ARMS10 10th Asian Rock Mechanics Symposium
The ISRM International Symposium for 2018 29 October to 03 November, 2018, Singapore

Rockfall mitigation measures in open pit mines. Case study quarry wall stabilisation and protection works at Mandai

R. Luis[a]* and H. Salzmann[a]

[a] *Geobrugg Group, Romanshorn, Switzerland*
* roberto.luis@geobrugg.com

Abstract

Very often the situation is presented in which the instability causes landslides of rocky blocks in areas that get in the access path of access to the orebody, which is almost impossible to stabilize. Then there is no more way out than to allow the rockfall to occur, of course, looking for possible solutions for their containment and / or reduction, as the fragments that generally fall can reach high speeds and kinetic energy, which makes the phenomenon extremely dangerous and complex to face. Mining operations are increasingly faced with achieving the operational safety ideal of zero harm, while at the same time increasing productivity. The implementation of approved mitigation measures against rockfall in opencast mines is becoming very common, due to the fast installation and cost-effectiveness of such measures. According to the guidelines for rockfall barriers, mines can rely on the approval issued by the EOTA (European Organisation for Technical Assessment). Liability insurance is issued by the suppliers, who guarantee the function of their rockfall barrier systems. In many cases the pit design can be optimized by increasing the slope inclination or reducing the berm width. The solution at Mandai Quarry located at Mandai District in the northern part of Singapore, will be presented in this paper, as a case study.

Keywords: rockfall protection, slope stabilisation, protective measures, shallow landslides

1. Introduction

1.1 Rockfall barriers

Rockfall belongs to gravitative natural hazard processes and endanger frequently human life, infra-structure and settlements. One of the last rockfall events happened some month ago at a main road from Austria to Italy at the Reschenpass causing a fatality as the car was hit (see figure 1).

Figure 1. Reschenpass B180 July 5th after rockfall event, source "meinbezirk.at".

The rockfall event was much larger than the existing rockfall barrier capacity, thus the barrier could not stop the block and it got severely damaged. It was a small rockslide with an estimated volume of around 80 m^3 according to the analysis of the geologist experts. The specialist responsible of taking protective measures face, the following problems:

- Difficulties in predicting the possible areas from which the landslides originate and the possible trajectories of the fragments.

- The dimensions of the type block, as well as the energy with which they can reach the access path or the area where they are intended to brake blocks.
- The influence that may be exerted by the material from which the own slope, on which the detachment occurs and which will obviously influence the speed trajectory of the rocks.

The efficiency and durability of the protection works in this case, as well as their economy, will depend on the correspondence and balance between the adopted design and the parameters that characterize the points mentioned above as difficulties. New methods for forecasting and analysing rockfall trajectories, intensities and bounce heights are required besides new methods to protect people from rockfall hazard. There has been an improvement in the modelling methods and also in the protection design side. The different points of improvement are described in the following sections.

1.2 Rockfall modelling

Some years ago, 2D-modelling was the state of the art method to model rockfall problems. Several different software's are available on the market, like for example Rockfall from Dr. Spang or Rofmod (Mohr 2015, Spang et al 2016). It was very important to focus on the field survey, to find the right profiles for modeling decisive sections which results in the maximum energies and bouncing heights. Ground conditions should be chosen as real as possible to be able to model inter-action between the rock and the slope while contact (Volkwein 2004). Nowadays, 3D-modelling programs have become the state of the art. One ex-ample of well-known 3D rockfall software is RAMMS rockfall from SLF/WSL -Swiss Federal Institute for Forest, Snow and Landscape Research- (Leine et al 2013).

1.3 Rockfall protection measures

Since the first rockfall guideline was developed in 2001 for flexible rockfall nets the development of rockfall barriers has been improved a lot (Gerber 2001). Since 2017 flexible protection barriers with ring nets, can reach an energy level of up to 10'000 kJ and are now on the same energy level as large protection dams.

