Journal of Rock Mechanics and Geotechnical Engineering 14 (2022) 67–81

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.jrmge.cn

Full Length Article

An operational approach to ground control in deep mines

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ARTICLE INFO

Article history:
Received 3 January 2021
Received in revised form
6 April 2021
Accepted 9 May 2021
Available online 14 August 2021

Keywords:
Ground control
Rock support
Deformation-based support design (DBSD)
Gabion panel
Deep mining
Support consumption
Preventive support maintenance (PSM)
Asset management

ABSTRACT

As mines go deeper and get larger, mine designs become more fragile largely due to the response of the rock mass to mining. Ground control and rock support become important levers in the mine construction schedule, production performance, and excavation health. For example, in cave mines, the production footprint together with associated mine infrastructure are significant investments in a modern caving operation. This investment must be protected and maintained to reduce the risk of ground-related production disruptions. It is necessary to preserve the health of these excavations and their maintenance through an effective rock support design. Rock support thus becomes a strategic element in asset management. This article focuses on support design for brittle ground when displacements induced by stress-fracturing consume much of the support's capacity. It deals with the functionality of the support in deforming ground. Several interlinked concepts are important when assessing excavation health. Designs must not only account for load equilibrium but also for deformation compatibility and capacity consumption. Most importantly, the support's displacement capacity is being consumed when the rock mass is deformed after support installation. Hence, it is necessary to design for the support capacity remaining at the time when the support is needed. If support capacity can be consumed, it can also be restored by means of preventive support maintenance (PSM). This concept for cost-effective ground control is introduced and illustrated on operational evidence. Furthermore, how design can impact construction costs and schedule are discussed. Support is installed to provide a safe environment and preserve an operationally functional excavation. It also must assure senior management that investments in high quality support and its maintenance will substantially reduce delays and with it, costs. It is demonstrated that the use of 'gabion-like' support systems can achieve these goals. A technical summary of the 'gabion panel' support system design is presented.

1. Introduction

Projections for copper demand suggest an increase of up to 350% by 2050 at which time the demand will exceed reserves (Elshkaki et al., 2016). The lack of new discoveries means that lower grade deposits at depth will be mined. The industry is thus faced with developing underground mines at higher production rates and greater depths. This will bring a new set of challenges in delivering a safe and productive environment.

At depth, excavations become more vulnerable to mining-induced stress and deformation changes that affect the load and displacement demands on the support. In rockburst-prone mines, dynamic loading of the rock near an excavation adds an energy demand. The outcome of these increased demands is that the production system is more fragile with higher safety risks and a higher potential for mine construction and production delays due to damage and rehabilitation unless the excavations are well-maintained during their operating life. A robust design must consider the functionality of the excavation, aspects of constructability, exposure of personnel, long-term behaviour of the rock mass containing the excavation, construction and maintenance schedules, and costs.

Excavations in underground mines such as crusher chambers, stopes, and drawpoints are major assets due to the level of investment in their constructions and duties in the mining cycle. As

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2021.05.008
1674-7755

major assets, these excavations must be designed with safety and functionality in mind. This task becomes more challenging at depth. Furthermore, with increased production rates, the consequences of inappropriate design, construction, and a lack of subsequent excavation maintenance can be highly disruptive and costly.

In the authors' opinion, support design approaches with an over-reliance on rock mass classification systems are no longer providing robust mine designs for the mining industry. These rock mass classification systems are useful to characterise the rock mass but not to arrive at efficient and effective support systems. The impact of mining-induced deformations on rock support performance must be considered when designing excavations in highly stressed ground, whether failing in a brittle manner or by squeezing. This can be achieved by following the deformation-based support selection approach introduced by Kaiser (2014). This approach, which is based on the concept of forming gabions of retained rock fragments to preserve the integrity of the surrounding rock mass, respects that support capacity is being consumed during mining and can be restored by timely and scheduled preventive support maintenance (PSM). The gabion concept is applicable for conditions where the excavation skin is stress-fractured or expected to stress-fracture during a rockburst.

2. Operational considerations

2.1. Overview

Industry forecasts indicate that a substantial portion of the future base metal supply will come from underground bulk mining with much of the investment trending toward caving. Though mining at depth is not new, for example deep gold mining in South Africa and nickel mining in Canada, the new caving operations are not only deep but impact large volumes of rock. For example, Freeport's DMLZ (Deep Mill Level Zone of PT Freeport Indonesia) cave is 1300–1700 m deep, and its Grasberg mine is 300 m below a 1200 m deep open pit, Newcrest's Cadia mine is some 1400 m below surface, and Rio Tinto's Resolution project is examining the feasibility of a 2000 m deep cave.

The subsequent discussion focuses on caving, because rock support has a greater effect on successful outcomes than that for other mining methods. This is due to the impact of support installation on schedule, and thus on the time to first ore (time value of money), followed by the ability of the support to deal with caving-induced deformations that arise during major stages of development, i.e. cave establishment, initiation, propagation, and breakthrough.

The installation of rock support in the development cycle can account for up to 50% of development costs and for between 30% and 50% of the development schedule while inadequate support in key development can result in damage and costly production interruptions (due to revenue losses). Rock support is a critical element in underground operations. The intent of support is to provide safe and functional excavations, given support comes with cost and schedule impacts.

2.2. Caving experience and lessons learned

2.2.1. Experience

In a caving operation (as in any underground mine), there are two broad types of excavation, those that are part of the mine infrastructure and those that are part of the production process. Mine infrastructure excavations typically need to function for the life of the mine. Production excavations have shorter lives, often being consumed by the production itself.

The two excavation types experience different demands over their operating life enduring different operational consequences to these demands. The most significant consequence, damage, occurs more frequently on the production footprint compared to that on the mine infrastructure. Footprint damage is often treated as an operational hazard while damage to infrastructure excavations can result in costly repairs and production interruptions. It is anticipated that the likelihood of damage will increase with greater depths of operation and higher production lifts.

Fig. 1 provides an example from an operating cave, showing the change in the percentage of temporary drawpoint closures for repair against the height of draw. Four stages are highlighted. The first is repairs that occur early in the life of a drawpoint, in part due to the support systems not functioning at design capacity and in part due to unfavourable construction practices. The second involves repairs arising from a mixture of damage due to secondary breaking, equipment interactions, and from cave induced deformations consuming installed support capacity. A reduction in repairs generally is observed during the third stage as non-performing drawpoints are closed. A substantial increase in repairs eventually occurs with higher heights of draw in the fourth stage. This is associated with increased cave-induced deformations resulting from higher cave loads, production pressures, and draw practices. Investigation into the causes of the damage revealed a skin of damaged rock in the walls of the production footprint varying in the thickness from less than 200 mm to over 1 m. It was evident from drilling the damaged skin that the rock had failed in a brittle manner and had bulked into the excavation.

Experience at other operations have shown similar behaviours, suggesting that single pass support systems may not be tenable for deep high-lift caves. And that repairing damaged ground was time-consuming, costly, and hazardous. A loss of support capacity was observed as the undercut advanced over the extraction level development which combined with the change in support demands that occur as caving initiated and propagated, consumed support capacity. If the design capacity is not maintained, the support system can fail and excavation damage ensues leading to repairs and production interruptions.

