchie criterion) and Table 4.1.
- 70^o, is location 7 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 80^o, the same as for 60^o bench face angle.
- 90^o, considering the data in Table C.72 and the fact that the maximum run-out distance

is less than 11.7 m, the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C73. Rockfall parameters for stack configuration 2, 15 m bench height, 60^o bench face angle, rock type One (File name on CD-R: buana37).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	33	34.5	36	37.5
Distance of barrier from toe of bottom bench (m)	3	4.5	6	7.5
Maximum bounce height (m)	2.45	2.95	3.9	4.4
Recommended height of barrier (m)	2.5	3	3.9	4.4
Number of rocks	8	489	111	144
Maximum total kinetic energy (kJ)	1.110	0.970	0.970	0.970

Table C74. Rockfall parameters for stack configuration 2, 15 m bench height, 70^o bench face angle, rock type One (File name on CD-R: buana38).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier
x-coordinate of barrier location (m)	25.5	27	28.5	30	31.5	33
Distance of barrier from toe of bottom bench	5.1	6.6	8.1	9.6	11.1	12.6
Maximum bounce height (m)	8.13	8.13	8.13	8.13	7.25	4.5
Recommended height of barrier (m)	5	5	5	5	5	4.5
Number of rocks	11	356	322	8	8	8
Maximum total kinetic energy (kJ)	0.500	0.333	0.666	0.833	0.833	1.000

Table C75. Rockfall parameters for stack configuration 2, 15 m bench height, 80^{o} bench face angle, rock type One (File name on CD-R: buana39).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of barrier location (m)	25.5	27	28.5	30	31.5	33	34.5
Distance of barrier from toe of bottom bench (m)	13.7	15.2	16.7	18.2	19.7	21.2	22.7
Maximum bounce height (m)	8.7	8.7	8.7	8.7	7.25	5.8	4.3
Recommended height of barrier	5	5	5	5	5	5	4.3
Number of rocks	42	100	179	104	108	67	25
Maximum total kinetic energy (kJ)	0.680	0.680	0.846	0.846	0.846	0.846	1.026

Table C76. Rockfal parameter for stack configuration 2, 15 m bench height, 90^{o} bench face angle, rock type One (File name on CD-R: buana40).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	8	9	10	11
Distance of barrier from toe of bottom bench (m)	4	5	6	7
Maximum bounce height (m)	11.1	4.4	3.33	1.01
Recommended height of barrier (m)	5	4.4	3.4	2
Number of rocks	6	28	6	38
Maximum total kinetic energy (kJ)	1.117	0.667	0.3687	0.225

The satisfactory location of barrier for bench face angle:
• 60^{o}, is location 1 as its maximum bounce height and maximum total kinetic energy

satisfy the first category of Table 4.1.

- 70^o, is location 6 (same reason as for 60^o bench face angle).
- 80^o, no position is suitable because any location of barrier does not satisfy both the 13.5 m (Modified Ritchie criterion) and Table 4.1.
- 90^o, considering the data in Table C.76 and the fact that the maximum run-out distance is less than 13.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C77. Rockfall parameters for stack configuration 2, 15 m bench height, 60^o bench face angle, rock type Two (File name on CD-R: buana41).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier
x-coordinate of barrier location (m)	36	37.5	39	40.5	42	43.5
Distance of barrier from toe of bottom bench (m)	6	7.5	9	10.5	12	13.5
Maximum bounce height (m)	8.56	8.56	7.88	7.5	5.9	3.9
Recommended height of barrier	5	5	5	5	5	3.9
Number of rocks	6	6	8	11	8	6
Maximum total kinetic energy (kJ)	0.590	0.590	0.783	0.783	0.783	0.883

Table C78. Rockfall parameters for stack configuration 2, 15 m bench height, 70^o bench face angle, rock type Two (File name on CD-R: buana42).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier
x-coordinate of barrier location (m)	24	25.5	27	28.5	30	31.5
Distance of barrier from toe of bottom bench (m)	3.6	5.1	6.6	8.1	9.6	11.1
Maximum bounce height (m)	7.9	7.9	7.9	6.6	5.9	3.3
Recommended height of barrier (m)	5	5	5	5	5	3.3
Number of rocks	6	6	8	8	6	6
Maximum total kinetic energy (kJ)	1.867	0.750	0.650	0.650	0.842	0.470

Table C79. Rockfall parameters for stack configuration 2, 15 m bench height, 80^o bench face angle, rock type Two (File name on CD-R: buana43).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	16.5	18	19.5	21	22.5
Distance of barrier from toe of bottom bench (m)	4.7	6.2	7.7	9.2	10.7
Maximum bounce height (m)	14.25	13.3	12.3	9.5	5.7
Recommended height of barrier (m)	5	5	5	5	5
Number of rocks	7	7	5	4	4
Maximum total kinetic energy (kJ)	1.513	1.340	1.340	1.340	1.340