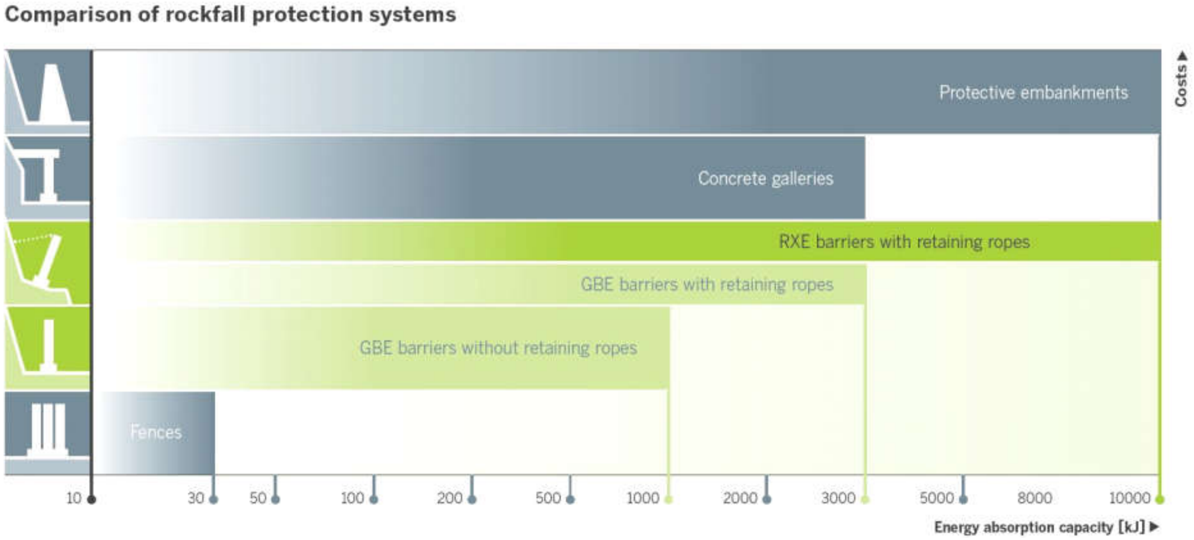

Figure 2. Overview of energy level of different rockfall protection measurements up to 10'000 kJ.

For much lower energy levels, up to max. 50 kJ rigid fences like Jersey elements or wooden timber barriers are also an option. Special applications of flexible nets like flexible rockfall galleries, drapery systems, attenuator systems and slope stabilization are also solutions that use flexible nets and meshes also often used in open pit mines.

1.4 Rockfall in open pit mines

Rockfall hazards in open-pit applications exist mainly on steep pit walls due to aggressive pit design, on flat walls without berms while following shallow-dipping orebodies, or locally on batter level. Areas with high damage potential such as decline portals or haulage ramps are especially hazardous. Dangers from falling rocks have to be reduced as much as possible. As the protection systems from Geobrugg that are described in this paper are made of highly flexible, high-tensile steel components, they can absorb energies of up to 10’000 kJ (figure 3). To obtain impact velocities and energies, the tests involve rockfall simulation utilizing actual slope characteristics.

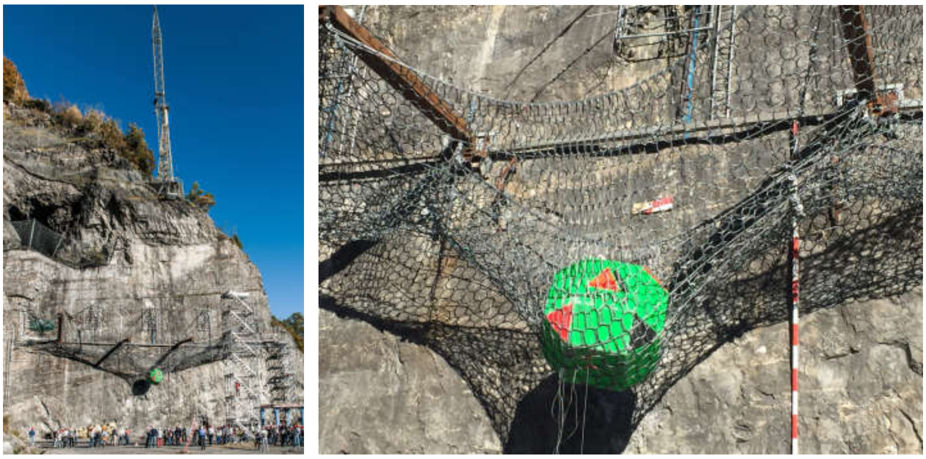

Figure 3. Vertical drop test site (42m, 25t), barrier energy 10’000kJ. Walenstadt, Switzerland.