Industry experience indicates that damage repair costs for the production footprints are typically 2–2.5 times the original development cost. This compares to about one quarter to half of the original development cost, if conducted as part of a preventative rock support maintenance program. Repair costs in infrastructure with fixed machinery (e.g. crushers and conveyors) can be

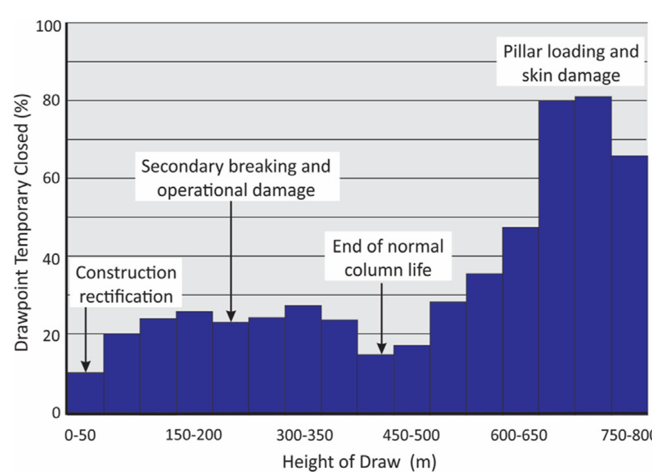


Fig. 1. Example of percentage of temporary drawpoints closed for repair and upgrade of support as a function of height of draw.

considerable, due to the size of excavation and difficulties in gaining access around fixed equipment. The temporary shutdown of critical facilities to carry out repairs can be lengthy, substantially impacting production.

The time to repair in active production areas can be a multiple of 4–5 times longer than that during the original development. By way of example, one caving operation typically develop the extraction headings at speed of 70 m/month, but rehabilitation speed in production areas is typically only 15 m/month (about 20% of the original rate), due to interference, congestion, short rounds, and ventilation constraints.

Repair times in non-active production areas can be around 1–3 times longer than that taken for original development. There are occasions when a drift can be repaired at the same speed as a new development drift, but more typically the excavation, support, and muck removal slow the process down by at least 50% and repairs take longer to implement than that taken to drive the original development. Repair of infrastructure with fixed plant installed (e.g. crusher in crusher station) is assessed on a case-by-case basis, but considerable time should be allocated. Carrying out a PSM program, whereby additional support components are installed to restore some of the capacity consumed by mining-induced deformations, will result in some disruption but can be proactively scheduled around planned maintenance of fixed equipment.

2.2.2. Lessons learned

(1) Construction

How excavations are constructed is critical. Constructability must be integrated into the design and implemented rigorously to provide development efficiency and ultimately operational effectiveness. Trade-offs in construction schedule and operational reliability must be made based on sound engineering principles, including support design. Project schedules are too often driven by ineffective construction practices. Short cuts are taken to achieve efficiencies that satisfy (unrealistic) schedules comprising the long-term effectiveness of the installed support and ultimately the 'health' of the asset. For example, good drill and blast control is required to reduce overbreak and to provide a reasonable regime for support placement. This will also increase trucking costs due to haul away overbreak. Shotcrete consumption increases with overbreak and it becomes increasingly difficult to develop an effective areal support.

(2) Timing

The timing when a support is installed is important. Work by Yazici and Kaiser (1992) and Hutchinson and Diederichs (1996) demonstrated that the holding capacity of unplated cable bolts can be lost during stress relaxation, resulting in cable bolts failing at loads well below their design capacity. In caving, there are major reductions in stress as the undercut is advanced over the extraction level development. This can lead to changes of the capacity of the installed support or to excessive loading of bolts or cables at the plate.

Support installed in footprint and infrastructure excavations are subjected to load changes and seismicity. These subject the excavation walls and the installed support to deformation, reducing the system's load, displacement, and energy dissipation capacity, and thus increase the vulnerability of the excavation to seismic hazards. Schedule pressures typically require a support (primary and secondary) to be installed prior to the ground experiencing deformation and relaxation. The associated loss of support capacity, again in terms of load, displacement, and energy, is rarely accounted for in the design and this leads to an increase in repairs during cave establishment (refer to Fig. 1).

(3) Knowledge

It is imperative to understand the way the ground responds to development and subsequent mining. For this purpose, accumulation of geotechnical knowledge to reduce uncertainty is vital. The amount of bulking that can occur during development and mine (cave) establishment must be closely measured, and the support adjusted accordingly. This highlights the imperative of comprehensive displacement or convergence monitoring to establish deformation rates and the depth of bulked ground.

(4) Monitoring

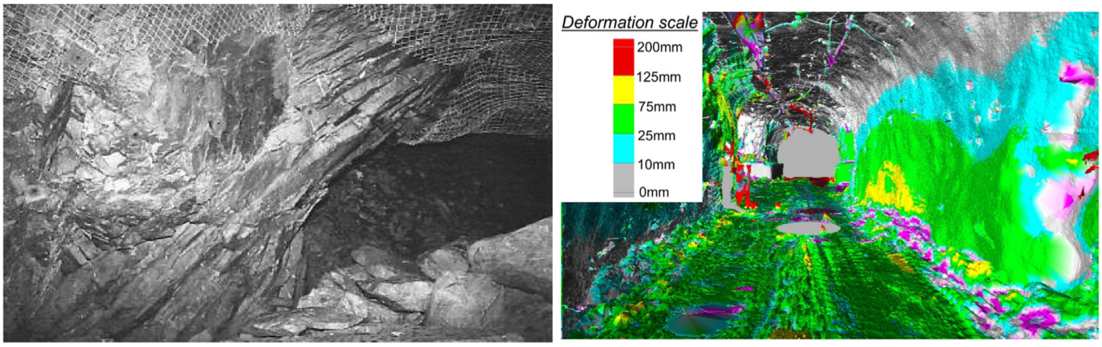
More attention to measurement of ground performance is required. With rapid advances in monitoring technology, particularly strain and displacement monitoring, new opportunities arise for safety and economic improvements in ground control. In open pits, advances in radar, LiDAR and photogrammetry technologies have already revolutionised slope design by a seamless integration of displacement data with design and performance assessments. Emerging displacement monitoring technologies for digital convergence monitoring in underground construction and mining (e.g. Fig. 2b) offer many opportunities to utilise displacements for design verification and optimisation, safety assessment, and scheduling of PSM. For example, Counter (2019) presented examples of "laser-based scanning to manage geotechnical risk in deep mining" for a mine experiencing repeated seismicity affecting rock support in domains of "significant deformation associated with mining at extreme depth". As with all new approaches, operational experience is required to take full advantage of the information that scanning provides. The scan is an excellent indicator of support consumption but must be analysed with other information (e.g. seismicity data) to obtain a good appreciation of rock mass behaviour.

The combination of new monitoring methods and deformation-based design provides opportunities for improved management of excavations in stressed and poor ground, and in tunnels when large deformations are induced by static mining-induced loading and during dynamic loading by blasts or rockbursts.

(5) Production governance

The final checks on the overall process of mitigating or managing ground related production interruptions come from good controls. Their importance lies not so much on the direct actions that must be undertaken regarding seismicity and excavation damage, but in formalised checklists, response plans, operating rules, and practices that provide a framework for design and management.

