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Slope geometry design as a means for controlling rockfalls in quarries

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Abstract

This paper presents a rockfall control method for rock quarries, based on benched rock slope design and catch-bench width control. The aim is to prevent rockfalls in quarries, which cause a significant number of accidents and even fatalities. Whereas catch ditches have traditionally been used as the main rockfall control method for roads and highways, benches carved into slopes are typically used in open-pit mining. In the road engineering field a simple empirical technique, recently reviewed and updated, has long been in use that is capable of ensuring slope designs that prevent falling rocks from reaching the travelled area of a road. Such techniques are lacking in the quarrying field, however, and this work is an attempt to develop a method similar to those developed for road engineering, but specifically adapted to quarry slope geometries. Using statistically significant data on the parameters affecting falling block trajectories, obtained from empirical data and from a back-analysis performed using a rockfall modelling code, we estimated geometries for quarry slopes that would prevent falling rocks from reaching work areas. This information was compiled and presented in the form of charts (for 2-bench, 5-bench and 8-bench slopes) that enable the user to design rockfall-safe slopes.

Keywords: Rockfall; Quarrying; Catch-bench width; Rock slope design; Mining safety

1. Introduction

Rockfalls are a significant hazard in open-pit mining and quarrying (Fig. 1) and in road and highway rock cuts (Fig. 2). They are also a hazard in mountain areas or villages and towns with abrupt topography, where it is not usually economically feasible to stabilise all the areas that may be sources of rockfalls. The problem with rockfalls is that they may adversely affect people or machines in mining exploitations, vehicles using roads and highways, and even people inhabiting populated areas in mountainous regions [1,2].

Even if the costs associated with rockfalls are typically much lower than those associated with large-scale slope instabilities, the number of accidents and fatalities arising as a consequence of either tend to be more or less equal, as has been pointed out by a number of authors [3,4]. These observations seem to concord with data for quarries in Northwest Spain, where, in a study of mining accidents over an 18-year period in the province of Pontevedra, thirty accidents involving fatalities or severe injuries were recorded [5], five of which were slope related (three associated with general slope instability, and two with rockfalls). Thus, 43% of slope-related accidents were caused by rockfalls. Note that this number of slope-related accidents is not excessive, explained by the fact that most of the quarries were ornamental granite quarries, where low fracturing of the rock mass means that blocks do not tend to become detached and fall.

The situation is rather different, however, in exploitations based on more fractured rock masses. ANEFA, the Spanish Association of Aggregate Producers [6], reported that over 20% of accidents in these quarries were due to rockfalls, the most common single cause of fatalities (Fig. 3). These alarming data—thirty-five rockfall-related fatalities in Spain over a nine-year period—inspired this study.

In the early stages of development of rock-slope engineering, efforts were focused on analyses of rock, discontinuity and rock-mass properties, and slope stability. In mining, the main aim was to ensure the

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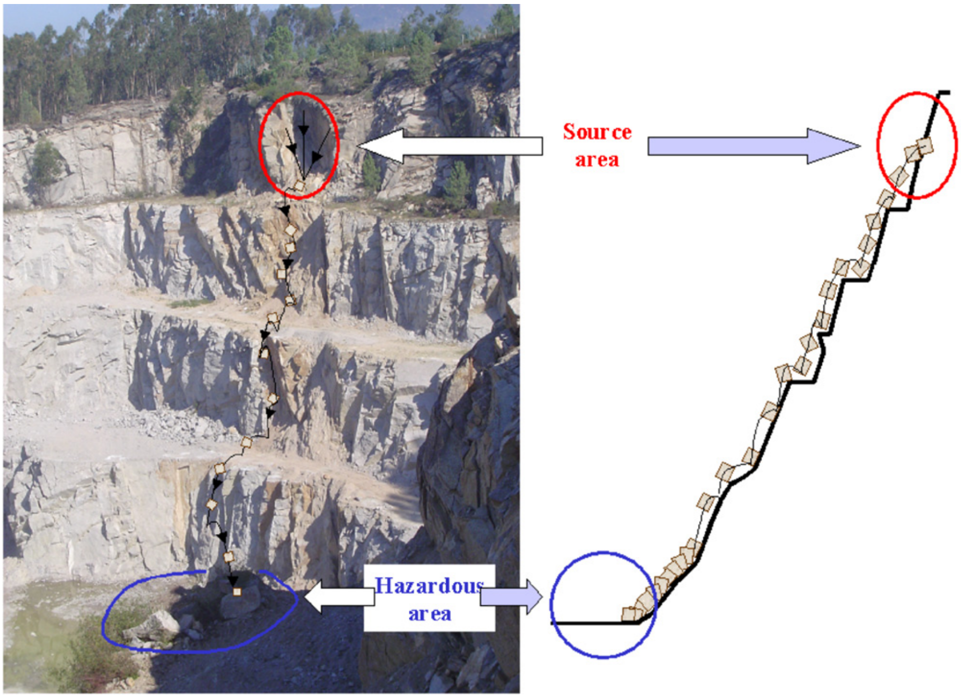


Fig. 1. Rockfall trajectory.

Fig. 2. Rockfall in late 2005 at a tunnel mouth in Northeast Spain resulting in one fatality [7].

stability of the general slope—an aim that was compatible with financial exploitation of the mineral. Ensuring bench stability usually implies very low dipping slopes, which generally renders mining non-profitable, and so general slope stability, rather than bench stability, is the goal.

With a view to developing accident prevention measures, in recent decades an interest has developed in the analysis of rocks that become detached from a rock mass, in terms of rock fall path, height, velocity, and energy. Apart from the software tools that have been developed to statistically estimate rockfall trajectories, empirical methods have also been applied to the identification and prioritisation of hazardous slopes.

The issue of rockfalls in open pit-mining has been analysed by a number of authors, who have proposed either simple estimate approaches, or more complex reliability-based methods aimed at maximising net profit [7–10]. The latter approach, however, is not suitable for quarry design.

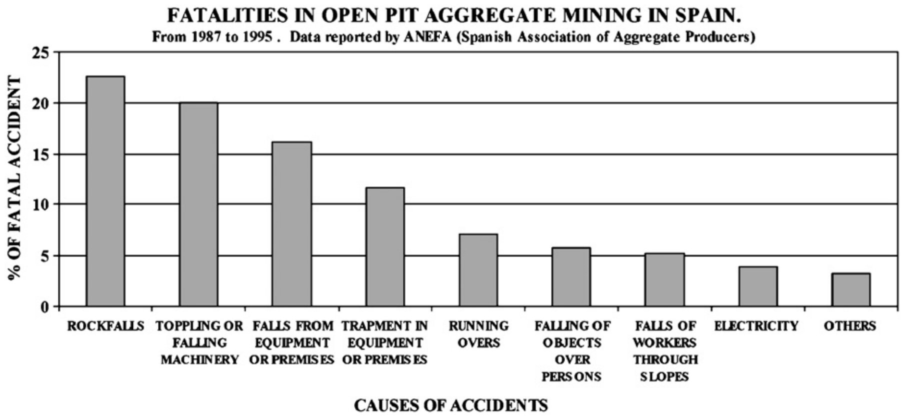


Fig. 3. Fatalities and their causes (%) in aggregate quarries in Spain 1987–1995 [6].

By now, in the opening years of the 21st century, improved safety is an issue that needs to be addressed in the rock mining field [11], as hazardous operations are not only regrettable but are also costly. Below we propose a method aimed at mitigating rockfall-related accidents and specially tailored to the quarrying environment. This method should go some way to ensuring a reduction in rockfall accident statistics in the future.

2. Background

In this section, we analyse rockfall trajectories (fall paths), fall-path simulation models (particularly RocFall 3.0 [12]), and significant rockfall parameter estimates. We also provide a brief description of protective measures and of empirical methods for assessing rockfall hazard and for designing roadway catch benches. Finally, the issue of rockfalls in open-pit mining is discussed.

2.1. Fall paths

Analysis of rockfall trajectories or fall paths has shown that four types of motion, some of which may take place simultaneously, are possible as a block proceeds along a slope: free-fall, bounce, roll, and slide. The three-dimensional nature of both rocks and slope surface, and the fact that a rock may break into smaller pieces during a fall, are also factors that need to be taken into account in an analysis of fall paths [13]. Developing a mathematical model that would correctly describe these four movements is obviously extremely complex, as such a model would need, for example, to consider the circumstances that lead to transition from one kind of movement to another (e.g., from roll to slide, or from roll to bounce).

Free-fall, which describes parabolic rock movement, is relatively easy to study. Bounce is more complex but can be simplified by considering restitution coefficients, which describe the behaviour of a falling rock impacting against a slope. Restitution defines loss of velocity in the normal and parallel directions of the slope. The normal (k_n) and tangential (k_t) coefficients of restitution are defined as

$$k_n = \frac{V_{nb}}{V_{ni}}; \quad k_t = \frac{V_{tb}}{V_{ti}}, \tag{1}$$

where V_{nb} and V_{ni}, respectively, are the normal components of bounce velocity and impact velocity (opposite in direction), and where V_{tb} and V_{ni}, respectively, are the tangential components of bounce velocity and impact velocity (identical in direction). Roll and slide are mainly controlled by the friction angle between the falling rock and the slope surface. Rock trajectory, however, may also be affected by the shape and orientation of the rock face in relation to the surface, the properties of the rock, the location of the impact point, and the direction of the momentum of inertia at the moment of impact, among other factors.

Giani et al. [14] studied the entire process using video-recorded data of mountain rockfalls and simulation techniques. Their method covered data recovery (slope topography and rock block geometry), parameter estimates (restitution coefficients and friction angles) and results analysis. Given the extreme difficult of correctly simulating these phenomena, the authors attested to the importance of performing real testing in order to evaluate the parameters controlling bounce and impact, although it was conceded that even in this case it would be very difficult to quantify the influence of bounce and impact, not to mention the influence of variations in each along a slope. Their main conclusion was that it is practically impossible to know a priori the fall path that a single block will follow.

Works by Ritchie [15] and especially by Pierson et al. [16], however, have demonstrated that even if it proved difficult to estimate the fall path for a single block, for slopes with a fairly simple geometry it would be possible to obtain reasonable statistical distributions of rock trajectory endpoints using empirical data.

2.2. Fall-path simulation models

Models that analyse trajectories need to incorporate the four types of motion indicated above (free-fall, bounce, roll and slide). From a practical perspective, available models can be classified as either lumped-mass models or rigorous models. In the lumped-mass models, the rock mass is concentrated in its centre of gravity and rock shape or volume are not considered; therefore, rolling is not simulated by this method. The rigorous models, on the other hand, include a range of approaches that take rock shape and volume into account. However, since it is extremely difficult to input realistic data for all these parameters, the method has not been much used in practice.