The current GBE or RXE rockfall barriers are tested under the most rigorous conditions in vertical drop situation, according to Federal Office for Environment in Switzerland (FOEN) and the European ETAG 027 guidelines and under the scrutiny of the WSL and carry the European Technical Assessment (ETA) and the CE marking.

1.5 Rockfall barriers design

Benching in open-pit mining is a common method to protect workers and equipment in the lower part of the wall against falling rocks from higher benches. For this purpose, the berm should be of a certain width. Ritchie (1963) proposes the following rolling rock criteria for the minimal berm width A_{min} in accordance to the bench height H:

$$A_{min} = 4.5 + 0.2H \qquad [m] \qquad (1)$$

A more sophisticated possibility is to define the wall profile with rockfall simulation software like for example RAMMS (Leine et al 2013). Considering slope parameters such as cut angle, length of slope line, composition of the rocky surface, surface roughness, and expected size and shape of the blocks that might become detached, among other aspects, the expected trajectory of the falling blocks can be estimated. With these trajectory estimations, the minimal berm width can be determined. The barrier to be installed is designed based on the results of these studies, see example figure 4 in ‘El Soldado’ mine, Chile.

Figure 4. Typical open pit design (left) and field test at ‘El Soldado’ mine, Chile (right)

The design parameters for the rockfall protection system are the bench height, the bench angle, the berm width, and the system characteristics. A system can be installed on every berm, or on every second or every third berm. A necessary condition for the use of catch fences is that the stability of the benches, the berms, and the foundations of the barrier is adequate. For this reason, the collaboration of the geotechnical engineers of the mine site and the product supplier is very important.

2. Mine specific parameters

2.1 Increasing the profitability of the mining operation

Generally, an economic feasibility study is carried out prior to the development and exploitation of a new mining project. The economic feasibility will depend on the market value of the ore and its ability to be sold under the prevailing market demand conditions, versus the total cost of exploiting and beneficiating the ore. If an open-pit operation is a cost-efficient method of exploitation, the orebody is accessed by the rationally optimized removal of the overburden (Balg et al 2012).

2.2 Reducing berm with

By using catch fences on the berms, it is possible to reduce the berm width because the fences take over the tasks of the berms. By this measure the overall angle of the wall can be made steeper. It may even be possible to make the bench angle steeper. The benefit of the catch fence installation is that the amount of waste material can be reduced, thus reducing mining costs (figure 5, left).

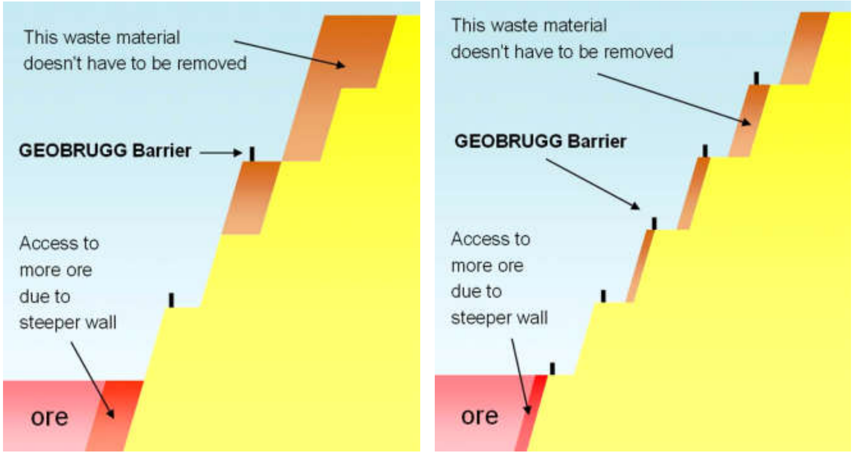

Figure 5. Reducing berm width (left) and double benching (right).