The hierarchy of key governing processes is illustrated by Fig. 3, with the foundation being the standard operating practices (SOPs), triggered action response plans (TARPs) and performance metrics that management uses to implement and control production. At the top of the pyramid is the policy set by the corporation. This specifies key business objectives and implicitly states the risk tolerance of the business. Underpinning the policy are 'Standards and Guidance' for the implementation of the standards, lessons and best practices, operating rules, and the various operating plans. Assurance then provides the link between the policy, standards, plans, and the reality of the operations (SOPs, TARPs, and metrics). The 'assurance' element provides senior management with an indication of how well an operation is implemented and complying with the plan, and whether the plan is in fact realistic and achievable.



(a) (b)

Fig. 2. (a) Stress-fractured ground with spalls driven from stress raisers in corner of excavation, and (b) displacement survey of sufficient accuracy for support performance assessment and for deployment of PSM.

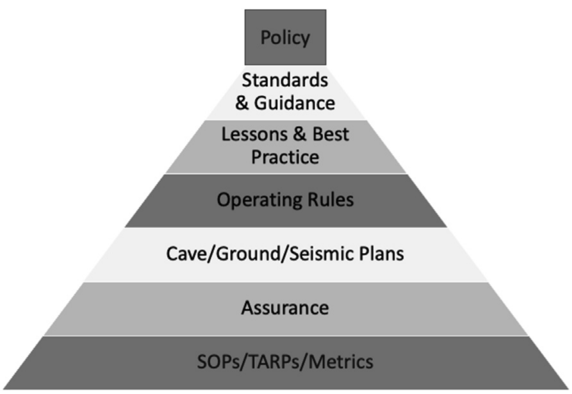


Fig. 3. Production governance hierarchy.

(6) Asset management

As mentioned in Section 1, the production footprint and the excavations associated with mine infrastructure are the significant investments in a modern caving operation, far greater than that in fixed and mobile equipment. These investments must be maintained to reduce the risk of ground related production interruptions. Standard measures used in asset management, such as availability, utilisation, mean time to repair need be used to establish excavation performance over time and to achieve the operational efficiencies required for reliable production.

(7) Excavation health, vulnerability, and fragility

Two interlinked concepts are important when assessing the health of any excavation. These are vulnerability and fragility. Vulnerability describes the state of exposure to the possibility of being physically damaged. Strictly speaking, it is the probability of damage without the consideration of the severity of the resulting damage. Fragility is described as the irreversible loss of functionality when a system encounters disorder. Fragility implies that there is more to lose than gain, i.e. more downside than upside. Options reduce the fragility of a system. Conversely a lack of options makes a system more fragile (Flyvbjerg, 2017). It is an indicator of how easily a structure can be broken (antonym: robustness) and damaged at a given damage level. For example, vulnerable excavations are more likely to suffer damage, but fragile excavations will suffer more damage than robust and well-supported excavations. Conditions leading to severe excavation damage, e.g. support damage classes R4 and R5 (Heal et al., 2006) involving multi-tonne failures are disruptive and can have detrimental impacts on the viability of a mining project.

Brittle rock masses become increasingly vulnerable to damage as induced stress levels increase. Once a critical load and deformation stage is reached, damage ensues. The transformation from a 'massive' to a 'damaged' rock mass is irreversible, fundamentally changing the excavation behaviour and support requirements. It is this fragility and the associated failure processes of brittle failure and bulking ground that drive the need for the deformation-based design approach described in Section 4. For example, the condition of the walls of an excavation is a function of applied stress and intact strength (i.e. the intensity of jointing tends to decay with depth, thus intact rock strength can become the key measure of rock quality). It is suggested that operationally an excavation moves from robust to fragile condition at the onset of moderate spalling and bulking. The increased bulking associated with spalling increases the demands on the installed support, resulting in an increasingly fragile system.

There are several steps in assessing the fragility and vulnerability of excavations. The first is to recognise where and when conditions exist for brittle rock failure and that for fragility. This depends, amongst other factors, on the depth, rock mass characteristics, and mine sequencing. Once brittle failure occurs, the objective is to manage the skin of damaged rock around an excavation to provide a safe and functional excavation by maintaining the support's load and displacement capacities, thereby limiting damage and lengthy production interruptions that ensue if repairs are required.

Assessments must be carried out at regular intervals or when specified targets described in TARPs are exceeded. It is imperative to establish the critical conditions or changes in conditions of excavations as mining progresses. This is done by measuring deformations and observing damage that the excavation or installed support experiences. The time between assessments depends on the criticality of the excavation to production. For example, there may be a need to increase the support intensity to retain overall reliability of the extraction level and the ore flow system because they are key to maintaining production. The vulnerability will change with time in response to changes in stress conditions and to the support consumption associated with this change.

An iterative process is followed (see Fig. 4) where the deformation is monitored to assess the response of the installed support to changing mining-induced demands and whether significant support capacity consumption has occurred. This allows the vulnerability of the excavation to be assessed based on the ratio of tangential stress near the excavation to the rock mass strength, the

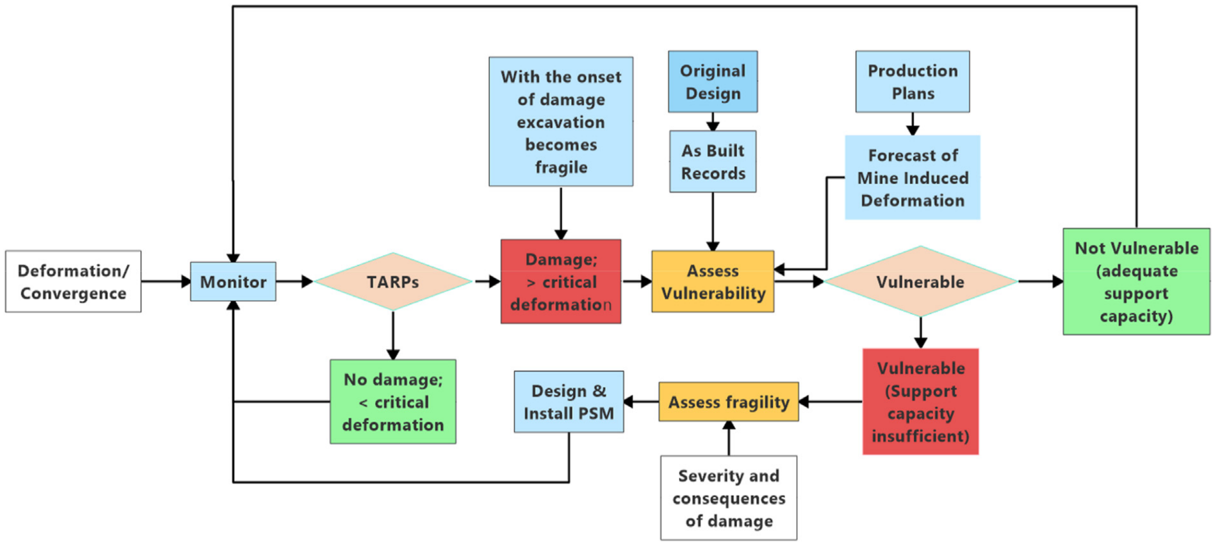


Fig. 4. Ground control process map.

energy stored near the excavation and the effectiveness of the installed support (Kaiser and Cai, 2021).