The lumped-mass methods assume a block to be a point, with a mass m and a velocity v that follows a ballistic path in the air (air friction is not taken into account). When the block impacts a surface, in accordance with Eq. (1), normal velocity changes direction and is reduced by a coefficient k_n, whereas tangential velocity maintains direction and is reduced by a coefficient k_t. These coefficients are assumed to take account of all kinds of energy loss in the impact. Note that rotational moments are not considered in this approach [13].

2.3. The RocFall code

RocFall 3.0 [12] is a lumped-mass method used to design safe slopes. Based on a statistical analysis of fall paths in 2D, it calculates trajectories and rebound energy for falling blocks as well as velocity and height for any point of a slope. It also estimates the location of the fall-path endpoint, which is the most significant factor affecting safety (Fig. 4).

In this code every rock is modelled as an infinitely small particle. Rock size is thus not considered, but the equations used in the sliding algorithm reflect shapes that are circular. Since each rock is infinitely small there is no interaction between particles, only with segments of slope, and so each rock behaves as if participating alone in the simulation. This means that non-cleaned catch benches are not well reflected in the code unless the debris slope is explicitly modelled as part of the slope.

RocFall 3.0 [12] is a more or less raw model of the mechanical process of a rockfall, as it does not take into account block shape, size or angular momentum. Nevertheless, it has the important advantages that its calculations include statistical distributions of the parameters and that it operates very rapidly. In a mining exploitation it is impossible to know falling block shape and size in advance; nonetheless, this code is appropriate for the purpose of modelling rockfall in quarries, given that it is not that difficult to assume statistical distributions for restitution coefficients and friction angles.

2.4. Rockfall parameter estimates

In simulations, the most significant parameters are the normal and tangential restitution coefficients and the

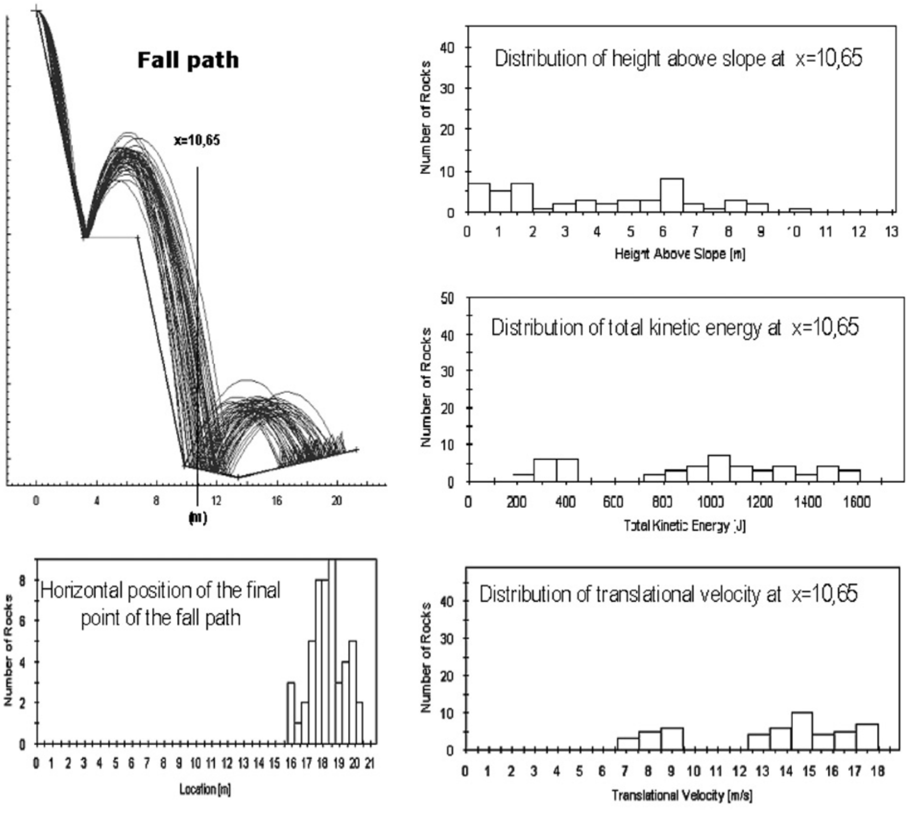


Fig. 4. Example of the results obtained using RocFall [12] for a simulation in which 100 rocks were thrown from the crest of a slope with a catch bench. The fall-paths of the blocks and their end points are shown on the left. The distributions for height above the slope, kinetic energy and translational velocity at a particular location on the slope ($x = 14.0$) are given on the right.

friction coefficient. Different authors have described the results obtained in their tests, usually giving a value for each restitution coefficient and for each particular material [2,12,14].

The actual values of the restitution coefficients are of paramount importance when using lumped-mass models. They should, therefore, be estimated with great care, on the basis of laboratory tests, calibration of fall-path results and field tests. Giani et al. [14] highlighted the marked variability of these parameters along large mountain slopes (even if formed of the same type of material) and in real scale observations, and indicated how these parameters depended not only on surface roughness but on impact type. For a slope in the Alps, for example, these authors calculated a restitution coefficient mean value that was smaller than the standard deviation.

The rolling friction coefficient $\mu = \tan\theta$ enables energy gain or loss and the translational velocity of a rock rolling along a dipping surface to be estimated. This is, therefore, a parameter that needs to be known in order to be able to estimate fall path and endpoint. It is usually considered equal to the sliding friction coefficient between the rock and the surface, but, as has been noted by Giani et al. [14], this is another parameter that is extremely variable and therefore difficult to estimate.

We can conclude that it is extremely difficult to estimate rockfall parameters from laboratory tests. If one wants to reliably model a rockfall process using a lumped-mass method, parameter calibration is necessary. To understand and quantify such complex phenomena, empirical methods are a good starting point.

2.5. *Empirical rockfall-hazard assessment methods*

In recent decades, empirical methods have developed in parallel to trajectory analysis techniques. Empirical methods are capable of assessing whether or not rockfall-related accidents are likely to occur on particular slopes. These methods not only account for rockfall trajectory, but also for the possible presence of rocks likely to fall down a slope and for the damage that might be caused to people, vehicles, etc. located at the toe of the slope. Empirical approaches are eminently suitable for analysing such highly complex phenomena.

The most popular of these methods used for rock cuts is the Rockfall Hazard Rating System (RHRS), developed by the Highway Division of Oregon [17] and applied in various states of the USA and also by a number of consultants. This simple system classifies slopes according to estimated hazard in order to prioritise the application of protective measures. Another similar method, also applied to highways, is the Rockfall Hazard Rating Ontario (RHRON), developed for the Canadian state of Ontario (initially developed by Franklin and Senior [18], it is being developed further by Senior et al. [19]). For mountain rockfall hazards affecting populated areas, Mazzocola and Hudson [20] proposed an empirical method capable of assessing rockfall risk in Alpine ranges.

There are significant differences between highways and mining slopes, particularly in terms of design safety factors and geometrical features (benches in mining, rock cuts with ditches in roads). The dynamic nature of mining slopes is also different, primarily because mining slopes experience vibrations occurring as a result of intermittent blasting. The fact that methods developed for highways do not function well in mining environments inspired Stockhausen and Alejano [21,22] to develop their method, still in a preliminary stage of development, entitled Rockfall Risk Assessment for Quarries (ROFRAQ).

The empirical methods described above, and particularly ROFRAQ, can be used to identify high-risk quarry slopes, to which the design techniques proposed in this study can be applied for corrective purposes.

2.6. *Protective measures*

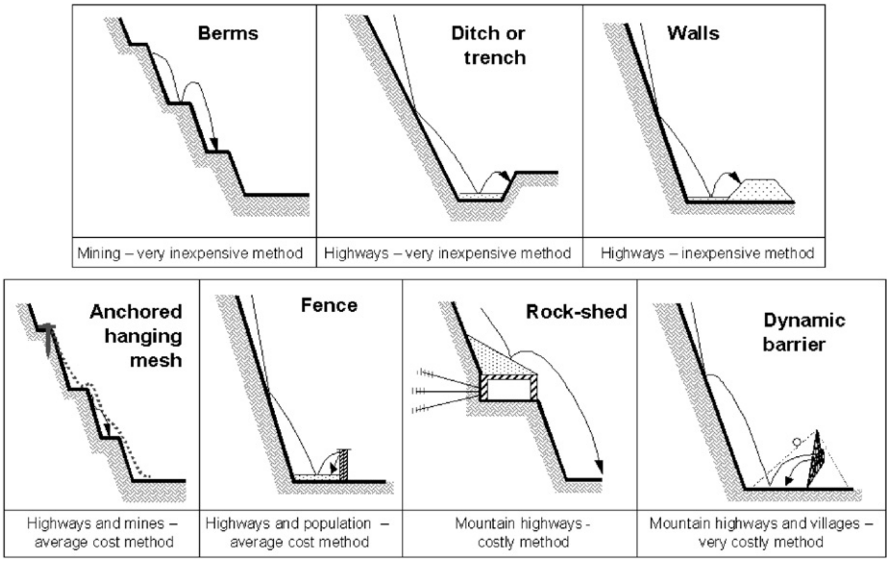
Since it is impossible to completely eliminate rockfalls, protective methods are needed to prevent accidents involving people and/or machines. Fig. 5, modified from [23], describes different protective measures used to control the damage associated with rockfalls, and also includes data on application field and cost. Traditionally, benches have been used in mining and quarrying, largely due to their low cost. Trenches or ditches, on the other hand, are preferred for highways for much the same reason, although different types of walls or fences are also considered in particular circumstances [2]. Other methods, such as dynamic barriers [24], may also be used, depending on local circumstances.

2.7. *Empirical techniques for designing roadway catch ditches*

The variable nature of both rockfalls and slopes makes it well nigh impossible to reliably estimate rockfall parameters. On the other hand, there are a number of widely used empirical ditch design techniques [15] that have demonstrated their usefulness. We back-analysed these techniques in order to obtain statistically representative values for the most important parameters. Two methods are briefly described below: the Ritchie approach [15] and the Pierson et al. approach [16], which can be viewed as an extension of Ritchie's method.

Ritchie proposed an empirical method for roadway ditch design, designed to prevent falling rocks from reaching the travelled area of a road. Using rockfall data collected over many years, Ritchie [15] created a ditch design table. This information was later compiled and presented in the form of a chart, which can be consulted in, for instance, Hoek [2] and Pierson et al. [16].

Ritchie's technique has been widely used. However, recent USA highway safety standards indicate that such ditches are obstacles that must be eliminated or enclosed. This new type of design is aimed at ensuring that, if a



Mining – very inexpensive method

Highways – very inexpensive method

Highways – inexpensive method

Highways and mines – average cost method

Highways and population – average cost method

Mountain highways - costly method

Mountain highways and villages – very costly method

Fig. 5. Rockfall hazard protective measures for different applications and cost levels. Adapted from [23].

vehicle enters the catchment area, the driver can retake control and return to the paved surface.