By using catch fences in existing operations, it is often possible to access more ore than without the optimized design, due to the steeper pit wall. This design is mainly applicable for benches with a height of about 30 – 40 m, where the benches can be reduced from 10 m (Ritchie, 1963) down to 6 m. It should be ensured that the barrier is at least 1.5 – 2 m away from the edge of the berm to avoid damages by blasting work for the next bench.

2.3 Double benching

Especially for benches with a height of about 15 – 20 m (like most of the open pits in Western Australia) it is favorable to increase the bench height to 30 – 40 m instead of reducing the berm width (figure 5, right). This approach has the advantage that the berms remain wide, thus more easily avoiding blasting damage. With this design, it is also possible to make the overall angle of the pit wall steeper, and thereby save mining costs. Also, it is likely that more ore will be accessible.

2.4 Omitting benches

For thin orebodies with an inclination of 40 – 50° it is more profitable to choose a pit design with rockfall barriers but without benches. Figure 6 (right) shows a 45° pit wall design with-out benches. If the angle of the orebody is steeper than the friction angle of the contact and steeper than the angle of repose, every bench developed will fail along this contact. In that case, only a design without berms but with catch fences can be considered.

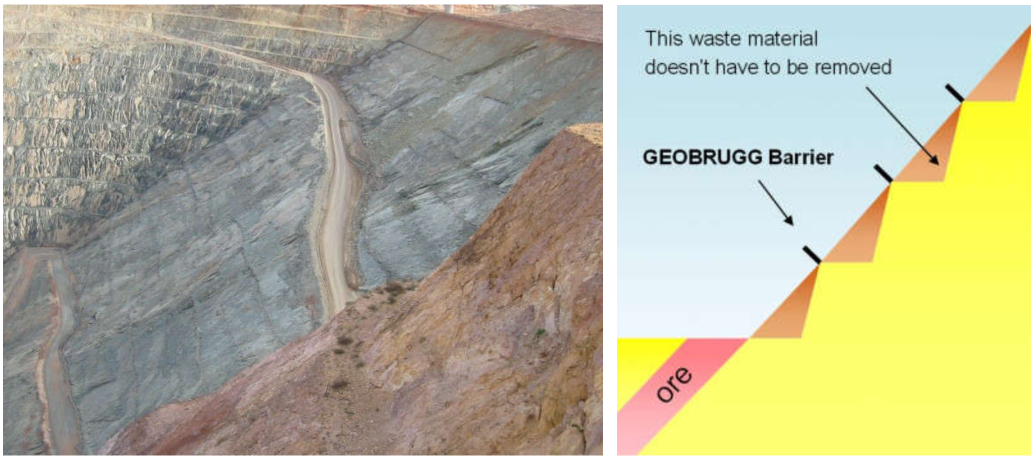

Figure 6. Pit design without benches.

2.5 Feasibility considerations

With the system costs C_{sys}, the saved mining costs C_{min} and the value of the additional ore V_{ore}, the investment condition can be defined as follows.

$$C_{sys} < C_{min} + V_{ore} \qquad (2)$$

If the costs of rockfall barriers are less than the saved mining costs and value of the additional ore, it makes economic sense to use the system.

It is even possible that a deposit that was economically marginal could become more profitable by using barriers.

3. Protection of high-risk areas

3.1 Weakening portals

Portals for underground operations are normally located at the bottom of open pits (figure 8, left). It is very important to make sure that the decline and the portal is never blocked, otherwise the whole operation will stop. For that reason, most of the portals are protected by extensive meshing of the pit wall above. Some portals are even meshed and shotcreted. However, installing a short catch fence above the portal mostly is more economical than meshing and shotcreting a large area.

Figure 8. Portal to underground operation (left) and failure in a pit wall (right).