Several key factors must be considered when following the process map illustrated by Fig. 4:

(i) Damage in a brittle rock mass typically manifests itself as a skin of stress-fractured, bulking rock adjacent to the wall or backs of an excavation (e.g. Fig. 2a).
(ii) Brittle rock failure is irreversible but can be managed by installing support to create gabion panels of well-retained, reinforced fractured rock once the rock mass strength has been exceeded and the broken rock highly strained. In a nutshell, the 'gabion panel' concept implies that a deformable self-supporting rock wall or arch has to be created to behave like gabions of broken rock.
(iii) These gabion panels act as an integrated support unit that enhances the self-supporting capacity of the rock mass.
(iv) Mining-induced stress can increase the demands on the gabion panels and consume support capacity.
(v) When the support system is heavily deformed, it must be maintained by installing additional support to ensure that load and displacement capacities are retained or restored and the likelihood for further rock mass bulking is reduced.

(8) New design processes are required for mining at depth in brittle rock masses

New approaches for support design are required to handle mining-induced deformations that occur at depth in generally hard, brittle rock masses. This requires a move from support for preventing joint-controlled failure to support that can meet the demands of brittle rock failure where stress-fracturing results in a damaged 'skin' of ground near the excavation that must be stabilised. A sound understanding of the rock mass characteristics, including stress-fracturing and geometric bulking that dominates the deformations in the 'skin' surrounding the excavation (see Fig. 2a), is of critical importance.

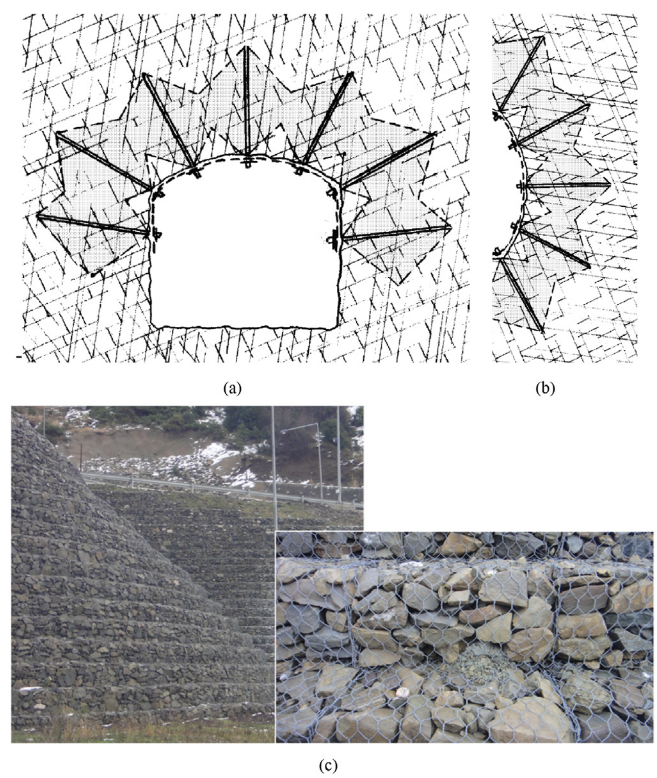


Fig. 5. (a) Supported rock arch principle Hoek et al., (1995), (b) representation of self-supporting wall 'arch' or 'gabion panel', and (c) slope support using gabions of broken rock (photos: Courtesy M. Diederichs).

3. Role of support in highly stressed ground – gabion concept

In moderately to highly stressed ground, bulking mechanisms in hard rock and dilation of squeezing ground impose large displacements on the support, and these displacements consume some or most of the capacity of a support system before the support is critically loaded, i.e. before dominant critical load, displacement, or energy demands are imposed. Furthermore, support design must focus on excavation skin management. For this purpose, effective areal support is used for rock retention, and for displacement control, displacement compatibility of the integrated support system and maintenance of this compatibility is essential. Hence, deformation-based support design (DBSD) principles must be applied and satisfied over the life of a support system, i.e. when loaded and deformed during static and dynamic mining-induced stress changes.

3.1. Creation of self-supporting arches or wall panels

The primary role of rock support is to establish self-supporting stable arches (Lang, 1961; Hoek et al., 1995, Fig. 5a) that restrict deformations. The challenge in highly stressed ground is to establish deformable self-supporting arches in the backs and walls (see Fig. 5b) that function like gabions and are able to deform with the surrounding ground. This is best achieved by the creation of gabion-like panels of well-retained blocky or fragmented rock (see Fig. 5c).

3.2. Key characteristics of 'gabion panels'

This 'gabion panel' concept works as an integrated system consisting of a robust surface support to facilitate optimal utilisation of the rock mass reinforcement capacity. Its performance depends on whether it is loaded by tangential wall rock straining between back and floor (or between the walls), or laterally loaded by a sudden bulking during a strainburst inside or behind the gabion (i.e. in the reverse direction of the arrows in Fig. 6).

The key elements of strong deformable support panels are highlighted in Fig. 7. A 'gabion panel' connects the robust retention system (or areal support) to a dense reinforcement pattern of full column grouted bolts to form a stack of 'gabions' and ties them back to stable ground by preferably ductile tendons (cable bolts; red in Fig. 6). In stress-fractured ground, debonding may not be required to achieve sufficient ductility due to an auto-debonding process of grouted plain cables that occurs in the relaxed damaged skin. The role and functions of the support are thus to control large deformations by.

(1) Reinforcing the damaged skin to reduce the effects of bulking;
(2) Retaining the rock mass between the reinforcing elements with a robust surface retention system that is well connected to reinforced elements; and
(3) Providing a tough deformable retaining system.

3.3. Application of 'gabion panels' to create self-supporting arches or walls

In civil tunnelling, yielding steel arches and longitudinal slots are used in weak ground to prevent excessive build-up of hoop stresses in steel sets or shotcrete linings (Fig. 7a). In mining applications, stable deformable arches can be established without steel arches by 'stacked' panels of reinforced rock or stacked 'gabion panels' (Fig. 7b). Such stacked panels must be tightly linked to prevent shear failure of the resulting deformable support arch (grey arrows in Fig. 7b), or special measures must be used to provide shear resistance between individual panels.

For pillar support in squeezing or strainbursting ground (Fig. 7c), single wall panels provide the ductility required to accommodate large lateral bulking movements. Furthermore, such panels provide a large mass (i.e. the mass of the 'gabion panel') to dissipate imposed energy from strainbursts or from ground motions emitted from large remote seismic events (Kaiser and Moss, 2021).