Pierson et al. [16] have demonstrated that Ritchie's design is capable of retaining around 85% of falling blocks. Evans [8] drew a similar conclusion based on real tests with mine benches. Designs of less than 100% are entirely adequate, as 100% retention of falling rocks would be overly costly, whereas a design that retains, for example, four out of every five blocks can be considered as being both reasonably safe and adequately cost-effective. The same authors indicated that Ritchie's proposal took only safety into account, but should, in fact, also consider the associated cost. To overcome these drawbacks, Ritchie's method was updated and improved by means of a detailed empirical study in which thousands of rocks were launched from the crest of rock slopes with different geometries.

In the Pierson approach [16] three slopes were prepared (12.2, 18.3 and 24.4 m high), each with four different slope gradients ($4V{:}1H$, $2V{:}1H$, $1.33V{:}1H$ and $1V{:}1H$). For each of the twelve slope-gradient combinations, three catchment areas were prepared (flat, a counter-slope of $1V{:}6H$, and a counter-slope of $1V{:}4H$). For these thirty-six cases, 250 rocks were launched, and point of impact and fall path were recorded. In some cases the fall was video-taped in order to record the velocity and energy of the falling rock. All these data were used to produce a series of graphs (of slopes with different heights and angles) and to calculate the percentage rockfall retained at a specific distance from the slope toe for various slope designs. With this information, a slope designer could decide a reasonable level of safety for a corresponding cost.

2.8. Rockfalls in open-pit mining

Call [9] analysed the specific problem of rockfalls in open-pit mines, focusing on optimising bench and catch-ditch design from a cost perspective compatible with safety standards. As an initial approach he proposed an evolved Ritchie's criterion applied to mining, in which minimum bench width was calculated from bench height (H) as follows:

$$\text{Minimum bench width (m)} = 4.5 + 0.2\,H. \tag{2}$$

In accordance with other studies undertaken in a mining environment [8], this criterion could be locally conservative, and so, starting from different catchment criteria [25], a new, less conservative version of Eq. (2) was proposed by Ryan and Prior [10]

$$\text{Minimum bench width (m)} = 3.5 + 0.17\,H. \tag{3}$$

These initial approaches, based on a simplified single-bench proposal, were designed in order to be further improved. However the open-pit mining problem proved too complex for any single criterion to be 100% effective. Due to the complex nature of the rockfall problem, Call [9], and later Ryan and Prior [10], approached the problem from a risk-management perspective, applying the so-called reliability-based approach to evaluating benched slopes. This complex method requires a large amount of data and is costly; in open-pit mines, where the cost implications of minor changes in slope angle may be significant, this sort of analysis can be extremely valuable for determining catch-bench width. However, in quarries a simpler approach is in order.

Another interesting issue that was raised in the mining approaches is in relation to what is referred to as backbreak (Fig. 6). Backbreak is defined as the horizontal distance between a planned and real bench crest. Backbreak is a pervasive phenomenon in mine benches. Tending to occur along pre-existing joints and blast-induced fractures, it should be accounted for in any catch-bench design.

We estimated a representative number of backbreak measurements for quarries in order to obtain mean and

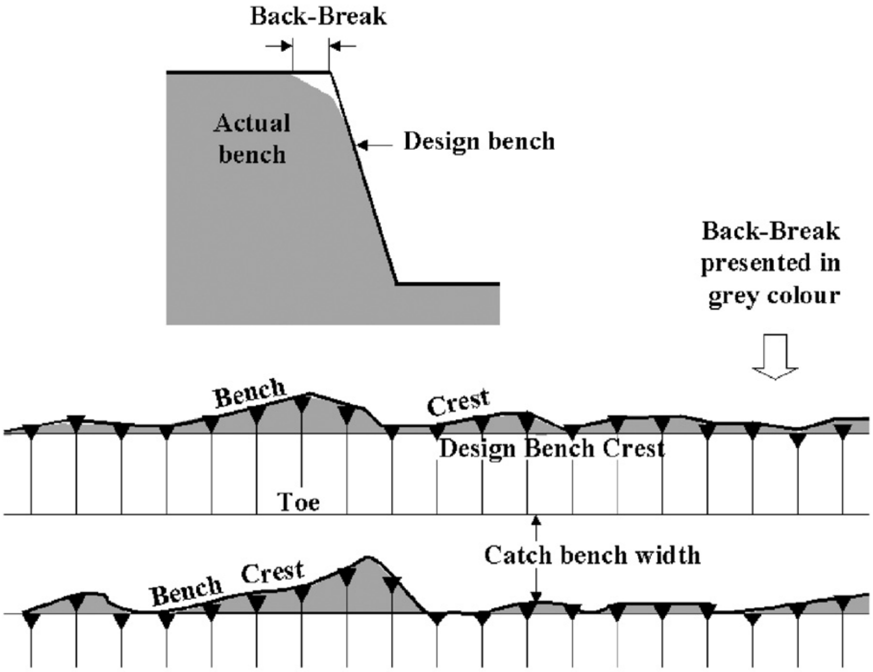


Fig. 6. Definition of backbreak [9].

standard deviation values for this parameter. Once the minimum recommended catch-bench width in the quarry was estimated, we added a length equal to the addition of mean backbreak plus the standard deviation for backbreak to account for this factor in the design.

3. Parameter calibration based on back-analysis of empirical methods

3.1. Introduction

A series of simulations using RocFall were performed in the search for a set of parameters capable of providing a good fit to the results obtained using the code versus the results of the techniques reviewed above. Although we assume that the Ritchie and Pierson methods are sufficiently representative of the kind of slopes to be found in hard rock quarries, this assumption may not be entirely valid, and so we will subsequently compare our results with real data from quarries and with data on safe catch benches in open-pit mines. Figs. 7 and 8 depict RocFall simulations corresponding to a Pierson case and a Ritchie case, respectively. In these simulations, 2000 blocks were launched from the crest of a slope, and the results were compared to the Ritchie and Pierson original methods [15,16].

Pierson's results were first analysed, as these are much more detailed and comprehensive than Ritchie's results; they provide the entire retention curve for different distances, whereas Ritchie only furnishes a single point supposedly corresponding to an 85% catch. The methodology proposed by Ritchie [15] has been extensively and successfully used, in the USA in the last four decades, for road catch-ditch design, which would indicate that the method works well. Since our analysis is an endeavour to

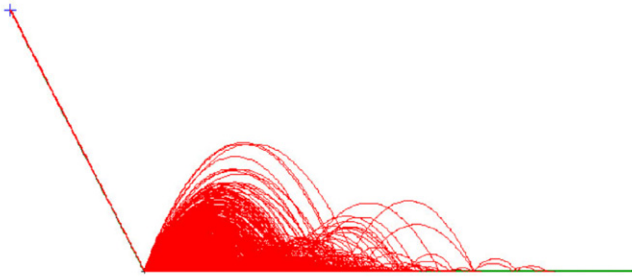


Fig. 7. RocFall simulation of a 18.3 m high 3V:1H slope with a flat catchment area, for comparison with empirical results from Pierson et al. [16].

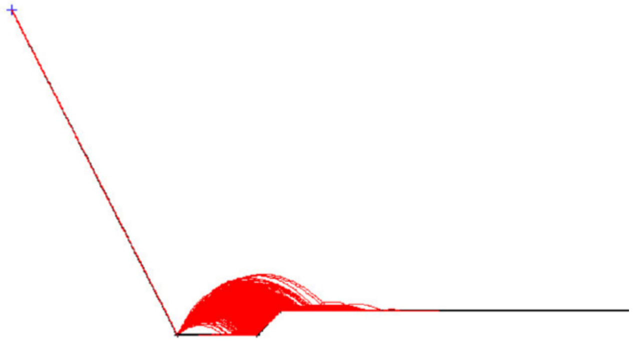


Fig. 8. RocFall simulation of a 24.4 m high—3V:1H slope with a catch ditch at its toe, for comparison with results from Ritchie [15] and assuming 85% retention.

develop a parallel method suitable for quarries, we have included a description of Ritchie's method in our study.

For each flat-ditch Pierson-type model, we fixed the geometry, and, using data from the literature, modified according to Giani et al. [14] and on the basis of our experience in hard-rock quarrying rockfall models [22], we performed simulations with varying sets of parameters in a search for a parameter set capable of offering realistic retention level results, especially above 50%. Table 1 describes the parameter set that was obtained as an appropriate fit. It should be pointed out that although these parameters may not necessarily represent a particular material, they provide a good fit that adequately represents actual observations of rockfalls in a good number of tests.

3.2. *RocFall compared to the Pierson approach*

Using the parameters from Table 1 and slopes simulating Pierson-tested cases (all combinations of 12.2, 15.2, 18.3, 21.3, and 24.4 m high slopes, with $4V{:}1H$ (76°), $2V{:}1H$ (63°), and $1V{:}1H$ (45°) gradients for the flat-ditch case—the most relevant to our study), a series of graphs were created to represent some of these cases (see Fig. 9). Each graph shows the percentage of blocks retained at different runout distances according to Pierson's empirical data and the simulations performed using RocFall. A reasonable level of similarity is observed. Obviously, with such complex and idiosyncratic phenomena, true accuracy is not feasible. However if we statistically analyse the differences between the methods for 75%, 80%, 85%, 90%, 95% and 99% retentions, the average value comes very close to zero.

It should be pointed out that Pierson's data were first taken as raw data and submitted to a regularisation process in order to prepare the design charts. It should also be noted that RocFall simulations are very sensitive to small changes in parameters (as can be observed in Fig. 10), which means that an improved fit in any one of the fifteen cases analysed implies a loss in accuracy in other cases.

Note that fits are more difficult for the higher retention percentages, i.e. 90%, 95% and 99%. This is because in these areas of the cumulative curves the horizontal trend of the graphed data tends to magnify error. Given that our intention is not to analyse results one by one but rather to obtain a general picture that is broadly coherent with the real results for a specific case, it can be concluded that the simulations performed using RocFall 3.0 and the parameters proposed above approximate sufficiently well the trend in the curves obtained empirically by Pierson et al [16].

In order to assess the sensitivity of results to different input data, parametric studies were performed for a series of particular cases, in which the means and standard deviations for the normal and tangential restitution coefficients, friction angles and slope roughness values were varied, together with slope height and angle. Results were graphed in the form of spider diagrams and analysed to show that the most significant parameters were the mean values for the restitution coefficients and slope angle. Although the sensitivity charts assisted greatly in obtaining the final calibrated parameters for this study, for the sake of brevity the heuristic process is not described in detail. By way of an example, however, Fig. 10 depicts the diagram obtained for a 18.3 m high, 63° dipping slope, showing a runout distance for 90% of blocks as the output value.