Table C80. Rockfall parameters fore stack configuration 2, 15 m bench height, 90^o bench face angle, rock type Two (File name on CD-R: buana44).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	10	11	12
Distance of barrier from toe of bottom bench (m)	6	7	8
Maximum bounce height (m)	7.5	3	1.5
Recommended height of barrier (m)	5	3	2
Number of rocks	6	6	4
Maximum total kinetic energy (kJ)	0.883	0.883	0.217

The satisfactory location of barrier for bench face angle:

- 60^o, is location 6 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 5. As only 6 rocks reach the maximum bounce height (5.9 m) while others have a height less than 3.95 m, so accepting a low risk in rockfall hazard point of view, a barrier with 4 m height will be installed.
- 80^o, is location 5. As only 4 rocks reach the maximum bounce height (5.7 m) while others have a height less than 4.75 m, so accepting a low risk in rockfall hazard point of view, a barrier with 4.8 m height will be installed.
- 90^o, considering the data in Table C.80 and the fact that the maximum run-out distance

is less than 13.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table C81. Rockfall parameters for stack configuration 2, 15 m bench height, 60^{o} bench face angle, rock type Three (File name on CD-R: buana45).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of barrier location (m)	39	40.5	42	43.5	45	46.5	48
Distance of barrier from toe of bottom bench (m)	9	10.5	12	13.5	15	16.5	18
Maximum bounce height	11.08	10.38	8.3	6.9	6.5	6.5	5.55
Recommended height of barrier	5	5	5	5	5	5	5
Number of rocks	156	33	8	50	122	44	6
Maximum total kinetic energy (kJ)	1.170	1.170	1.170	1.170	0.638	0.638	0.638

Table C82. Rockfall parameters for stack configuration 2, 15 m bench height, 70^{o} bench face angle, rock type Three (File name on CD-R: buana46).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of barrier location (m)	27	28.5	30	31.5	33	34.5	36
Distance of barrier from toe of bottom bench (m)	6.6	8.1	9.6	11.1	12.6	14.1	15.6
Maximum bounce height (m)	10.8	10.8	7.75	6.17	7	5.4	3.88
Recommended height of barrier (m)	5	5	5	5	5	5	3.9
Number of rocks	33	11	33	8	6	22	22
Maximum total kinetic energy (kJ)	1.160	1.255	0.967	1.063	0.388	0.585	0.388

Table C83. Rockfall parameters for stack configuration 2, 15 m bench height, 80^{o} bench face angle, rock type Three (File name on CD-R: buana47).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4of barrier	Location 5 of barrier	Location 6 of barrier	Location 7 of barrier
x-coordinate of barrier location (m)	19.5	21	22.5	24	25.5	27	28.5
Distance of barrier from toe of bottom bench (m)	7.7	9.2	10.7	12.2	13.7	15.2	16.7
Maximum bounce height (m)	13.67	12.5	10.5	8	8	5.7	4.55
Recommended height of barrier (m)	5	5	5	5	5	5	4.6
Number of rocks	71	196	64	54	29	21	36
Maximum total kinetic energy (kJ)	1.000	0.833	1.333	1.333	0.833	0.833	0.500

Table C84. Rockfall parameters for stack configuration 2, 15 m bench height, 90^{o} bench face angle, rock type Three (File name on CD-R: buana48).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	11	12	13	14
Distance of barrier from toe of bottom bench (m)	7	8	9	10
Maximum bounce height (m)	14.38	9.6	4.8	1.6
Recommended height of barrier (m)	5	5	4.8	2
Number of rocks	7	5	7	7
Maximum total kinetic energy(kJ)	1.333	1.333	0.442	0.442

The satisfactory location of barrier for bench face angle:

- 60^o, no position is suitable because any location of barrier does not satisfy the 13.5 m (Modified Ritchie criterion) and Table 4.1.
- 70^o, same as for 60^o bench face angle.
- 80^o, same as for 60^o bench face angle.
- 90^o, considering the data in Table C.84 and the fact that the maximum run-out distance is less than 13.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

APPENDIX D

Tables containing typical rockfall parameters for stack configuration (3) and their specified file names in CD-R.