In summary, the practical benefits of 'gabion panels' are:

(1) Deformability inside the 'gabion panel' and of the panels themselves relative to the surrounding ground against 'loading from behind';

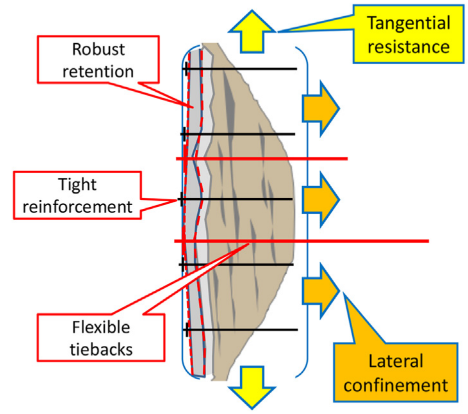


Fig. 6. Critical elements of deformable 'gabion panels': Retention, reinforcement, and tieback support to hold 'gabion panel' back to stable ground.

(2) Tangential and lateral resistances while deforming into the excavation;
(3) Ability to dissipate energy due to the large mass provided by the reinforced 'gabion panel' (adding a reliable mass to dissipate impact energy); and
(4) Ability to maintain substantial remnant load and energy capacities as the panels are deformed.

3.4. Illustration of benefits of 'gabion' concept

The concept of gabion support and deformation control has been applied at PT Freeport Indonesia's DMLZ mine where strainbursts occurred early in the cave establishment. In places, damage was observed to have led to total wall collapse (R5 damage), as illustrated in Fig. 8a. Substantial efforts were made to better understand the response of the rock mass to caving-induced stress and the role of support in managing the skin of stress-fractured, bulked rock. Support was upgraded to develop deformable 'gabion panels' in the walls resulting in the prevention of collapses through better bulking and deformation control. Even though excavation damage with large convergence still occurred at critically loaded locations (see Fig. 8b), access was still available, and the repair of the damaged support was easier and quicker than before. It is noted that the well-constructed 'gabion panel' retained its integrity with little or no 'shotcrete rain'. This is attributed to the fact that the entire 'gabion panel' in the pillar wall moved inward as a unit during the strainburst causing this support damage at a lower rate of deformation.

Recent experience at the DMLZ has demonstrated that support design using the 'gabion' concept can survive self-initiated or dynamically loaded strainburst events exceeding local magnitudes $M = 2$ as illustrated in Fig. 9. Furthermore, the application of the 'gabion panels' has drastically reduced the extent of severe excavation damage (ranging from R4 to R5). The length of development requiring repair to remain functional, decreased from some 20% to about 2% of the development within the undercut abutment once deformation control was established with the introduction of gabion support together with an associated reduction in damage related delays and costs. This was the first step in a cave establishment/propagation process that included pre-conditioning, cave shaping, and rigorous undercut management.

In summary, experience has shown that the implementation of the 'gabion panel' concept can be effective in reducing the detrimental impact of caving-induced seismicity on mine excavations.

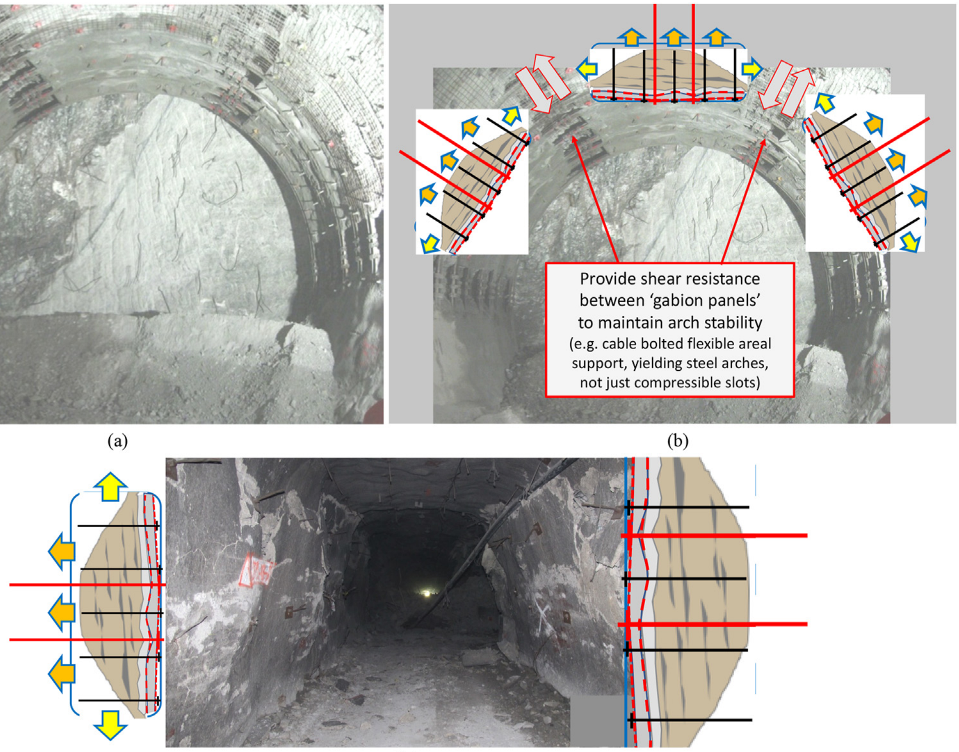


Fig. 7. (a) Deformable steel arch support for squeezing ground, (b) equivalent deformable arch with stacked deformable 'gabion panels' (Kaiser, 2019), and (c) mining application of laterally deformable 'gabion panels' for pillar support in strainbursting ground (photos: Courtesy PT Freeport Indonesia).

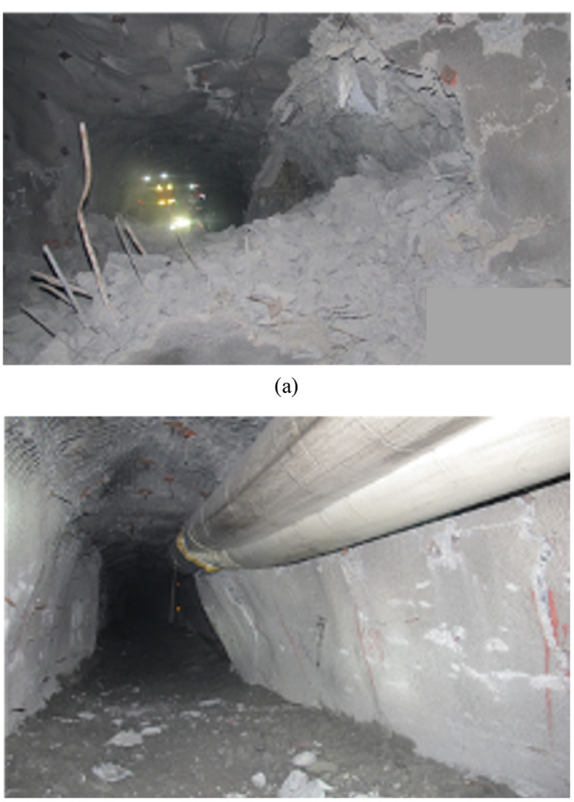


Fig. 8. (a) Excavation damage in inadequately supported ground, and (b) excavation damage with deformable 'gabion wall panel' (photos: Courtesy PT Freeport Indonesia and R. Bewick).

The first step is to recognise the failure process, i.e. where the rock mass exhibits brittle characteristics, the size of the potential skin damage (bulked) zone can be estimated, for example, by using the empirical methods first proposed by Kaiser et al. (1996) and later refined by Martin et al. (1999) and others as summarised in Cai and Kaiser (2018). This provides the broad dimensions of the gabion to be constructed. The reinforcing and retention elements can then be selected to achieve an appropriate factor of safety (*FS*) with due consideration given to all three demand types on the system (load, deformation, and energy).