Table 1
RocFall calibration process output parameters

Calibrated material features						
k_n		k_t		θ		Slope roughness
Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	
0.35	0.15	0.85	0.05	25	2	0.1

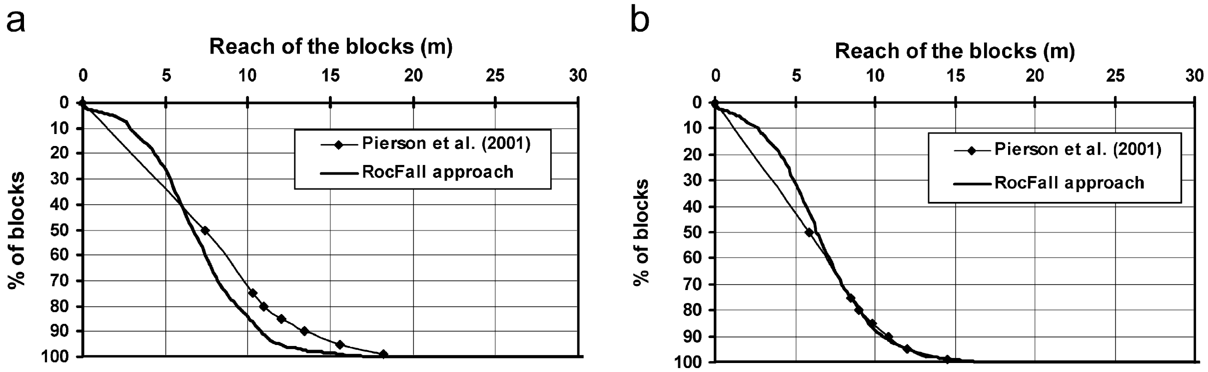
3.3. *RocFall compared to the Ritchie approach*

When comparing RocFall simulations to Ritchie's data [15] a problem arises in that Ritchie's catch ditches were supposedly designed with a gravel bed at the bottom which would, in theory, require a new set of parameters. Another issue is that Ritchie offers a single solution (according to Pierson et al. [16], apparently corresponding to 85% retention). With this in mind and considering the selected parameters to be an average representation of real data, RocFall models corresponding to 45°, 63° and 76° slopes with heights ranging from 12.2 to 24.4 m were compared to Ritchie's ditches. The RocFall results are presented in Fig. 11, which shows the runout distances for 80% and 85% of the blocks.

Results compare quite well for the steeper slopes. However, for the higher 45° slopes, RocFall results for 85% retention far exceed the expected Ritchie results, due to the fact that many of the blocks out-ran the ditch counter-slope. This offset was reduced for 80% retention and disappeared for 70% retention. Our conclusion is that softer parameters should perhaps be included to represent gravel in a catch-ditch gravel bed.

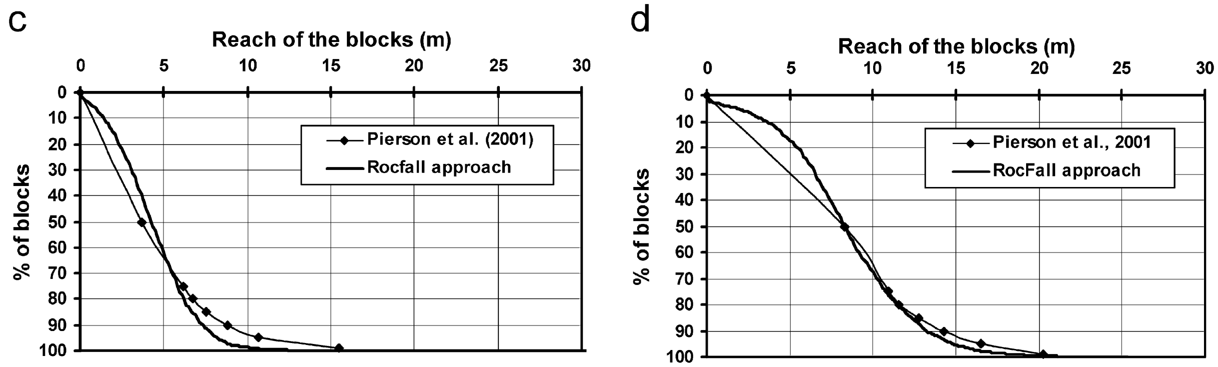
3.4. *Calibration conclusions*

The RocFall simulations for a series of tests compare reasonably well with empirically based design techniques. This code, together with the selected parameters (see Table 1), enables rockfalls to be realistically simulated. It should, however, be borne in mind that small changes in parameters or geometries can produce important changes in results, and that changes in slope geometry, rock breakage, rock heterogeneity, the presence of rockfall debris and so on, may in practice produce non-typical results. Using simulations it is possible to obtain average results for catch-bench widths for quarries that are capable



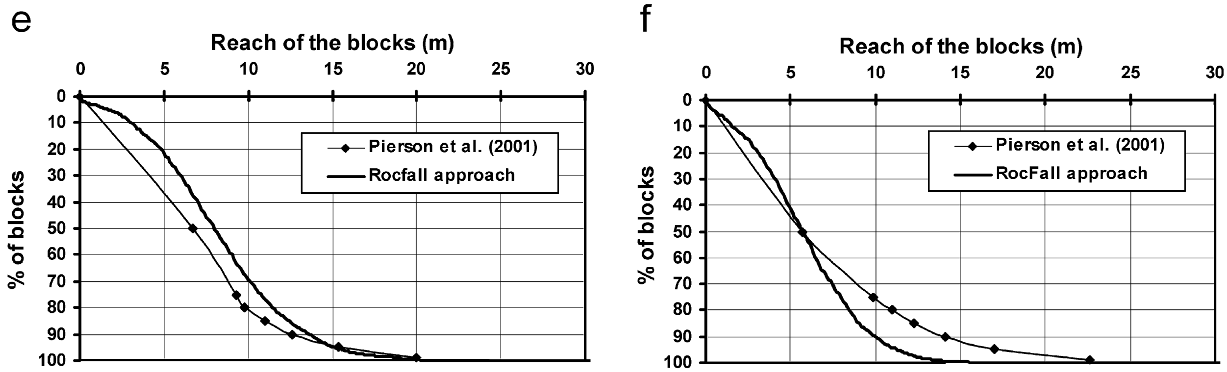
12.2 m high, 45° dip slope

12.2 m high, 63° dip slope



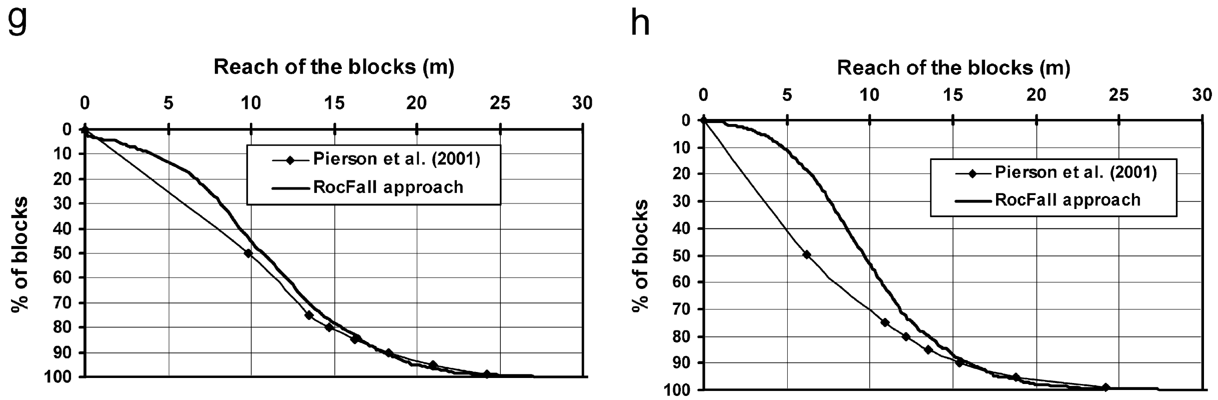
15.2 m high, 76° dip slope

18.3 m high, 45° dip slope



18.3 m high, 63° dip slope

21.3 m high, 76° dip slope



24.4 m high, 45° dip slope

24.4 m high, 76° dip slope

Fig. 9. Graphs for block retention percentages and block runouts that compare Pierson et al. [16] and the RocFall simulation using calibrated parameters. The following slope face angles are illustrated: (a) 12.2 m high 45° dip slope, (b) 12.2 m high 63° dip slope, (c) 12.2 m high 76° dip slope, (d) 18.3 m high 45° dip slope, (e) 18.3 m high 63° dip slope, (f) 21.3 m high 76° dip slope, (g) 24.4 m high 45° dip slope, and finally (h) 24.4 m high 76° dip slope. As can be observed, a generally good picture is obtained, with some local discrepancies.

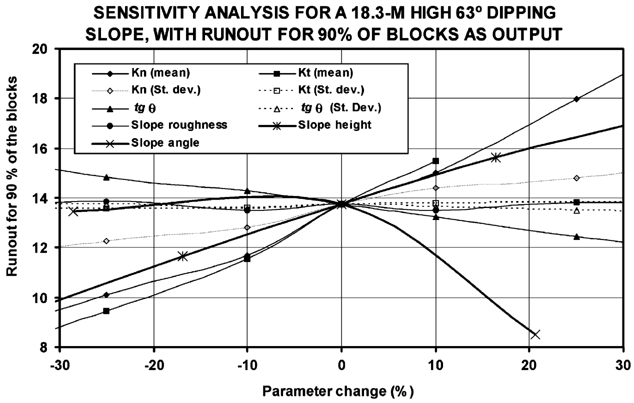


Fig. 10. Spider diagram representing a sensitivity analysis for the rockfall parameters and geometry for a 18.3 m high 63° slope, where the output parameter is runout for 90% of the blocks.