Table D1. Rockfall parameters for stack configuration 3, 8 m bench height, 60^o bench face angle, rock type One (File name on CD-R: buana49).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of falling rocks on the catch bench	27	28.5	30	31.5
Run-out distance (m)	2.6	4.1	5.6	7.1
Maximum bounce height (m)	1.8	2.23	2.67	2.67
Number of rocks	6	89	11	11
Maximum total kinetic energy (kJ)	0.733	0.733	0.733	0.733

Table D2. Rockfall parameters for stack configuration 3, 8 m bench height, 70^o bench face angle, rock type One (File name on CD-R: buana50).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	25.5	27	28.5	30
Distance of barrier from toe of bottom bench (m)	7.9	9.4	10.9	12.4
Maximum bounce height (m)	6.06	4.5	3	2.41
Recommended height of barrier (m)	5	4.5	3	2.5
Number of rocks	8	22	211	89
Maximum total kinetic energy (kJ)	0.940	1.175	1.290	0.820

Table D3. Rockfall parameters for stack configuration 3, 8 m bench height, 80^o bench face angle, rock type One (File name on CD-R: buana51).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	18	19.2	20.4	21.6
Distance of barrier from toe of bottom bench (m)	6.4	7.6	8.8	10
Maximum bounce height (m)	5.69	6.4	5.69	4.25
Recommended height of barrier (m)	5	5	5	4.3
Number of rocks	4	4	4	100
Maximum total kinetic energy (kJ)	1.100	0.488	0.488	0.488

Table D4. Rockfall parameters for stack configuration 3, 8 m bench height, 90^o bench face angle, rock type One (File name on CD-R: buana52).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate barrier location (m)	9	10	11
Distance of barrier from toe of bottom bench (m)	3	4	5
Maximum bounce height (m)	4.63	1.17	0.6
Recommended height of barrier (m)	4.7	2	2
Number of rocks	4	31	11
Maximum total kinetic energy (kJ)	0.460	0.183	0.090

The satisfactory location of barrier for bench face angle;

- 60^o, is location 2 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 2 (same reasons as for 60^o bench face angle).
- 80^o, is location 1. As only 4 rocks reach the maximum bounce height (5,69 m) while others have a height less than 4.25 m, so accepting a low risk in rockfall hazard point of view and considering the first category of Table 4.1, a barrier with 4.3 m height will be installed.
- 90^o, considering the data in Table D.4 and the fact that the maximum run-out distance is less than 10.9 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table D5. Rockfall parameters for stack configuration 3, 8 m bench height, 60^{o} bench face angle, rock type Two (File name on CD-R: buana53).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	27	28.5	30	31.5
Distance of barrier from toe of bottom bench (m)	2.6	4.1	5.6	7.1
Maximum bounce height (m)	4.5	4.5	3.4	1.69
Recommended height of barrier (m)	4.5	4.5	3.4	2
Number of rocks	6	6	6	6
Maximum total kinetic energy (kJ)	0.310	0.413	0.413	0.310

Table D6. Rockfall parameters for stack configuration 3, 8 m bench height, 70^{o} bench face angle, rock type Two (File name on CD-R: buana54).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	21	22.5	24	25.5
Distance of barrier from toe of bottom bench (m)	3.4	4.9	6.4	7.9
Maximum bounce height (m)	5.4	4.88	4.3	2.17
Recommended height of barrier (m)	5	4.9	4.3	2.2
Number of rocks	6	8	6	6
Maximum total kinetic energy (kJ)	1.000	0.408	0.467	0.350

Table D7. Rockfall parameters for stack configuration 3, 8 m bench height, 80° bench face angle, rock type Two (File name on CD-R: buana55).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	15.6	16.8	18	19.2
Distance of barrier from toe of bottom bench (m)	4	5.2	6.4	2.63
Maximum bounce height (m)	6.55	4.58	3.25	2.63
Recommended height of barrier (m)	5	4.6	3.3	2.7
Number of rocks	7	5	4	5
Maximum total kinetic energy (kJ)	0.630	0.900	0.270	0.270

Table D8. Rockfall parameters for stack configuration 3, 8 m bench height, 90° bench face angle, rock type Two (File name on CD-R: buana56).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	8	9	10
Distance of barrier from toe of bottom bench (m)	2	3	4
Maximum bounce height (m)	8.25	3.45	1.4
Recommended height of barrier (m)	5	3.5	2
Number of rocks	3	5	3
Maximum total kinetic energy (kJ)	0.500	0.300	0.100

The satisfactory location of barrier for bench face angle:

- 60°, is location 1 as its maximum bounce height and maximum kinetic energy satisfy the first category of Table 4.1.
- 70°, is location 2 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 80°, is location 2 (same reason as for 70° bench face angle).
- 90°, considering the data in Table D.8 and the fact that the maximum run-out distance is less than 10.9 m, the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table D9. Rockfall parameters for stack configuration 3, 8 m bench height, 60^{o} bench face angle, rock type Three (File name on CD-R: buana57).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	28.5	30	31.5	33
Distance of barrier from toe of bottom bench (m)	4.1	5.6	7.1	8.6
Maximum bounce height (m)	6.19	5.46	3.63	3.3
Recommended height of barrier (m)	5	5	3.7	3.3
Number of rocks	17	22	11	28
Maximum total kinetic energy (kJ)	0.505	0.617	0.617	0.392