Fig. 9. Drill drive in DMLZ after a local magnitude $M = 2$ event in close proximity. Note that there is minimal wall damage and little shotcrete ejection despite signs of floor heave (Photo: Courtesy PT Freeport Indonesia).

Second, it is essential to effectively manage the damaged skin by helping the ground to support itself through appropriate levels of reinforcement and retention of the skin (mesh and shotcrete) while constructing the 'gabion wall' to hold the reinforced skin in place (e.g. by holding 'gabion panels' with cable bolts).

Next, the concept of support consumption and consequently scheduled PSM by restoring the support capacity forms a critical component of support design. This is particularly important for seismically active mines where repeated seismically induced deformations, by 'seismic hammering' or repeated co-seismic rock mass straining, gradually consumes the support's capacity.

Kaiser et al. (1996) have stated, as reiterated by Kaiser and Cai (2013), that the goal of support in burst-prone ground is to mitigate the potential consequences of rockbursts. Support must therefore meet load, displacement, and energy demands under the anticipated static and seismic loading to maintain the integrity of the excavation. Because it is often not practically feasible to stop the driving deformation, it is necessary to manage it in a safe and cost-effective manner.

4. Technical considerations in excavation and support design

The industry has (over-) relied on empirical rock support design systems for many years. Because these systems were mostly derived from experience in shallow ground and data from civil engineering tunnels, there are limitations in the applicability of rock mass classifications for rock support design in highly stressed brittle ground in mines. Due to on-going operations, the ground experiences cycles of mining-induced stress changes that can alter conditions leading to brittle failure which is a fragile process. They are associated with generalisations of failure mechanisms and difficulties in reliably catering for changing conditions. More robust and reliable approaches are required for the new generation of deep mines.

There are six key steps in arriving at DBSD:

(1) Proper characterisation of ground in terms of rock mass strength and in situ stress;
(2) Identification of the relevant potential failure mechanisms that need to be assessed by recognizing that there often is more than one possible failure mode (e.g. imposing loads by wedges, deformations by stress-fracturing, and energy demands from stress-fracturing or stress waves) and that failure modes may change with depth and over the mine life;
(3) Understanding the consequences of depth on excavation behaviour (stress and rock quality);
(4) Identifying the cause and severity of the failure process to establish driving forces or deformation demands based on the premise that support primarily serves to stabilise yielded or fractured rock near the excavation (i.e. skin management);
(5) Definition of a 'design event', i.e. the intensity of demand that needs to be survived or is acceptable (allowed) for a given design period, and selection of an appropriate safety margin for each possible failure mechanism and design parameter (load, displacement, and energy); and
(6) Assessment of and accounting for support capacity consumption by displacements imposed during the mine life.

Fig. 10 shows the broad workflow for DBSD in burst-prone ground. The design objectives for the three elements of skin management are:

(1) To reinforce and retain broken rock by constructing a deformable 'gabion panel';
(2) To minimize the wall-to-wall convergence so as to minimize rock mass bulking; and
(3) To use stress-change insensitive holding elements for deep anchorage.

Currently available support tools for ground control can be deployed for the purposes listed in the last column in Fig. 10.

4.1. Rock mass characterisation

Many rock mass characterisation systems (i.e. rock mass rating (RMR), *Q*, geological strength index (GSI), and others) have been developed over the years, building on the rock condition classes developed by Terzaghi (1946) for rock load estimation. He distinguished rock mass classes largely based on block size and joint condition:

(1) For massive rock: Class 1: hard and intact; Class 2: hard stratified or schistose;
(2) For jointed rock: Class 3: sparsely or moderately jointed; Class 4: moderately blocky and seamy; Class 5: very blocky and seamy; Class 6: completely crushed but chemically intact;
(3) For squeezing rock: Class 7: at moderate depth; Class 8: at great depth.

Classes 1–4 impose no and Class 5 no or little side pressure; Class 6 imposes considerable side pressure (and potentially floor pressure). All-round support is needed in Classes 7 and 8. These three groupings are sufficient to establish the excavation behaviours for support design (Kaiser, 2019). It is unnecessary to go into excessive detail when characterising the rock mass quality (RMQ) but it is essential to independently describe the prevailing stress condition, e.g. by a stress level index (SLI).

The rock mass quality can be established using Terzaghi's approach (block size and block boundary condition) or one of the other classification systems listed in Table 1.

The SLI is used to characterise the stress causing damage near excavations. Because the in situ stress is modified by mining, and the stress ratio (vertical to horizontal) is not considered when using the commonly adopted principal stress indicator σ_1/UCS, the SLI is used, where σ_1 is the maximum principal stress perpendicular to a drift or tunnel at the boundaries of the representative volume of rock containing the excavation, and *UCS* is the unconfined compressive strength of the rock. It is defined as the normalised maximum stress σ_{max} around a circular excavation in elastic rock loaded by mining-induced stresses in a representative volume containing the excavation. The maximum stress σ_{max} is normalised to a calibrated *UCS* (UCS') of the intact rock or rock blocks: $SLI = \sigma_{max}/UCS'$. The maximum stress, $\sigma_{max} = 3\sigma_1 - \sigma_3$, where σ_3 is the minimum principal stress of the rock. Laboratory *UCS* values are often excessively variable, depending on the sample size, thus the average *UCS* values typically underestimate the rock block strength. Hence, a representative UCS' has to be back-analysed such that $SLI < 0.4 \pm 0.1$ when no sign of spalling or other stress-driven rock deterioration is observed. If no underground access is available, it is often meaningful to set UCS' as the upper 75 percentile value of the *UCS* obtained from specimens without defects.

Based on SLI, three stress intensity classes are identified as listed in Table 2. Accordingly, excavation behaviour can be grouped by three rock mass quality classes (RMQ 1–3; Table 1) and three stress level indices (SLI 1–3; Table 2).

4.2. Classification of rock mass behaviour near excavations

The RMQ and SLI classes, listed in Tables 1 and 2, are sufficient to identify dominant excavation behaviour modes. These two tables

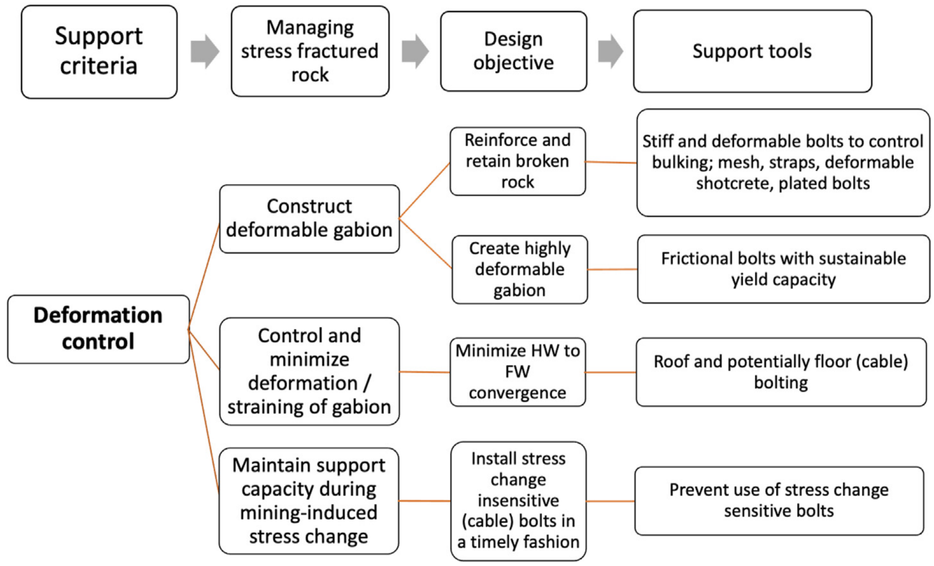


Fig. 10. Workflow of deformation-based support selection.

define nine failure modes that need to be considered for support design (Kaiser, 2019; in modified form in Kaiser and Moss, 2021).