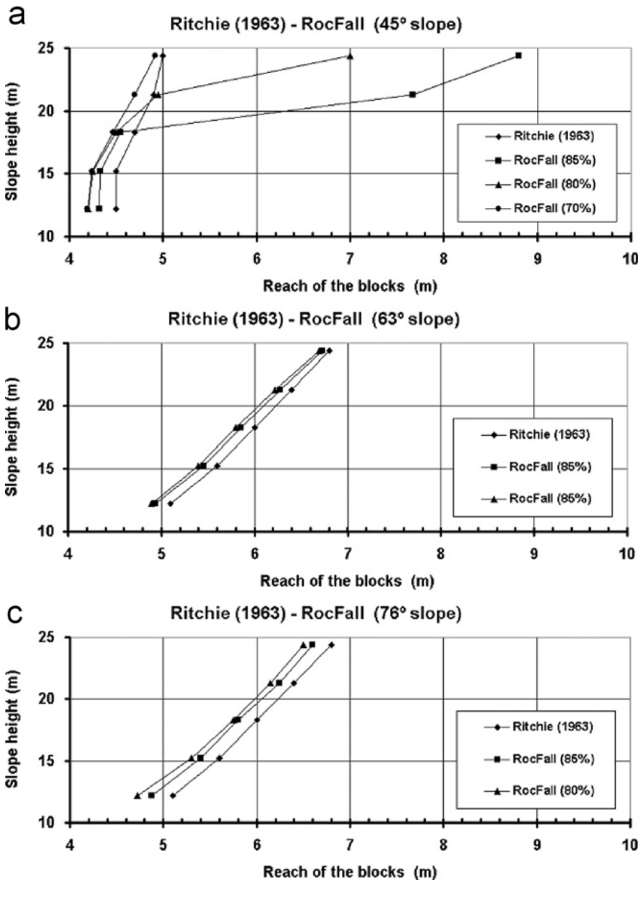


Fig. 11. Ritchie's proposal (roughly corresponding to 85% retention) compared to RocFall simulations (80% and 85% retentions) for (a) 45°, (b) 63° and (c) 76° slopes of different heights.

of providing geometry guidelines that focus on controlling rockfall-related accidents in this particular mining environment.

Due to the significance of the results in relation to the restitution coefficients, friction angles and geometry, a detailed analysis of particular and non-standard cases where more reliable results are required would require local calibration of the aforementioned data by means of in situ tests.

4. Results

Since the calibrated parameters are considered to be sufficiently representative of typical hard-rock behaviour in a rockfall situation, they can be used to simulate quarry slopes with benches and catch benches and with different geometries, as per Fig. 12.

The parameters that govern the geometry of a quarry slope are: general slope angle, bench height, number of benches, and either catch-bench width or bench-face angle. Fixing the first three aspects, we performed simulations involving blocks thrown from the crest of the upper bench so as to estimate the catch-bench width needed to retain a given percentage of blocks. Once general slope angles, bench height, bench number, and the required retention were fixed, simulations were performed to estimate catch-bench width. With these data, the total height of the slope and the bench-face angle could then be immediately fixed.

4.1. Obtaining charts for rockfall control slope design

Simulations were performed by throwing 2000 blocks from the highest point of the slope. Note that, in practice, rockfalls may commence anywhere on a slope, although they occur more commonly in the upper parts of benches (due to the de-stressing that produces backbreaks or that aggravates other failure mechanisms). Falls from lower benches or from operational mining faces are not considered in this method; since these rocks would always reach the toe of the slope, they should be handled using a different approach. Simulations with RocFall were performed for 2-bench, 5-bench and 8-bench slopes (considered to be representative of a wide range of quarry slopes)

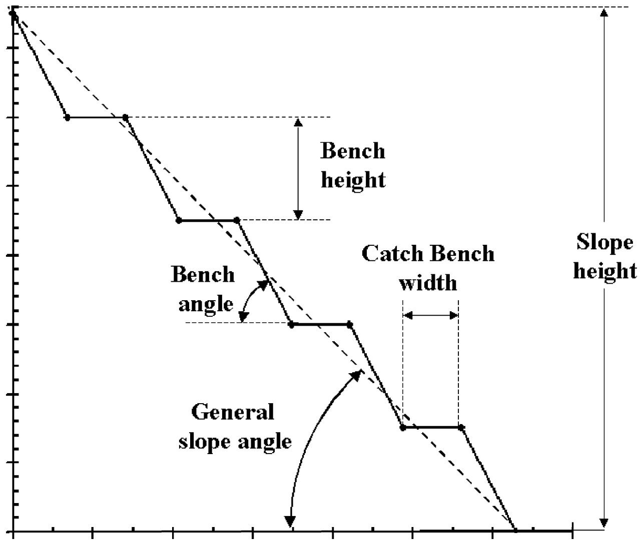


Fig. 12. Geometrical descriptions of quarry and mine slopes.

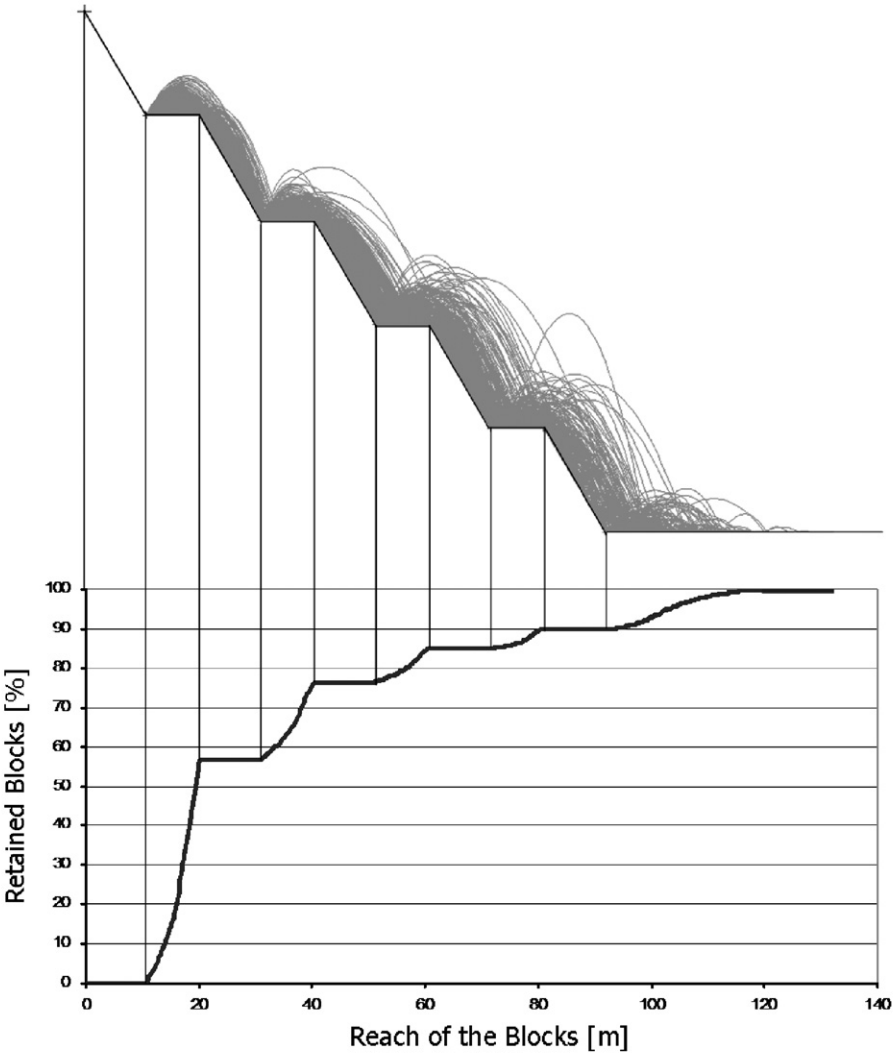


Fig. 13. RocFall (Rocscience, 2002) simulation results for a 5-bench slope (18.3 m high) with a general angle of 50°, adjusted for a 90% block retention level.

and catch-bench widths that retained 75%, 90% and 95% of the blocks were calculated.

As an example, Fig. 13 shows the case of a 5-bench slope with a general slope angle of 55°, with catch-bench width adjusted until the width that retained 90% of the falling rocks was identified. More than 1000 simulation trials were required in order to create a sufficiently large database.

All the results are summarised in graph format in Figs. 14–16, corresponding to 2, 5 and 8 benches, respectively, for retention percentages of 75%, 90% and 95%. These graphs can be used to calculate the minimum recommended catch-bench width required to retain a particular percentage of blocks for a particular slope geometry. As mentioned previously, catch-bench width should take backbreak into account, which is why we increased length by an amount equivalent to the inclusion of mean backbreak plus backbreak standard deviation.

The selected retention values correspond to cases in which 1 in 4, 1 in 10 and 1 in 20 blocks arrived to the toe of the quarry slope. Retention of 100% was not considered, for the simple reason that a slope with this level of retention is non-feasible in cost terms. The retention levels were chosen on the basis of a risk level estimated according to rockfall risk assessment criteria; thus, for instance, in non-hazardous areas (RHRS < 300 or ROFRAQ < 100), 75% retention is usually adequate; but in areas where rockfall occurs frequently (300 < RHRS < 400, 100 < ROFRAQ < 250), 90% retention would be preferable (or even 95% for riskier slopes). Given that bench-face angle is frequently fixed for blasting purposes, the charts also include lines depicting the designs for standard drill inclinations, marking the most common bench-face angles, and in particular, bench gradients or angles of $2V{:}1H$ (63.43°), $3V{:}1H$ (71.56°) and $4V{:}1H$ (75.96°).

We propose using these charts primarily for initial quarry design (to calculate the catch-bench width needed to obtain a specific desired retention percentage). They can also be used to correct the retention level of a particular quarry whenever rockfall-related problems are detected,

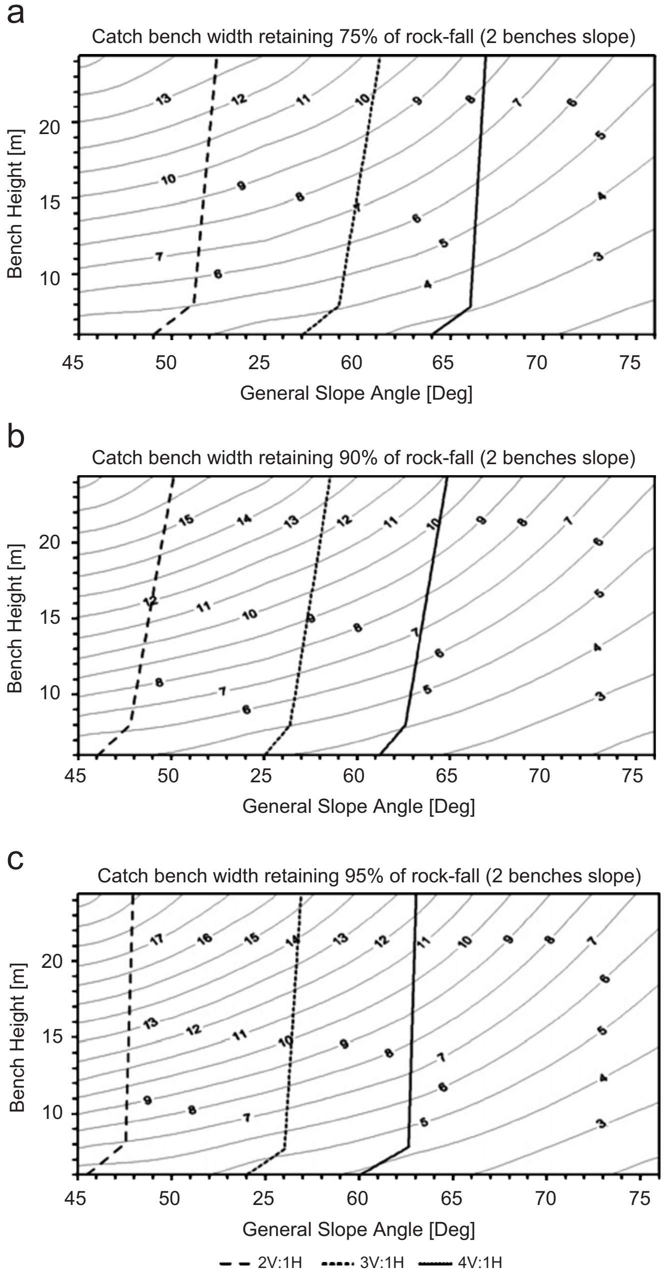


Fig. 14. Catch-bench design charts for 2-bench quarries. Results for (a) 75% (3 out of 4 rocks), (b) 90% (9 out 10 rocks) and (c) 95% (19 out of 20 rocks) retention rates.