3.2 Failures in the pit wall

In some cases, it is not possible to mesh parts of the pit wall due to poor conditions (old stops, failures, poor rock condition). Figure 8 (right) shows a failure in the wall of an open pit mine in Africa. In such situations, a rockfall protection barrier is an effective protection measure.

3.3 Protection against landslides

Figure 9 shows a situation where part of a berm less pit wall failed and caused a slide of a large amount of loose material. The figure also shows that the installed catch fences were too weak to stop the slide. Well-designed barriers are even capable of stopping large quantities of sliding rocks, as proven by field experiments (Wendeler et al 2014).

Figure 9. These catch fences are not adequate to stop a small rockslide (left) and shallow landslide barrier during test.

4. Case study. Mandai Quarry

Mandai Quarry is located at Mandai District in the northern part of Singapore. The quarry was operational for a 30 years period and produced high strength, high durability aggregates. Geologically the area belongs to the Bukit Timah Granite.

4.1 Geological Situation

The Bukit Timah Granite was formed during the Triassic period. This granite is light gray in colour and medium to coarse grained (2 to 5 mm). According to the geological study the main minerals are quartz, feldspar, biotite and hornblende. Four different weathering states of the granite are considered in the geological study: highly weathered granite, moderately weathered granite, slightly weathered granite and fresh granite. Beside the Bukit Timah Granite residual soil is the second dominant formation. The residual soil forms the overburden of the granite in wide areas whereas the thickness of this layer varies from 3.6 to 61.5 m. The residual soil is heavy sandy loam with stiff to hard properties. The clay content decreases with depth whereas the coarse grain content and strength increase with depth. No groundwater outflows from the bottom and side walls of the quarry pit were detected. After rainfalls, some water outflows following the sub-horizontal joints can be observed. Hydrogeological investigations showed that the drainage amount of the quarry pit is nearly equal to the sum of rainfall and evaporation capacity.

4.2 Design Principles

The following design principles and tools were used to dimension the rockfall barriers and the slope stabilisation systems.

4.2.1 Rockfall fences

Rockfall by Dr. Spang as rockfall simulation software. This program allows to calculate rock trajectories, bounce heights and impact energies based on a given cross section and on a so-called design boulder for specific barrier locations.

The triggering mechanisms can lead to rockfall events in the area of the quarry pit.

- natural weathering and/or rainfalls: weathering processes reduce the strength of the rock mass especially in the uppermost exposed layer and therefore lead mainly to slope surface parallel fracturing and jointing. Rainfall or precipitation affects mainly the strength of the joints. The increase in pore- and joint water pressure leads to a reduction of cohesion and friction between sound and weathered rock and is often a triggering mechanism for rockfall events. Whereas the highest rockfall potential is directly correlated to the amount of precipitation.

- earthquakes: boulders which are already in a labile balance located on the natural slope surface or at the disintegrated rock surfaces may start to move caused by ground acceleration caused through earthquake. Furthermore, boulders which are embedded in natural talus layered at its friction angle may start to roll or move downslope caused by decrease of cohesion and friction angle due to ground acceleration.
- blasting: the effect of blasting works to the nearby surface is comparable to the earthquake situation. The main differences between the two mechanisms are that the area affected by blasting is relatively small compared to the earthquake case and that the ground acceleration is predictable and can be minimized using an optimized blasting pattern and delayed ignition.
- human beings or animals: animals like monkeys can trigger smaller rocks up to 25cm which themselves can release larger boulders by direct impact and lead to powerful rockfall events.

Other failure types such as toppling, slope parallel or wedge failure leading to rockfall are not considered, since the failure type has no major influence on the final energy and bounce height of the boulder and therefore does not affect the design and dimensioning of the rockfall fences. Larger wedge failures are considered to separate into smaller rock fractions due to the downslope movement of the wedge mass and will therefore not impact into the barrier at the same time and location.