At low stress (SLI 1), where gravity-driven failure modes define the load demand, Terzaghi's rock load model is representative. The safety margin or factor of safety ($FS_{\mathrm{L\ for\ Load}}$) (i.e. FS_L = *load capacity*/*load demand*) is defined by force equilibrium considerations. Unravelling risk and stand-up time issues can be managed by in-cycle support (e.g. shotcrete), shorter rounds, and generally good construction practices.

At intermediate stress (SLI 2), stress-induced fracturing and slip along block forming joints locally influence both the depth of gravity-driven failure modes and the bulking of stress-fractured blocky ground, as illustrated by Fig. 11. This increases the displacement demand. The safety margin or *FS* is defined by force and displacement (FS_D = *displacement or straining capacity*/*displacement or strain demand*) equilibrium considerations. Unravelling risk is manageable in RMQ 1 and RMQ 2 but stand-up time issues require special construction measures (e.g. spilling, pre-grouting) in RMQ 3. Minor to moderate strainbursting is to be anticipated in RMQ 1 and RMQ 2, and the safety margin or *FS* in terms of energy balance (i.e. FS_E = *energy dissipation capacity*/*energy demand*) must also be assessed. Local, moderate squeezing is to be expected in laminated or foliated ground.

At high stress (SLI 3), the extent of stress-induced fracturing and rock mass yield involves the entire excavation (walls, backs, and floors; Fig. 12). This further expands the extent of gravity-driven failure modes and imposes high displacement demands on the support due to bulking of stress-fractured and dilation of disturbed or sheared ground. Whereas the safety margin or *FS* still needs to be assessed in terms of force and displacement equilibrium considerations, the latter tends to dominate support design.

Moderate to severe strainbursting is to be anticipated in RMQ 1 and possibly RMQ 2. The safety margins or factors of safety (FS_D and FS_E) must be simultaneously assessed. Moderate squeezing conditions with large displacements are to be expected in RMQ 2 and severe squeezing, likely with time-dependent displacements, is to be expected in RMQ 3.

In summary, support in active mining areas needs to account for mining-induced stress changes and related displacements:

(1) Gravity-driven failure modes are to be assessed in most ground conditions;
(2) DBSD principles are to be adopted for SLI 2 and SLI 3;
(3) Retention of fractured or broken rock by effective areal support is critical with decreasing RMQ and particularly with increasing SLI;
(4) Construction quality becomes increasingly important with higher RMQ and SLI classes;
(5) Support capacity consumption by mining-induced displacements must be accounted for when mining-induced stress-changes cause rock mass fracturing and impose displacements after support installation;
(6) Rock mass classifications are useful to establish the RMQ, but standard support selection charts cannot be applied when support capacity consumption is anticipated;
(7) Energy-based design approaches in burst-prone mines must account for support capacity consumption by mining-induced displacements; and
(8) The impact of stress-changes (loading or relaxation), i.e. changes in SLI, must be considered.

4.3. Behaviour of brittle hard rock

For the selection of an effective support system in brittle ground, generally with high intact strength and high modulus ratio (Chapter 1 by Deere and Chapter 4 by Hoek in Stagg and Zienkiewicz, 1968), it is important to understand the bulking process that occurs when stress-fractured moderately jointed or blocky rock is deformed. The rock adjacent to the walls of an excavation is not well confined by the installed support or the prevailing stress regime, and spalling occurs, resulting in a skin of damaged ground ('inner shell' or red zone in Fig. 13b). Intact blocks of rock or rock fragments must readjust as the damaged rock mass bulks due to geometric incompatibilities. This bulking process is driven by tangential straining in the walls (or backs and floors) and is a function of the mining-induced stresses or strains (vertical arrows in Fig. 13a). This bulked rock can only move toward the excavation, resulting in a magnified radial deformation that is predominantly perpendicular to the excavation walls and thus parallel to the installed reinforcement and perpendicular to the installed areal support (horizontal arrow in Fig. 13a).

In other words, brittle hard rock assumes a dual personality when highly stressed. In the skin of the excavation, brittle rock failure promotes rock fragmentation and bulking due to geometric

Table 1
Rock mass quality (RMQ) classes for excavation behaviour identification (after Kaiser, 2019).

Rock mass quality class	Block size (m) (edge lengths)	*RMR*	*Q′*	*GSI*
RMQ 1 – MASSIVE to discontinuously jointed/veined, strong rock	>1	>75 Very good to good	>40 Exceptionally to very good	>70 Massive to blocky
RMQ 2 – BLOCKY, persistently jointed/veined or fractured strong rock with interlock and good to poor block defining joint conditions	0.1–1	75 to 35 Good to poor	40 to 0.4 Good to very poor	70 to 30 Blocky to very blocky
RMQ 3 – DISTURBED, very blocky, weak and soft, folded and sheared rock	<0.1	<35 poor and very poor	<0.4 Very to exceptionally poor	<30 Disturbed and sheared

Note: Because stress is treated separately in Q' with $J_w/SRF = 1$, Q' rather than Q is to be used to describe the RMQ.

Table 2
Stress level index classes for excavation behaviour identification (after Kaiser, 2019).

In situ or mining-induced stress	*SLI*	Comment
SLI 1 – Low	<0.4 ± 0.1	No signs of stress-driven rock failure (spalling or fracturing) near the location with σ_{max}.
SLI 2 – Intermediate	0.4 –1.15(±0.1)	Depth of visible stress-driven failure of unsupported ground is typically less than one equivalent excavation radius. Rock fracturing/failure is typically localised (notch near σ_{max}).
SLI 3 – High	>1.15 ± 0.1	Rock fracturing or yielding typically involves the entire excavation (walls and back/floor) and is deep seated (>one equivalent excavation radius).

Fig. 11. Example of blocky ground created in the immediate vicinity of the excavation by stress-fracturing of a moderately jointed rock mass. Open fractures and shears illustrate the related bulking process due to geometric non-fit of blocks of hard rock.

incompatibility of strong rock fragments or blocks, whereas in the 'confined zone' beyond the stress-damage ground, the rock mass strength increases rapidly due to confinement and may become prone to strainbursting.