Table D10. Rockfall parameters for stack configuration 3, 8 m bench height, 70^{o} bench face angle, rock type Three (File name on CD-R: buana58).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	22.5	24	25.5	27
Distance of barrier from toe of bottom bench (m)	4.9	6.4	7.9	9.4
Maximum bounce height (m)	7.55	5.67	5.67	2.5
Recommended height of barrier (m)	5	5	5	2.5
Number of rocks	61	133	33	11
Maximum total kinetic energy (kJ)	0.810	0.475	0.338	0.610

Table D11. Rockfall parameters for stack configuration 3, 8 m bench height, 80^o bench face angle, rock type Three (File name on CD-R: buana59).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	16.8	18	19.2	20.4
Distance of barrier from toe of bottom bench (m)	5.2	6.4	7.6	8.8
Maximum bounce height (m)	7.5	6.75	5.25	3.75
Recommended height of barrier (m)	5	5	5	3.8
Number of rocks	6	25	38	44
Maximum total kinetic energy (kJ)	1.133	0.663	0.663	0.380

Table D12. Rockfall parameters for stack configuration 3, 8 m bench height, 90^o bench face angle, rock type Three (File name on CD-R: buana60).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	10	11	12
Distance of barrier from toe of bottom bench (m)	4	5	6
Maximum bounce height (m)	7.8	5.2	0.75
Recommended height of barrier (m)	5	5	2
Number of rocks	4	4	4
Maximum total kinetic energy (kJ)	0.625	0.313	0.100

The satisfactory location of barrier for bench face angle:

- 60^o, is location 3 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 4 (same reason as for 60^o bench face angle).
- 80^o, is location 4 (same reason as for 60^o bench face angle).
- 90^o, considering the data in Table D.12 and the fact that the maximum run-out distance is less than 10.9 m, the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table D13. Rockfall parameters for stack configuration 3, 10 m bench height, 60^{o} bench face angle, rock type One (File name on CD-R: buana61).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	43.5	45	46.5	48
Distance of barrier from toe of bottom bench (m)	14.4	15.9	17.4	18.9
Maximum bounce height (m)	2.6	3.25	3.25	3.25
Recommended height of barrier	2.6	3.3	3.3	3.3
Number of rocks	44	78	189	367
Maximum total kinetic energy (kJ)	0.992	0.695	0.695	0.695

Table D14. Rockfall parameters for stack configuration 3, 10 m bench height, 70^{o} bench face angle, rock type One (File name on CD-R: buana62).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	27	28.5	30	31.5
Distance of barrier from toe of bottom bench (m)	6.6	8.1	9.6	11.1
Maximum bounce height (m)	7.6	7.6	5.3	4.5
Recommended height of barrier (m)	5	5	5	4.5
Number of rocks	78	6	33	156
Maximum total kinetic energy (kJ)	1.644	1.644	0.825	0.988

Table D15. Rockfall parameter for stack configuration 3, 10 m bench height, 80^o bench face angle, rock type One (File name on CD-R: buana63).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	25.5	27	28.5	30
Distance of barrier from toe of bottom bench (m)	12.4	13.9	15.4	16.3
Maximum bounce height (m)	7.6	5.7	4.75	2.83
Recommended height of barrier	5	5	4.8	2.9
Number of rocks	4	33	13	8
Maximum total kinetic energy (kJ)	0.988	0.811	0.988	0.652

Table D16. Rockfall parameters for stack configuration 3, 10 m bench height, 90^o bench face angle, rock type One (File name on CD-R: buana64).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	9	10	11
Distance of barrier from toe of bottom bench (m)	3	4	5
Maximum bounce height (m)	6.5	4.69	1.6
Recommended height of barrier (m)	5	4.7	2
Number of rocks	13	5	11
Maximum total kinetic energy (kJ)	0.610	0.610	0.610

The satisfactory location of barrier for bench face angle:

- 60^o, no position is suitable because any location of barrier does not satisfy both the 12.5 m (Modified Ritchie criterion) and Table 4.1.
- 70^o, is location 4 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 80^o, the same as for 60^o bench face angle.
- 90^o, considering the data in Table D.16 and the fact that the maximum run-out distance is less than 12.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table D17. rockfall parameters for stack configuration 3, 10 m bench height, 60^o bench face angle, rock type Two (File name on CD-R: buana229).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	33	34.5	36	37.5
Distance of barrier from toe of bottom bench (m)	3.9	5.4	6.9	8.4
Maximum bounce height (m)	5.6	5	5	3.75
Recommended height of barrier (m)	5	5	5	3.8
Number of rocks	12	18	6	6
Maximum total kinetic energy (kJ)	0.525	0.600	0.525	0.525

Table D18. Rockfall parameters for stack configuration 3, 10 m bench height, 70^o bench face angle, rock type Two (File name on CD-R: buana230).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	25.5	27	28.5	30
Distance of barrier from toe of bottom bench (m)	5.1	6.6	8.1	9.6
Maximum bounce height (m)	6.25	5	5	2.5
Recommended height of barrier (m)	5	5	5	2.5
Number of rocks	6	8	6	6
Maximum total kinetic energy (kJ)	0.575	0.575	0.480	0.383