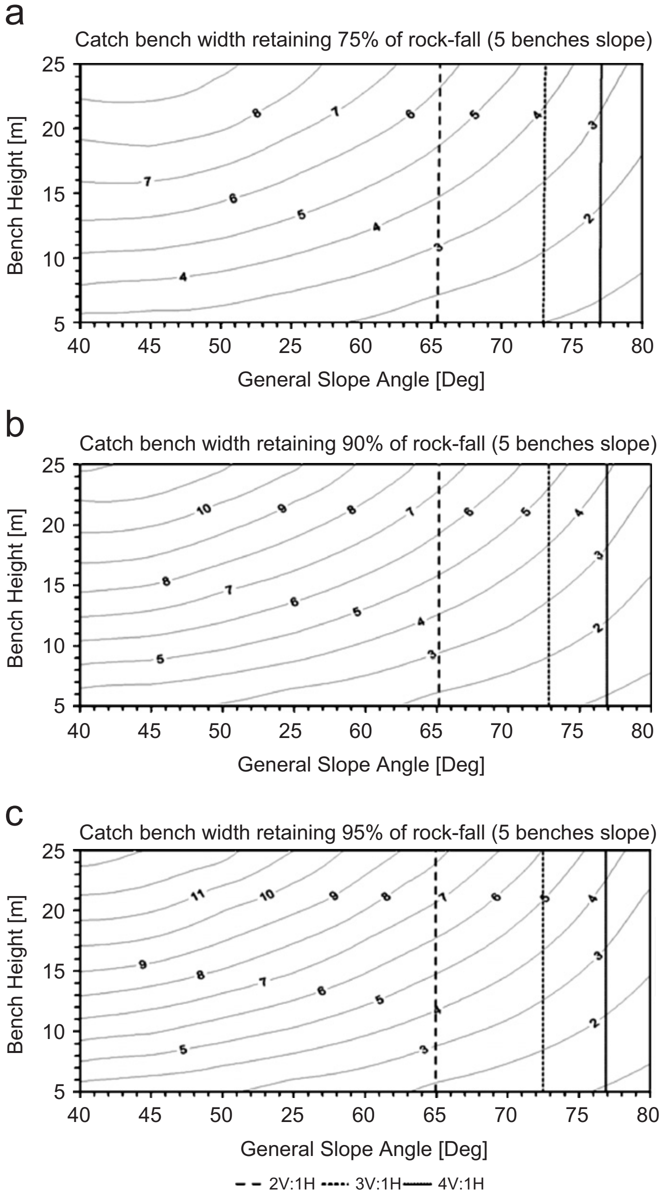


Fig. 15. Catch-bench design charts for 5-bench quarries. Results for (a) 75% (3 out of 4 rocks), (b) 90% (9 out 10 rocks) and (c) 95% (19 out of 20 rocks) retention rates.

whether by direct observation or using empirical rockfall hazard methods (ROFRAQ or RHRS, for example).

In view of its perspective and development stage, the methodology presented here reflects average values for hard-rock slopes, and so should only be used as a broad guide. More detailed and/or local analyses would require field studies to obtain relevant site-specific data.

4.2. Use of the charts

The charts can be used in either of two ways: to design a rockfall-proof quarry or to analyse the rockfall retention capabilities of slopes in an existing quarry. Note, however, that when there is no danger of falling rocks, there is—obviously—no need for retaining structures to ensure safety. For both design of a new quarry and analysis of an existing quarry, the required retention capacity needs to be pre-determined for 75%, 90% and 95% retentions (for instance, using predefined criteria based on rockfall hazard assessment techniques).

For quarry design purposes, once the required retention capacity and number of benches have been established, the two basic operational parameters for quarry design are entered in the corresponding chart (i.e. bench height as the *Y*-axis value and general slope angle as the *X*-axis value). This results in an initial value for a catch-bench width capable of retaining the pre-determined percentage of

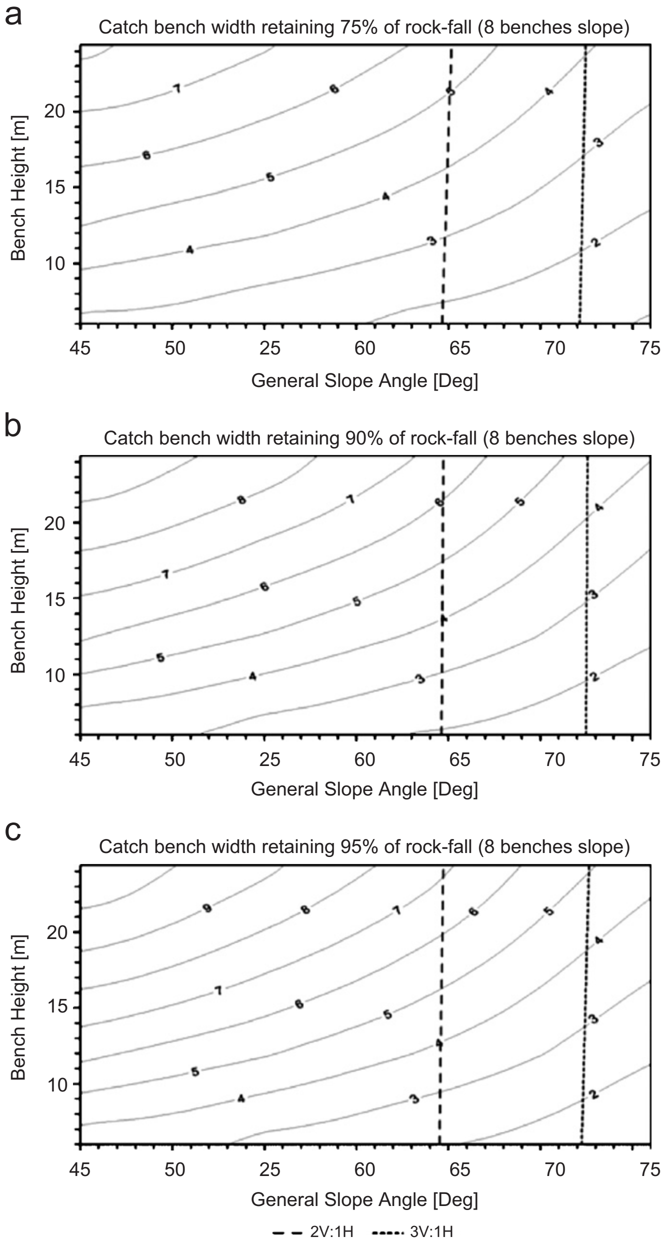


Fig. 16. Catch-bench design charts for 8-bench quarries. Results for (a) 75% (3 out of 4 rocks), (b) 90% (9 out 10 rocks) and (c) 95% (19 out of 20 rocks) retention rates.

blocks. Note that it is possible to substitute general slope angle for face gradient of the bench ($2V{:}1H$, $3V{:}1H$ or $4V{:}1H$) if this value is permitted in the corresponding chart. The initial value for catch-bench width should be increased by a value representing the average expected backbreak plus standard deviation (henceforth referred to as the backbreak correction). For design purposes and as a rough rule-of-thumb, this backbreak correction should be 0.5 m for pre-split benches, 1 m for carefully blasted good-quality rock masses, and 2 m for less carefully blasted average-quality rock masses. The outcome of the back-break correction is a final minimum catch-bench width capable of reasonably controlling quarry rockfall.

For analysis of an existing quarry, once the desired retention capacity has been established, a backbreak correction needs to be estimated from in-situ observation. The quarry is then divided into a number of slopes having roughly the same orientation, geometry and rock features. Each of these slopes is profiled in terms of number of benches, general slope angle, average bench height, and mean and minimum widths for existing catch benches. Next, the average values for bench width and general slope angle are entered in the corresponding chart (for the desired retention capacity and corresponding number of benches). The result is an initial value for catch-bench width, and, making the backbreak correction, the final catch-bench width capable of retaining the pre-determined percentage of falling blocks is obtained. If this catch-bench width is greater than the real minimum catch-bench width, then the slope is capable of retaining more than the pre-determined percentage of blocks. Should this criterion not be satisfied, the ideal catch-bench width is compared with the real mean catch-bench width. If the former width is greater than the latter width and if the dispersion of real catch-bench widths is less than 15%, then the retention capacity is close to the pre-determined value. So, even though the criterion is not strictly fulfilled, in certain circumstances, the slope geometry may be considered acceptable. The following section illustrates the application of this method using an example.

It is important to highlight that this method tests the retention capacity of slopes and not a slope's capacity for releasing blocks, which is why it is proposed for use where rockfalls have already been observed or where empirical methods indicate a certain rockfall hazard.

5. Application examples

Although the method described above is primarily intended for initial quarry design, it is also useful for analysing safety conditions in operational quarries. In this section we analyse granite and schist quarries in the light of the results described above.

5.1. *A granite aggregate quarry*

An aggregate quarry with an annual production of around 600,000 tons of crushed granite was studied. The objective of this application was to analyse whether the slopes of the quarry were adequately designed to retain most of the potential block falls. The slopes of the quarry had been monitored for several years, and although some rockfalls had been observed, no accidents had been reported. Fig. 17 illustrates backbreak, estimated at 0.65 m with a standard deviation of 0.33 m, in this quarry with 15 m high benches in hard rock.