4.2.2 Slope Stabilisation system

Ruvolum software is used as design tool for the dimensioning of the slope stabilisation systems. This calculation method allows to calculate anchor grid and anchor dimensions based on a specific mesh to be used as membrane in between the anchor points. The basis for the design calculations are site specific boundary conditions such as inclination of slope, material properties, thickness of layer to be stabilised and the mesh properties. All stability calculations were carried out with partial safety factors according to Eurocode 7. The factors and the values as used are summarized on table 1.

Table 1 Slope parameters. Partial factor of safety according Eurocode 7

Geotechnical Parameters	Factor of safety	Calculation method
Cohesion (c_k)	$\gamma_c = 1.60$	$c_d = c_k / \gamma_c$
Specific weight (γ_k)	$\gamma_\gamma = 1.00$	$\gamma_d = \gamma_k / \gamma_\gamma$
Friction angle (ϕ_k)	$\gamma_\phi = 1.25$	$\phi_d = \arctan((\tan \phi_k) / \gamma_\phi)$

c_d, γ_d and ϕ_d are parameters which are reduced according to the above specified factors of safety and used for the calculations.

4.2.3 Rock Nailing

For the rock nailing, it is assumed that the boulders to be secured are presently in a labile balance (Fs 1.00). Cohesion and friction forces between the boulders and the sound rock are neglected and be a kind of hidden safety additional to the input safety factors. The nails will be carried out as fully grouted (passive anchors) and are therefore considered to be loaded with shear forces only. The factors of safety for the input parameters according to Eurocode 7 are on Table 2.

Table 2 Factors of safety according Eurocode 7

Input Parameter	Factor of safety
Bearing resistance of permanent nail	1.50
Density or Volume of boulder	1.35

4.3 Design sections

The slope sections (figures 10 to 13) which will be draped with slope stabilisation systems will be cleaned from loose material prior to the installation of the anchors and mesh or net panels. Cleaning works will be performed by hand and with handheld tools only, starting from the top. It is not foreseen to clean the slope sections down to the sound rock, big loose boulders will be nailed individually.

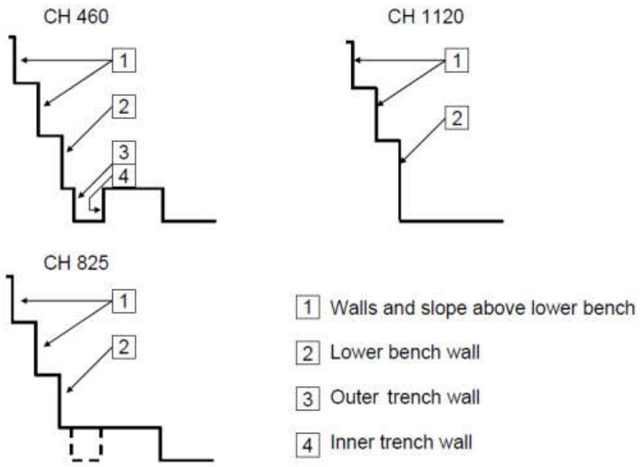

Figure 10. Design sections examples

Figure 11. Chainage 360 – 560 (left) Chainage 540 – 640 (right)

Figure 12. Chainage 590 - 850 (left) Chainage 850 – 1200 (right)

Figure 13. Inner and outer trench walls from CH 490 to CH 1100 (left) and walls + slope above lower bench from CH 1600 to CH 1650 (right)

4.3.1 Rockfall protection

The walls above the lower bench in the section between CH 290 and CH 580 show no recent failures. The rock walls are fractured and jointed due to production blasting, but no big loose portions were detected during the site investigations. The width of the existing bench with the uppermost ring road varies between 8 and 17 m. Table 3 shows the summary simulation results for the main cross sections. The yellow-reddish strips on the rock wall above the bench indicate waterflows from the natural slopes above the cut rock face and are potential sources for mud flows caused by heavy rainfalls. Generally, these mudflows will spread in width when they impact onto the bench and then flow towards the barrier. The area from CH 580 to 640 may be affected by frequent mudflows as observations over the last two years showed. The mud flow material consists mainly of the residual soil which forms the natural slopes above the rock face and embedded boulders of various sizes. The proposed barriers will also be able to stop these mudflows safely before they can affect the ring road.