Table D19. Rockfall parameters for stack configuration 3, 10 m bench height, 80^o bench face angle, rock type Two (File name on CD-R: buana231).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	18	19.5	21	22.5
Distance of barrier from toe of bottom bench (m)	4.9	6.4	7.9	9.4
Maximum bounce height (m)	9.1	7.25	3.6	3.6
Recommended height of barrier (m)	5	5	3.6	3.6
Number of rocks	4	4	11	4
Maximum total kinetic energy (kJ)	0.920	0.920	0.350	0.350

Table D20. Rockfall parameters for stack configuration 3, 10 m bench height, 90^o bench face angle, rock type Two (File name on CD-R: buana232).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	9	10	11
Distance of barrier from toe of bottom bench (m)	3	4	5
Maximum bounce height (m)	8.3	4.6	0.95
Recommended height of barrier (m)	5	4.6	2
Number of rocks	4	4	6
Maximum total kinetic energy (kJ)	0.950	0.417	0.140

The satisfactory location of barrier for bench face angle:

- 60^o, is location 2 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, is location 2 (same reason as for 60^o bench face angle)
- 80^o, is location 3 (same reason as for 60^o bench face angle).
- 90^o, considering the data in Table D.20 and the fact that the maximum run-out distance is less than 12.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table D21. Rockfall parameters for stack configuration 3, 10 m bench height, 60^o bench face angle, rock type Three (File name on CD-R: buana233).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	34.5	36	37.5	39
Distance of barrier from toe of bottom bench (m)	5.4	6.9	8.4	9.9
Maximum bounce height (m)	7.88	7.2	4.6	4.6
Recommended height of barrier (m)	5	5	4.6	4.6
Number of rocks	17	11	72	8
Maximum total kinetic energy (kJ)	0.740	0.740	0.740	0.410

Table D22. Rockfall parameters for stack configuration 3, 10 m bench height, 70^o bench face angle, rock type Three (File name on CD-R: buana234).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	27	28.5	30	31.5
Distance of barrier from toe of bottom bench (m)	6.6	8.1	9.6	11.1
Maximum bounce height (m)	8.88	6.67	6.67	4.45
Recommended height of barrier (m)	5	5	5	4.5
Number of rocks	17	39	22	8
Maximum total kinetic energy (kJ)	0.863	0.950	0.517	0.688

Table D23. Rockfall parameters for stack configuration 3, 10 m bench height, 80° bench face angle, rock type Three (File name on CD-R: buana235).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	21	22.5	24	25.5
Distance of barrier from toe of bottom bench (m)	7.9	9.4	10.9	12.4
Maximum bounce height (m)	8.3	7.5	5	2.5
Recommended height of barrier (m)	5	5	5	2.5
Number of rocks	54	35	12	35
Maximum total kinetic energy (kJ)	0.875	0.750	0.500	0.500

Table D24. Rockfall parameters for stack configuration 3, 10 m bench height, 90° bench face angle, rock type Three (File name on CD-R: buana236).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	11	12	13
Distance of barrier from toe of bottom bench (m)	5	6	7
Maximum bounce height (m)	10.8	6.5	1.1
Recommended height of barrier (m)	5	5	2
Number of rocks	4	6	6
Maximum total kinetic energy (kJ)	1.071	0.612	0.094

The satisfactory location of barrier for bench face angle:

- 60°, is location 3 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70°, is location 4 (same reason as for 60° bench face angle).
- 80°, is location 3 (same reason as for 60° bench face angle).
- 90°, considering the data in Table D.24 and the fact that the maximum run-out distance is less than 12.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table D25. Rockfall parameters for stack configuration 3, 12 m bench height, 60^o bench face angle, rock type One (File name on CD-R: buana65).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	51	52.7	54.4	56.1
Distance of barrier from toe of bottom bench (m)	17.1	19.1	20.8	22.5
Maximum bounce height (m)	3.17	4	4	4
Recommended height of barrier (m)	3.2	4	4	4
Number of rocks	89	156	500	500
Maximum total kinetic energy (kJ)	0.760	0.650	0.540	0.540

Table D26. Rockfall parameters for stack configuration 3, 12 m bench height, 70^o bench face angle, rock type One (File name on CD-R: buana66).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	34	35.7	37.4	39.1
Distance of barrier from toe of bottom bench (m)	10.6	12.3	14	15.7
Maximum bounce height (m)	8.13	5.4	5.4	4.5
Recommended height of barrier (m)	5	5	5	4.5
Number of rocks	6	8	8	8
Maximum total kinetic energy (kJ)	0.787	1.182	0.985	0.985