Fig. 18 is a map of the quarry showing 6 slopes for which the geometry in terms of rockfall retention was studied. Average bench height, which was very regular, was estimated for each slope. Next, catch-bench width was

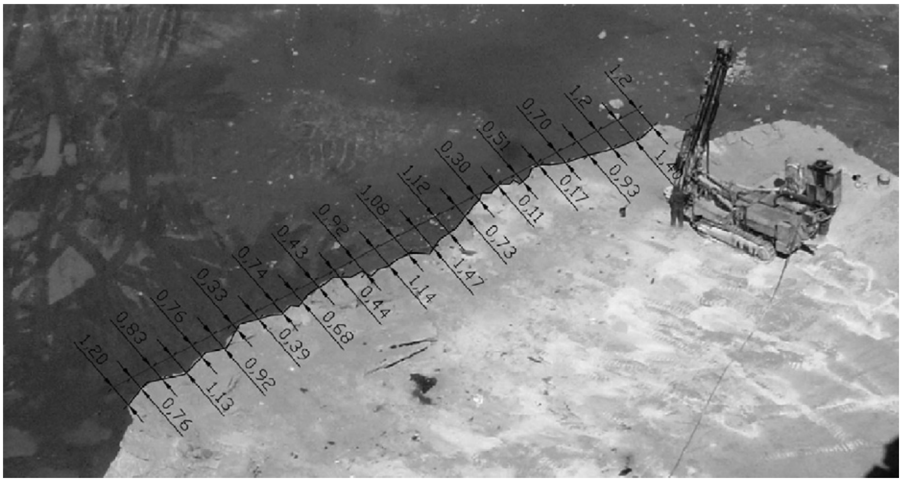


Fig. 17. View of a bench edge from one of the upper benches, which was used to graph backbreak in an aggregate quarry slope.

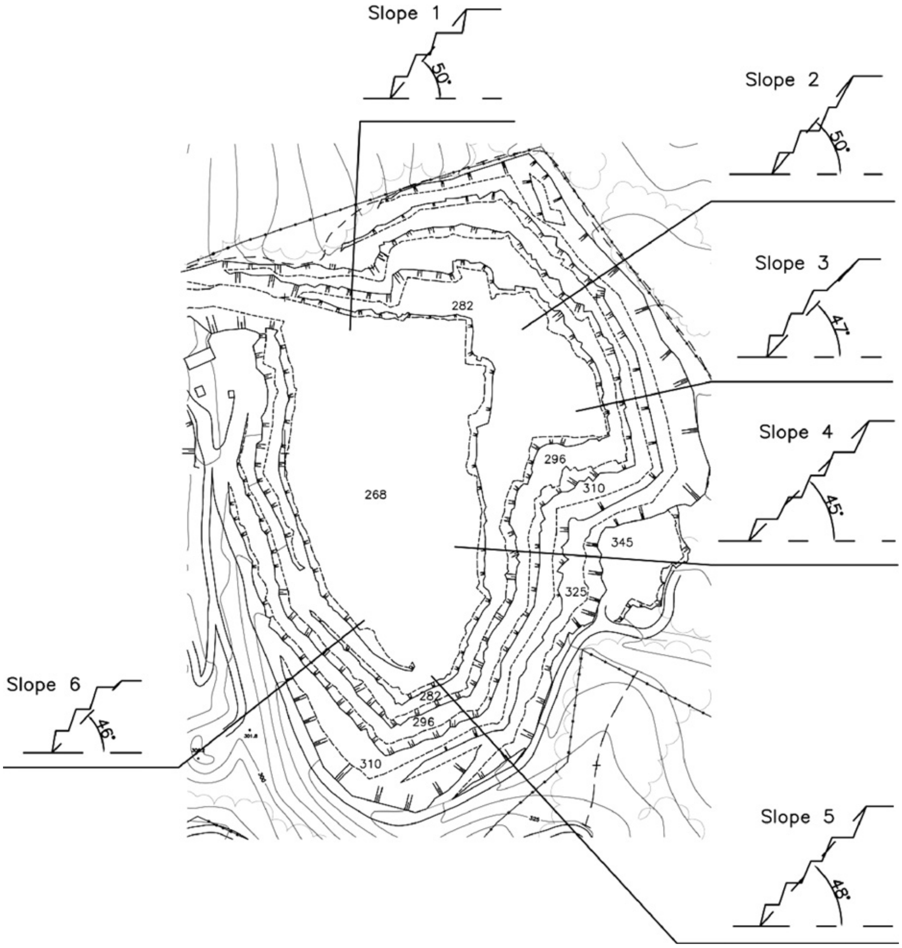
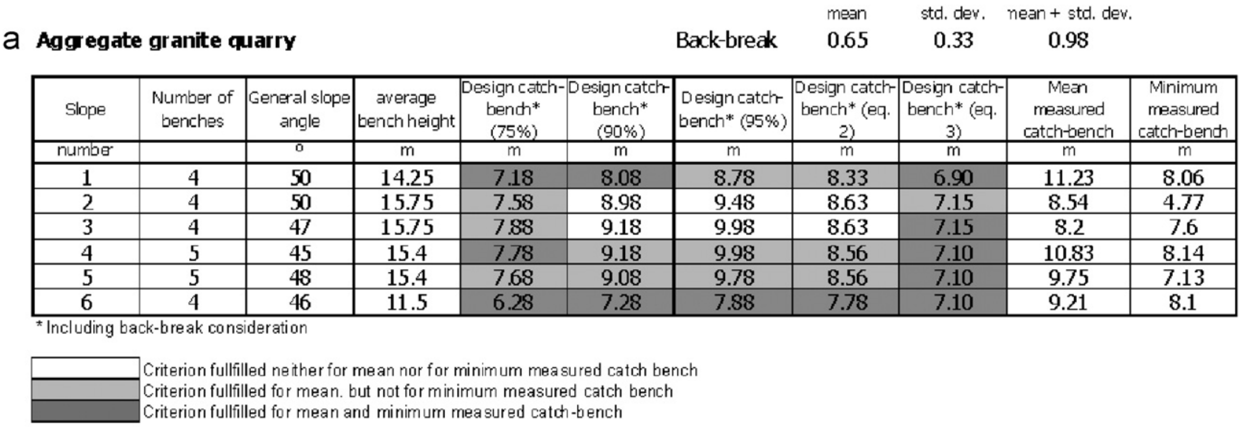


Fig. 18. Topography of the granite aggregate quarry together with six geometry-based sections and profiles for the analysed slopes.

estimated (including the correction for backbreak) for 75%, 90% and 95% rockfall retention (using the method described above). Safe catch-bench width was calculated according to Eq. (2) (Call's criterion based on Ritchie et al.) and Eq. (3) (the riskier criterion). Finally, the average and minimum real catch-bench widths—as estimated from the topographic levelling map—were measured. These data are summarised in the first table in Fig. 19, where a colour-coding system indicates the degree to which criteria were fulfilled.

Using Slope 1 of this quarry, we illustrate how to obtain the values for the tables in Fig. 19. The topography



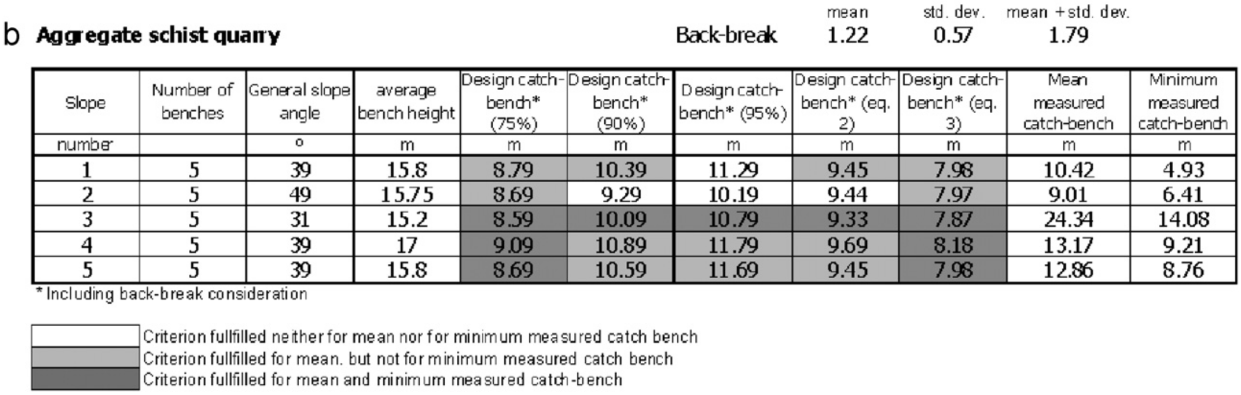
a Aggregate granite quarry

	mean	std. dev.	mean + std. dev.
Back-break	0.65	0.33	0.98

Slope	Number of benches	General slope angle	average bench height	Design catch-bench* (75%)	Design catch-bench* (90%)	Design catch-bench* (95%)	Design catch-bench* (eq. 2)	Design catch-bench* (eq. 3)	Mean measured catch-bench	Minimum measured catch-bench
number		°	m	m	m	m	m	m	m	m
1	4	50	14.25	7.18	8.08	8.78	8.33	6.90	11.23	8.06
2	4	50	15.75	7.58	8.98	9.48	8.63	7.15	8.54	4.77
3	4	47	15.75	7.88	9.18	9.98	8.63	7.15	8.2	7.6
4	5	45	15.4	7.78	9.18	9.98	8.56	7.10	10.83	8.14
5	5	48	15.4	7.68	9.08	9.78	8.56	7.10	9.75	7.13
6	4	46	11.5	6.28	7.28	7.88	7.78	7.10	9.21	8.1

* Including back-break consideration

□ Criterion fullfilled neither for mean nor for minimum measured catch bench
▨ Criterion fullfilled for mean. but not for minimum measured catch bench
■ Criterion fullfilled for mean and minimum measured catch-bench



b Aggregate schist quarry

	mean	std. dev.	mean +std. dev.
Back-break	1.22	0.57	1.79

Slope	Number of benches	General slope angle	average bench height	Design catch-bench* (75%)	Design catch-bench* (90%)	Design catch-bench* (95%)	Design catch-bench* (eq. 2)	Design catch-bench* (eq. 3)	Mean measured catch-bench	Minimum measured catch-bench
number		°	m	m	m	m	m	m	m	m
1	5	39	15.8	8.79	10.39	11.29	9.45	7.98	10.42	4.93
2	5	49	15.75	8.69	9.29	10.19	9.44	7.97	9.01	6.41
3	5	31	15.2	8.59	10.09	10.79	9.33	7.87	24.34	14.08
4	5	39	17	9.09	10.89	11.79	9.69	8.18	13.17	9.21
5	5	39	15.8	8.69	10.59	11.69	9.45	7.98	12.86	8.76