Table 3 Summary result for main cross sections

Chainage (cross section)	CH 375	CH 620	CH 670	CH 775	CH 1050
Weight design boulder	11.3t	11.3t	11.3t	11.3t	11.3t
Max. impact energy	226kJ	354kJ	737kJ	317kJ	234kJ
Min. impact energy	0	41kJ	21kJ	21kJ	9kJ
Probability of impact	81%	58%	74%	82%	61%
Barrier type					
Energy	250kJ	500kJ	1500kJ	500kJ	250kJ
Total length	290m	60m	110m	100m	350m
Fence height	2m	3m	4m	3m	2m

4.3.2 Rock nailing

A big loose rock mass, completely separated from the sound rock at the wall above the lower bench at CH 760 will be individually nailed with rock nails. Due to the drilling of the boreholes for the rock nails were carried out perpendicular to the joint plane, the nails take shear forces only. The nails were passives, be fully grouted and are not foreseen to be pre-tensioned. In CH 780 to CH 805, since the width of the bench is reduced by the trenching works to less than 3 m the rockfall barrier will located close to the toe of the slope to stop bouncing boulders originating from the wall above the lower bench.

4.3.3 Slope stabilization

The slopes forming the lower bench wall in the area between CH 700 and CH 1200 are old rock faces which remain from the quarry production. For this reason, they contain a considerable number of loose boulders and gravel. In general, these slopes show no failures caused by overall stability problems. The input parameters as used for the dimensioning of the slope stabilisation systems are therefore the same as used for a part of the trench walls (table 4). For the uppermost section of the walls between CH 900 and CH 1000 the cohesion value is neglected since the slope comprises of very loose and disintegrated material. The cohesion for the loose rock in this section is also neglected, due to these walls were not excavated by contour blasting and were exposed to natural weathering for approx. 30 years. Therefore, it is considered that due to the slope parallel stress release the cohesion along existing joints and fractures is neglectable.

Table 4 Summary of input parameters and results for slope stabilisation

Type of rock	Friction angle [º]	Cohesion [kN/m²]	Density [kN/m³]	Slope [º]	Nail distance [m]	Nail type
Loose rock (t = 0.75 m)	56.3	0	27.0	75	3.20	GEWI 32
	56.3	0	27.0	80	2.95	GEWI 32
	56.3	0	27.0	85	2.75	GEWI 32
Loose material (t = 1.00 m)	56.3	0	27.0	55	3.05	GEWI 32
	56.3	0	27.0	60	2.85	GEWI 32

The solution it’s drapery with mesh type Tecco® G65 mesh in combination with rock nailing. Nailing grid according to table 4 depending on the face conditions. Nail lengths 3m for loose rock and 4m for loose material.

The inner and outer trench walls comprise of fresh excavated Bukit Timah granite. The use of contour blasting technique should reduce the fracturing and disintegration of the excavated walls to a minimum. Although this technique should be used along the entire stretch of the trench walls there are big changes in rock surface quality. Since only a small part of the trench is excavated up to date, it is assumed that three different rock conditions must be considered for the design of the slope stabilisation systems, table 5.

- Intact rock, the excavated surface is clean and stable and the drill holes are still visible on the rock face.
- Loose rock, the trench wall comprises of jointed and fractured rock, but the boreholes are still visible on a part of the surface.
- Shear zone, where the rock surface is heavily fractured and jointed and no or only very few boreholes are visible after the excavation.

Table 5 Summary of input parameters and results for slope stabilisation

Type of rock	Friction angle [º]	Cohesion [kN/m²]	Density [kN/m³]	Slope [º]	Nail distance [m]	Nail type
Intact rock (t = 0.5 m)	59.0	2.0	27.0	80	3.50	GEWI 32
	59.0	2.0	27.0	85	3.20	GEWI 32
	59.0	2.0	27.0	90	2.95	GEWI 32
Loose rock (t = 0.6 m)	56.3	1.6	27.0	80	3.15	GEWI 32
	56.3	1.6	27.0	85	2.90	GEWI 32
	56.3	1.6	27.0	90	2.75	GEWI 32
Shear zone (t = 0.75 m)	56.3	0	27.0	80	2.95	GEWI 32
	56.3	0	27.0	85	2.75	GEWI 32

The solution it’s drapery with mesh type Tecco® G65 in combination with rock nailing. Nailing grid according to table 4 depending on the face conditions. Nail lengths 2m for intact rock, 3m for loose rock and 4m for the shear zone.