Table D27. Rockfall parameters for stack configuration 3, 12 m bench height, 80^o bench face angle, rock type One (File name on CD-R: buana67).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	28.5	30	31.5	33
Distance of barrier from toe of bottom bench (m)	14.1	15.6	17.1	18.6
Maximum bounce height (m)	10	8.5	6.5	6.5
Recommended height of barrier (m)	5	5	5	5
Number of rocks	15	20	50	5
Maximum total kinetic energy (kJ)	0.779	0.985	0.985	1.176

Table D28. Rockfall parameter for stack configuration 3, 12 m bench height, 90^o bench face angle, rock type One (File name on CD-R: buana68).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier (m)	9	10.5	12
Distance of barrier from toe of bottom bench (m)	3	4.5	6
Maximum bounce height (m)	7.1	3.55	0.88
Recommended height of barrier (m)	5	3.6	2
Number of rocks	92	6	46
Maximum total kinetic energy (kJ)	0.750	0.600	0.150

The satisfactory location of barrier for bench face angle:

- 60^o, no position is suitable because any location of barrier does not satisfy both the 14.1 m (Modified Ritchie criterion) and Table 4.1.
- 70^o, is location 4 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 80^o, the same as for 60^o bench face angle.
- 90^o, considering the data in Table D.28 and the fact that the maximum run-out distance is less than 14.1 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table D29. rockfall parameters for stack configuration 3, 12 m bench height, 60^{o} bench face angle, rock type Two (File name on CD-R: buana69).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	39.1	40.8	42.5	44.2
Distance of barrier from toe of bottom bench (m)	5.5	7.2	8.9	10.6
Maximum bounce height (m)	7	6.3	6.3	5.08
Recommended height of barrier (m)	5	5	5	5
Number of rocks	6	11	6	6
Maximum total kinetic energy (kJ)	0.688	0.588	0.588	0.688

Table D30. Rockfall parameters for stack configuration 3, 12 m bench height, 70^{o} bench face angle, rock type Two (File name on CD-R: buana70).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	27.2	28.9	30.6	32.3
Distance of barrier from toe of bottom bench (m)	3.8	5.5	7.2	8.9
Maximum bounce height (m)	6.55	6.55	5.8	5.08
Recommended height of barrier (m)	5	5	5	5
Number of rocks	17	6	11	6
Maximum total kinetic energy (kJ)	1.467	0.567	0.567	0.567

Table D31. Rockfall parameters for stack configuration 3, 12 m bench height, 80^o bench face angle, rock type Two (File name on CD-R: buana71).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	21	22.5	24	25.5
Distance of barrier from toe of bottom bench (m)	6.6	8.1	9.6	11.1
Maximum bounce height (m)	11.25	10.17	5.6	4.5
Recommended height of barrier (m)	5	5	5	4.5
Number of rocks	5	4	11	7
Maximum total kinetic energy (kJ)	0.923	1.238	0.825	0.688

Table D32. Rockfall parameter for stack configuration 3, 12 m bench height, 90^o bench face angle, rock type Two (File name on CD-R: buana72).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	9	10.5	12
Distance of barrier from toe of bottom bench (m)	3	4.5	6
Maximum bounce height (m)	14.67	5.67	2.25
Recommended height of barrier (m)	5	5	2.3
Number of rocks	5	10	3
Maximum total kinetic energy (kJ)	1.333	1.000	0.167

The satisfactory location of barrier for bench face angle:

- 60^o, is location 4. As only 6 rocks reach the maximum bounce height (5.08 m) while others have a height less than 3.8 m, so accepting a low risk in rockfall hazard point of view, a barrier with this latter height will be installed.
- 70^o, is location 4. As only6 rocks reach the maximum bounce height (5.08 m) while others have a height less than 4.3 m, so accepting a low risk in rockfall hazard point of view, a barrier with this latter height will be installed.
- 80^o, is location 4 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 90^o, considering the data in Table D.32 and the fact that the maximum run-out distance is less than 14.1 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table D33. Rockfall parameters for stack configuration 3, 12 m bench height, 60^o bench face angle, rock type Three (File name on CD-R: buana73).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	42.5	44.2	45.9	47.6
Distance of barrier from toe of bottom bench (m)	8.9	10.6	12.3	14
Maximum bounce height (m)	7.88	7.1	5.5	4.7
Recommended height of barrier (m)	5	5	5	4.7
Number of rocks	22	17	22	44
Maximum total kinetic energy (kJ)	0.850	0.850	0.533	0.745

Table D34. Rockfall parameters for stack configuration 3, 12 m bench height, 70^o bench face angle, rock type Three (File name on CD-R: buana74).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	32.3	34	35.7	37.4
Distance of barrier from toe of bottom bench (m)	8.9	10.6	12.3	14
Maximum bounce height (m)	7.7	8.55	6.8	5.13
Recommended height of barrier (m)	5	5	5	5
Number of rocks	144	72	44	6
Maximum total kinetic energy (kJ)	0.833	0.938	0.730	0.938