* Including back-break consideration

□ Criterion fullfilled neither for mean nor for minimum measured catch bench
▨ Criterion fullfilled for mean. but not for minimum measured catch bench
■ Criterion fullfilled for mean and minimum measured catch-bench

Fig. 19. Tables presenting calculated and estimated data for the slopes of the aggregate granite quarry (a) and aggregate schist quarry (b).

revealed that this slope had a general slope angle of 50°, an average bench height of 14.25 m, and 4 benches. To calculate preliminary catch-bench width, we entered 14.25 m as the *Y*-axis value and 50° as the *X*-axis value in the corresponding charts (Fig. 15). For 75% retention (Fig. 15a) we obtained an initial catch-bench width of 6.2 m, to which we added the backbreak correction of 0.98 m (see upper left-hand side of the table in Fig. 19a). We thus obtained a catch-bench width suitable for retaining 75% of falling blocks, i.e. a final width of 7.18 m, as shown in the table in Fig. 19a. Likewise, for 90% and 95% retentions (charts in Figs. 15b and c), initial values for catch-bench widths were calculated as 7.1 and 7.8 m, respectively. Adding in the backbreak corrections, the final values obtained were, respectively, 8.08 and 8.78 m, as shown in the upper table of Fig. 19. To obtain catch-bench widths according to both Call [9] and Ryan and Pryor [10], we applied Eqs. (2) and (3), respectively. Entering a bench height of 14.25 m in Eq. (2), an initial catch-bench width of 7.35 m was obtained. This value was backbreak-corrected in order to obtain the final value of 8.33 m that is featured in the table in Fig. 18. Likewise, Eq. (3) produced an initial value of 5.82 m, resulting in a corrected value of 6.90 m, as shown in the upper table of Fig. 19.

The first step was to select an adequate retention level. This quarry was excavated in hard rock with a rock mass rating in the 60–70 range; normally only 5 machines work in the quarry and to date no accidents have been reported. Under these circumstances, 75% retention could be considered adequate. Rockfall risk assessment techniques were applied that demonstrated a good level of safety for five of the six slopes. Slopes 1, 4 and 6 fulfilled the criteria for both mean and minimum catch-bench measurements. Slope 1 had a retention over 90% and Slope 6 had a retention of over 95%. Although Slopes 3 and 5 did not exactly fulfill the criterion for minimum catch-bench width, an offset of around half a metre was considered acceptable. Finally, Slope 2 was the only slope that could not be considered safe, because even though the criterion for mean catch-bench width was fulfilled, minimum catch-bench width was very low (4.77 m).

Fully consistent with Ryan and Prior's comments [10] is the fact that the results obtained via Eq. (2) [9] are more conservative than our results, whereas our criterion is more conservative than that represented by Eq. (3).

The application of the proposed technique to this quarry indicates that, with the exception of Slope 2, the retention capabilities of the benched slopes in the quarry are adequate. Slope 2 had long been identified as an area where local toppling took place (Fig. 20) and an area where many rockfalls were observed. Even though the benches are well designed, these rockfalls have caused the catch-benches to diminish in width, a fact which has been observed in the application of empirical methods such as

Fig. 20. Picture of a bench on Slope 2 of the aggregate quarry where toppling was recorded.

ROFRAQ. The short-term safety measure implemented in the quarry is, in fact, for miners only to work on Slope 2 during the summer, when fewer rockfalls are expected. In the medium term it is planned to remake this slope gradually from above, maintaining a general slope angle of 49°, and ensuring a minimum catch-bench width of at least 8.70 m. This operation will be carried out over several years, so as to spread the cost over several financial periods.

5.2. *A schist aggregate quarry*

An aggregate quarry producing 700,000 tons of crushed schist annually was also studied. The main aim of this application was to study the retention capabilities of the slopes in the quarry. No accidents had been reported for this quarry, and average measured backbreak was estimated at 1.22 m with a standard deviation of 0.57 m.

The relevant information is summarised in the second table in Fig. 19, which was obtained following the criteria explained in the third paragraph of Section 5.1 for a different quarry. Given the conditions in this quarry, which has relatively few machines and workers, a 75% retention rate could be considered adequate. Slope 3 fulfilled this criterion (and, as it happens, even the 95% retention criterion), for both mean and minimum catch-bench measurements. Slopes 4 and 5 fulfilled the criterion for minimum catch-bench width, and so these could also be considered safe.

Finally, although the criterion for mean catch-bench width was fulfilled for Slopes 1 and 2, minimum catch-bench width was very low in both cases, and so these slopes could not be considered safe. However, as can be observed in the 3D model in Fig. 21, neither people nor machines use the lower parts of these slopes, and most of the mine dumpers use the haulage road in the upper bench to get to the crusher. For this reason the upper benches are wider, and so, given the operational conditions of the quarry, Slopes 1 and 2 can be taken as reasonably safe. It should be pointed out, moreover, rock mechanics practice is such that site-specific considerations are crucial to the management of technical problems.

Note that regularity of catch-bench width is clearly important for both this schist quarry and the granite quarry studied above.

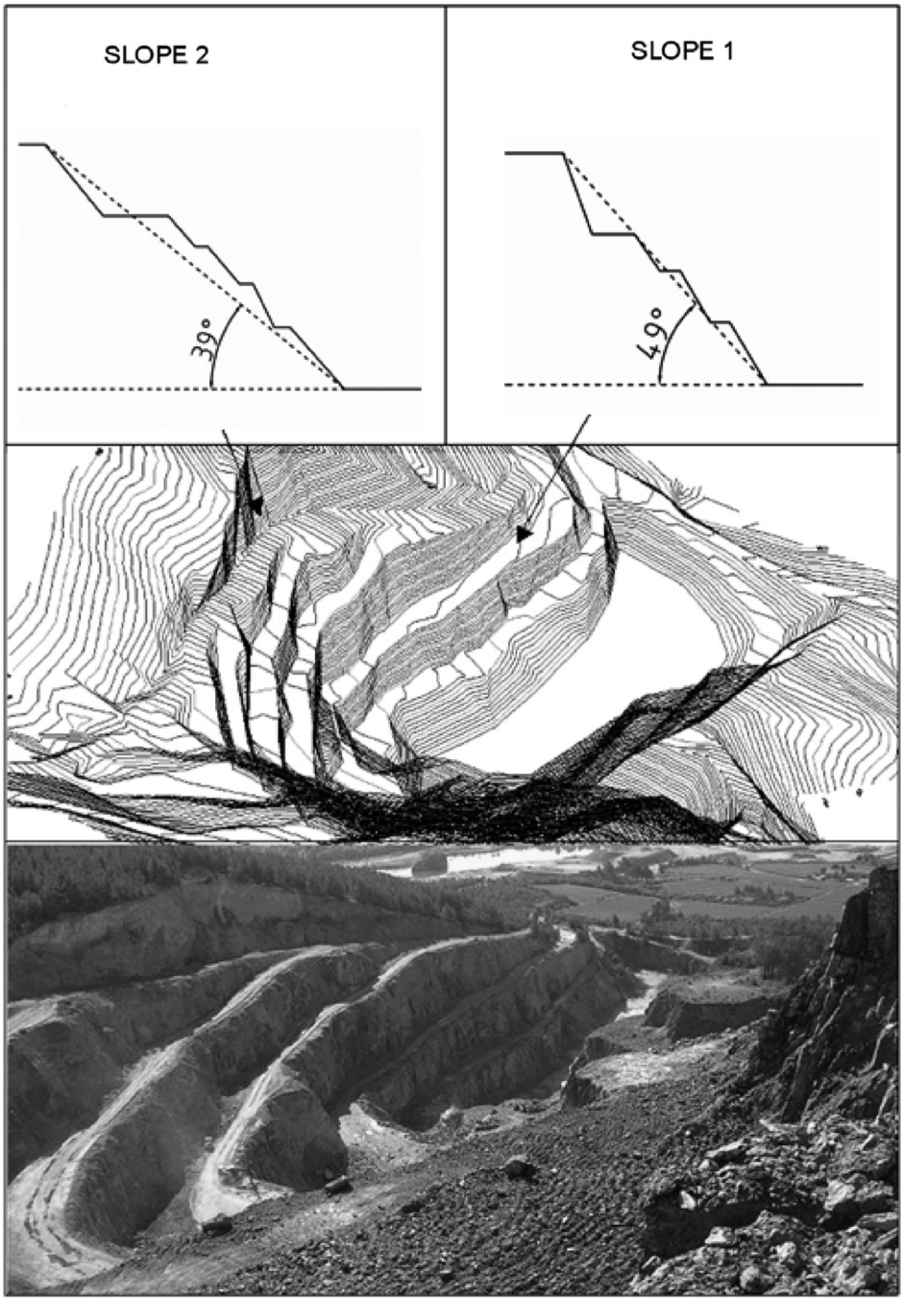


Fig. 21. Three-dimensional topography and general view of the quarry together with profiles of two of the analysed slopes.

6. Conclusions

There has been a relatively high occurrence of rockfall-related accidents in aggregate quarries in recent years in Spain. We have described a simple method—implemented in the form of charts—for establishing a safe catch-bench width. Final catch-bench design is calculated by adding, to the initial charted value, a width increase that accounts for observed backbreak.

Our method is based on a back-analysis of empirical rockfall control techniques used in the road engineering field to prevent rockfalls reaching paved road surfaces. The back-analysis was performed using a lumped-mass code capable of supporting a normal distribution of parameters. Although a facility for introducing different statistical distributions (log-normal, Weibull, etc.) would improve the results, comparison of empirical results with modelling methods based on calibrated parameters representing hard rock show a satisfactory degree of agreement.

Using these data and the RocFall code, quarry slope geometries required to ensure 75%, 90% and 95% retention rates were calculated and presented in chart form. These graphs were then used to calculate the geometries needed to control rockfalls. It was also considered appropriate to include a backbreak estimate in the design catch bench width. Observations and technical reports on quarries would indicate that the average proposed catch-bench widths are appropriate.

It must be emphasised that our method provides average catch-bench width values for well managed hard-rock quarries, to be used by quarry designers, mining companies, insurance companies and government bodies as broad guidelines for controlling rockfalls. It must be pointed out, however, that given the variable nature of rock masses, there may be cases (very hard or soft rock masses, for example) where this method may fail to produce reliable results; in such cases site-specific studies would be indicated.

The general focus of our method is justified by the fact that the quarrying sector does not generate revenues to the same degree as the metals or energy mining industries, and so it is not normal for rockfalls to be taken into account in quarry design and operation—despite the fact that rockfalls are the main cause of accidents in the quarry sector. We are of the opinion that the tool described in this research is ideal for use in the quarrying sector, particularly when combined with empirical methods for calculating rockfall risk [18,21].

Acknowledgements

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