The rock wall above the entrance to the explosive deposit will be secured by means of a drapery with wire rope net panels for the loose sections located directly above the entrance gate and by rock nailing for the wedge-shaped rock body and for the loose boulders close to the crest of the wall.

4.4 Construction process

In the following figures 14 and 15, a couple of points of the sequence of execution of the barriers are shown, first the collation of the posts and then the final closure with the Rocco® ring net.

Figure 14. Top view of the barriers during installation

Figure 15. Lateral and bottom view of the barriers once installed

As complement to the rockfall barriers, slope stabilization systems composed of Tecco® G65 mesh anchored with 32mm variable length variable, were installed. Below, it is observed how efficient the operation of this system has been (figure 16).

Figure 16. Tecco® stabilization system containing large blocks

Due to torrential rains in 2006 some blocks fall down the cliff accompanied by shallow landslides were duly intercepted by the previously installed rockfall fences, see bellow some photos (figure 17) that describe the type of impact.

Figure 17. Barrier subjected to combination loads, detachment of single blocks and shallow landslides with granular material.

5. Conclusion

The capacity of rockfall protection systems has evolved together with design and 3D simulation methodologies, only a few days ago, the Geobrugg rockfall fences have exceeded the 10MJ threshold, are undoubtedly the best alternative to the protective embankments. In the open pit design process, the reduction of the width of berms from the use of rockfall fences, is a useful, safe and very efficient practice that allows the increase in productivity, while the double berm combined with barriers is efficient against blast damage, additionally it is upright to note that in many cases it is more profitable, design the slopes using rockfall barriers without berms. The cost of the barriers location is much lower with respect to the benefit obtained in the production process and access to additional material ore. The practice of recent years has shown that rockfall barriers also work efficiently in areas of potential high-risk. In the case study of Mandai Quarry the combined solution, corroborates that the use of rockfall barriers and drapes, together with slope stabilization systems, allows a very efficient growth, into the safety factor, during the mining exploitation. In this paper, it was shown that high-tensile steel components are a suitable option to help to solve rockfall problems in open pit mines. In this application, a proper field test and component test is required to end up in a final designed and developed protection measure.

Acknowledgements

The authors appreciate the kind collaboration of the organizing committee for the presentation of this written contribution.

References

Balg, C., Sims, G. and Schoevaerts B. (2012). Rockfall mitigation and slope stabilization measures in Opencast MINES. SHIRMS 2012.

Ritchie, A. M. (1963). Evaluation of rockfall and its control. Washington State Highway Commission, Highway Research Record, United States, Vol. 17, pp. 13-28.

Gerber, W. 2001. Guideline for the approval of rockfall protection kids, Swiss agency for environment, forest and landscape SAEFL and WSL, Switzerland.

Leine, R.; Schweizer, A.; Christen, M.; Glover, J.; Bartelt, P. & Gerber, W. 2013. Simulation of rockfall trajectories with consideration of rock shape. Multibody System Dynamics, 1-31.

Mohr, H. 2015. Geologischer Bericht Sturzmodellierung Mit ROFMOD4.2, Büro für Technische Geologie AG, Schweiz.

Spang, C. 2017. Optimized rockfall protection by 'rockfall'. Rockfall simulation Software.

Teen, A. and Salzmann, H. (2001) Quarry wall stabilisation and protection works at Mandai. Project design report.

Volkwein, A., (2004) Numerical simulation of flexible rockfall protection systems. Dissertation PhD, ETH, Zurich, Switzerland.

Wendeler, C., Glover J. (2014) Multiple load case on flexible shallow landslide barriers – mudslide and rockfall, IAEG Turin, Italy.