Table D35. Rockfall parameters for stack configuration 3, 12 m bench height, 80^o bench face angle, rock type Three (File name on CD-R: buana75).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	24	25.5	27	28.5
Distance of barrier from toe of bottom bench (m)	9.6	11.1	12.6	14.1
Maximum bounce height (m)	10	9.05	7.05	5
Recommended height of barrier (m)	5	5	5	5
Number of rocks	140	125	25	95
Maximum total kinetic energy (kJ)	1.536	0.940	0.940	0.621

Table D36. Rockfall parameters for stack configuration 3, 12 bench height, 90^o bench face angle, rock type Three (File name on CD-R: buana76).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	9	10.5	12
Distance of barrier from toe of bottom bench (m)	3	4.5	6
Maximum bounce height (m)	21.5	12.75	7.67
Recommended height of barrier (m)	5	5	5
Number of rocks	44	28	6
Maximum total kinetic energy (kJ)	2.203	2.203	1.109

The satisfactory location of barrier for bench face angle:

- 60^o, is location 4 as its maximum bounce height and maximum total kinetic energy satisfy the first category of Table 4.1.
- 70^o, no position is suitable because any location of barrier does not satisfy both the 14.1 m (Modified Ritchie criterion) and Table 4.1.
- 80^o, is location 4 (same reason as for 60^o bench face angle).
- 90^o, considering the data in Table D.36 and the fact that the maximum run-out distance is less than 14.1 m, the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table D37. Rockfall parameters for stack configuration 3, 15 m bench height, 60^{o} bench face angle, rock type One (File name on CD-R: buana77).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	62.1	64.4	66.7	69
Distance of barrier from toe of bottom bench (m)	21.5	23.8	26.1	28.4
Maximum bounce height (m)	2.9	4.88	4.88	4.88
Recommended height of barrier (m)	2.9	4.9	4.9	4.9
Number of rocks	39	7	444	500
Maximum total kinetic energy (kJ)	1.100	0.820	0.683	0.683

Table D38. Rockfall parameters for stack configuration 3, 15 m bench height, 70^{o} bench face angle, rock type One (File name on CD-R: buana78).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	41.1	43.7	46	48.3
Distance of barrier from toe of bottom bench (m)	13.6	15.9	18.2	20.5
Maximum bounce height (m)	7.7	7.7	6.6	4.4
Recommended height of barrier (m)	5	5	5	4.4
Number of rocks	278	167	256	294
Maximum total kinetic energy (kJ)	0.929	0.929	1.169	1.169

Table D39. Rockfall parameters for stack configuration 3, 15 m bench height, 80^o bench face angle, rock type One (File name on CD-R: buana79).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier
x-coordinate of barrier location (m)	34.5	36.8	39.1	41.4	43.7
Distance of barrier from toe of bottom bench (m)	18.1	20.4	22.7	25	27.3
Maximum bounce height (m)	12.5	10.68	8.84	5.27	3.56
Recommended height of barrier (m)	5	5	5	5	3.6
Number of rocks	75	42	4	6	117
Maximum total kinetic energy (kJ)	0.972	1.222	1.463	0.981	0.981

Table D40. Rockfall parameters for stack configuration 3, 15 m bench height, 90^o bench face angle, rock type One (File name on CD-R: buana80).

	Location 1of barrier	Location 2 of barrier
x-coordinate of barrier	12	14
Distance of barrier from toe of bottom bench (m)	6	8
Maximum bounce height (m)	5	1.25
Recommended height of barrier (m)	5	2
Number of rocks	4	6
Maximum total kinetic energy (kJ)	0.368	0.188

The satisfactory location of barrier for bench face angle:

- 60^o, no position is suitable because any location of barrier does not satisfy both the 16.5 m (Modified Ritchie criterion) and Table 4.1.
- 70^o, the same as for 60^o bench face angle.
- 80^o, the same as for 60^o bench face angle.
- 90^o, considering the data in Table D.40 and the fact that the maximum run-out distance is less than 16.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table D41. Rockfall parameters for stack configuration 3, 15 m bench height, 60^{o} bench face angle, rock type Two (File name on CD-R: buana81).

	Location 1of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier
x-coordinate of barrier location (m)	43.7	46	48.3	50.6	52.9	55.2
Distance of barrier from toe of bottom (m)	3.1	5.4	7.7	10	12.3	14.6
Maximum bounce height (m)	6.42	7.05	7.67	7.05	5.13	3.19
Recommended height of barrier	5	5	5	5	5	3.2
Number of rocks	6	8	6	6	6	6
Maximum total kinetic energy (kJ)	1.900	0.550	0.410	0.550	0.817	0.950

Table D42. Rockfall parameter for stack configuration 3, 15 m bench height, 70^{o} bench face angle, rock type Two (File name on CD-R: buana82).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	32.2	34.5	36.8	39.1
Distance of barrier from toe of bottom bench (m)	4.4	6.7	9	11.3
Maximum bounce height (m)	12	9.2	6.5	5.5
Recommended height of barrier (m)	5	5	5	5
Number of rocks	6	6	22	6
Maximum total kinetic energy (kJ)	1.902	0.963	1.274	0.799

Table D43. Rockfall parameters for stack configuration 3, 15 m bench height, 80^o bench face angle, rock type Two (File name on CD-R: buana83).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	26	28	30	32
Distance of barrier from toe of bottom bench (m)	9.6	11.6	13.6	15.6
Maximum bounce height (m)	11.5	10	8.6	5.75
Recommended height of barrier (m)	5	5	5	5
Number of rocks	5	3	3	3
Maximum total kinetic energy (kJ)	1.339	0.890	0.669	0.449

Table D44. Rockfall parameters for stack configuration 3, 15 m bench height, 90^o bench face angle, rock type Two (File name on CD-R: buana84).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	10	12	14
Distance of barrier from toe of bottom bench (m)	4	6	8
Maximum bounce height (m)	16	9.63	1.6
Recommended height of barrier (m)	5	5	2
Number of rocks	2	2	2
Maximum total kinetic energy (kJ)	1.533	1.317	0.225

The satisfactory location of barrier for bench face angle:

- 60^o, is location 5. As only 6 rocks the maximum bounce height (5.13 m) while others have a height less than 4.5 m, so accepting a low risk in rockfall hazard point of view, a barrier with this latter height will be installed.
- 70^o, is location 4. As only 6 rocks reach the maximum bounce height (5.5 m) while others have a height less than 4.6 m, so accepting a low risk in rockfall hazard point of view, a barrier with this latter height will be installed.
- 80^o, is location 4. As only 3 rocks reach the maximum bounce height (5.75 m) while others have a height less than 4.3 m, so accepting a low risk in rockfall hazard point of view, a barrier with this later height will be installed.
- 90^o, considering the data in Table D.44 and the fact that the maximum run-out distance

is less than 16.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.

Table D45. Rockfall parameters for stack configuration 3, 15 m bench height, 60^{o} bench faced angle, rock type Three (File name on CD-R: buana85).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	52.9	55.2	57.5	59.8
Distance of barrier from toe of bottom bench (m)	12.3	14.6	16.9	19.2
Maximum bounce height (m)	9.67	8.5	5.8	3.88
Recommended height of barrier (m)	5	5	5	3.9
Number of rocks	22	56	11	6
Maximum total kinetic energy (kJ)	1.113	0.975	0.833	0.700

Table D46. Rockfall parameters for stack configuration 3, 15 m bench height, 70^{o} bench face angle, rock type Three (File name on CD-R: buana86).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier	Location 5 of barrier	Location 6 of barrier
x-coordinate of barrier location (m)	39.1	41.1	43.7	46	48.3	50.6
Distance of barrier from toe of bottom bench (m)	11.3	13.6	15.9	18.2	20.5	22.8
Maximum bounce height (m)	10	10	6	6	6	4
Recommended height of barrier (m)	5	5	5	5	5	4
Number of rocks	11	8	22	8	11	11
Maximum total kinetic energy (kJ)	1.067	1.067	0.800	0.533	0.533	0.667

Table D47. Rockfall parameters for stack configuration 3, 15 m bench height, 80^o bench face angle, rock type Three (File name on CD-R: buana87).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier	Location 4 of barrier
x-coordinate of barrier location (m)	30	32	34	36
Distance of barrier from toe of bottom bench (m)	13.6	15.6	17.6	19.6
Maximum bounce height (m)	12.5	10	7.83	4.58
Recommended height of barrier (m)	5	5	5	4.6
Number of rocks	53	3	11	6
Maximum total kinetic energy (kJ)	1.314	1.500	0.564	0.564

Table D48. Rockfall parameters for stack configuration 3, 15 m bench height, 90^o bench face angle, rock type Three (File name on CD-R: buana88).

	Location 1 of barrier	Location 2 of barrier	Location 3 of barrier
x-coordinate of barrier location (m)	12	14	16
Distance of barrier from toe of bottom bench (m)	6	8	10
Maximum bounce height (m)	24.06	14.1	2
Recommended height of barrier (m)	5	5	2
Number of rocks	5	5	5
Maximum total kinetic energy (kJ)	3.196	4.571	4.116

The satisfactory location of barrier for bench face angle:

- 60^o, no position is suitable because any location of barrier does not satisfy both the 16.5 m (Modified Ritchie criterion) and Table 4.1.
- 70^o, the same as for 60^o bench face angle.
- 80^o, the same as for 60^o bench face angle.
- 90^o, considering the data in Table D.48 and the fact that the maximum run-out distance is less than 16.5 m (Modified Ritchie criterion), the use of the catch fence to reduce the required width of the catch bench is no more technically feasible.