The primary target of the support therefore is to use the broken rock near the excavation when formed by stress-fracturing to create a self-supporting arch or panel of retained rock fragments, preserving interlock, and controlling rock mass bulking. By analogue, the goal is to create arches or panels of 'gabions' of retained broken rock. The second target of the support is to tie the self-supporting arch or panel(s) back to stable ground and to provide confinement to the highly stressed rock in the 'confined zone' (orange arrows in Fig. 13c) and to resist the tangential load (yellow arrows in Fig. 13c).

Support is installed to manage this skin of damaged, bulking ground. The load demand is controlled by the geometry of the bulked rock volume, and the displacement demand is a function of the depth of failure and the rock mass bulking factor (Kaiser, 2016). During a strainburst, when brittle rock failure occurs suddenly, the failing ground bulks and deforms rapidly. It loads the support system 'from behind' or 'from within' the reinforced rock mass by a sudden radial ground motion, impacting the reinforced ground and imposing an energy demand inside and on the support arch or panel. If simultaneously loaded by ground motions from a remote seismic event, the load and displacement demands are magnified, adding further load, displacement, and energy demands on the support system. Under dynamic loading, this energy demand must be dissipated as the support capacity is being consumed by the displacement imposed by static and dynamic bulking (Cai and Kaiser, 2018; Kaiser and Cai, 2021).

Support in highly stress-fractured ground must therefore simultaneously meet load, displacement, and energy demands under anticipated static and seismic loading to:

(1) Control the deformation before it reaches operationally allowable displacement limitations;
(2) Reinforce the damaged skin to reduce the detrimental effects of bulking on the rock reinforcement; and
(3) Provide a tough deformable retaining system to survive the bulging action from bulking ground.

4.4. Dynamic resistance capacity of 'gabion' arches

Dr. Wenge Qiu (personal communication (Qiu, 2016) and reported by Kaiser, 2019) built a test facility for static and dynamic testing of gabion arches and compared the behaviour of a reinforced lining with two types of 'gabion' arches, one with circular and the other with trapezoidal cross-sections (Fig. 14a and b).

Under static loading (Fig. 14c) with 1.75 m overburden (32 kPa), the reinforced concrete liner arch deflected 1 mm and the 'gabion' arches deflected 26 mm and 4 mm with circular and trapezoidal 'gabion' shapes, respectively. The steel used to form the trapezoidal 'gabion' arch was less than one third (29%) of the reinforcement in the concrete arch.

Most importantly, the reinforced concrete liner was punctured when a 200 kg of weight was dropped from a height of 4 m (Fig. 14d and e), exerting a kinetic energy of 7.8 kJ (roughly 30 kJ/m^2) with the reinforcement mesh holding the drop weight after more than 0.3 m sag. The trapezoidal 'gabion' arch flexed and rebounded repeatedly thereby stopping the drop weight without breaking the 'gabion' arch by consuming the entire impact energy. The impact forces were approximately 8 MN on the concrete liner and 2 MN on the trapezoidal 'gabion' arch.

This example of deformable support arch performance illustrates the resilience of 'gabion' arches to dynamic loading, in part because of its mass and internal frictional resistance capacity.

4.5. Support design goals

The goal of rock support is to construct a structure skin to a 'gabion panel' in the wall or a set of stacked 'gabion panels' in the back to provide:

(1) Immediate retention of damaged rock;
(2) Reinforcement of broken rock in the skin of the excavation;
(3) Surface pressure to increase self-supporting capacity of broken rock; and

(a) (b)

Fig. 12. Examples of slabbing and severe excavation damage in highly stressed massive rock. (a) shows spalled rock delaminating between bolts, and (b) shows deep fracturing, related bolts and cable failures.

(4) Enough mass to dissipate energy released from seismic events (proximal and distal to the excavation).

The excavation behaviour matrix (Kaiser, 2019; modified in Kaiser and Moss, 2021) provides guidance to establish the applicable support design criteria. It also serves as a simple means for communicating to mine operators such that instability risks can be assessed and addressed during underground inspections. Furthermore, it allows ground control engineers to identify constructability issues, e.g. that increasing amounts of overbreak must be expected in RMQ 2 and RMQ 3 and at SLI 2 and SLI 3. The overall design goals are summarised in Table 3 for each ground condition.

A full description of the gabion concept and associated DBSD principles and methods for burst-prone ground is presented by Cai and Kaiser (2018) and Kaiser and Moss (2021).

4.6. Support system capacity consumption (SSCC)

The effectiveness of support systems can be compromised by quality deterioration (e.g. corrosion; not covered here) and by the consumption of a support system's displacement and energy capacity. Mining not only causes stress changes but also produces associated deformations and tunnel convergence which deform and strain the support. As these displacements increase, more and more of a support's displacement and energy dissipation capacity get consumed. The remnant support system capacity decreases while mining continues.

For example, if a support system is deformed to a wall deformation of δ_1 (Fig. 15), the support will reach its yield load and begins to work by plastic deformation (area under the load–displacement curve). Its elastic energy capacity E_1 is consumed when the yield point is reached. The remnant displacement capacity is gradually reduced as the support is deformed from δ_1 to δ_3, i.e. to the point where support system degradation starts (red and blue lines in Fig. 15). As a support is deformed during mining and the displacement capacity is consumed, the energy capacity is also eroded, i.e. by $-\sum E = -(E_1 + E_2 + E_3)$.

Fig. 16a provides a schematic example of the load capacity evolution with a drop in load capacity at 150 mm central displacement of the areal support between the bolts when the rebar fails, and failure of the most ductile support component at 205 mm when the entire support system including cable bolts fails. Fig. 16b presents the energy capacity evolution in black and the remnant capacity in red. For this schematic example, the energy capacity is gradually lost until all of its capacity is consumed at 205 mm of imposed central displacement. At 150 mm central displacement, only 8 kJ/m^2 or 40% of the initial energy capacity of the rock and cable bolts remain.

This example illustrates how the support system capacity is being consumed by mining-induced displacements, i.e. by displacements imposed in a static manner or by co-seismic deformations in seismically active mines (Kaiser, 2017). With digital monitoring technology, support consumption can be monitored in the field and the remnant safety margin in terms of load, displacement, and energy capacities can be assessed.

4.7. Support system capacity restoration by PSM

The most important practical implication of support system capacity consumption is that a support system rarely exhibits its full capacity that was available at the time of support installation. If too much capacity has been consumed, it will be necessary to restore some of the consumed capacity by PSM. The 'timing' of the PSM installation is based on the measured deformation of the wall and back, e.g. based on digital displacement measurements as illustrated by Fig. 2b. The frequency of monitoring depends on a number of factors including excavation use, occupancy, and criticality. In major excavations, such as crusher chambers, it is becoming increasingly common to have fixed real time scanning while in production drives measurement is dependent on production activity and drive performance, ranging from daily to monthly. Fig. 17 demonstrates this process:

(1) Once a drive is excavated and the base support (primary and secondary) is installed, the damaged skin deforms due to mining-induced stress changes, consuming some of the capacity of the support. It can deform to a critical displacement level (100 mm in illustrative example of Fig. 17);
(2) At this threshold, established by field observations (i.e. TARPs), additional support (PSM) is installed to provide sufficient support capacity by extending the allowable displacement limit;

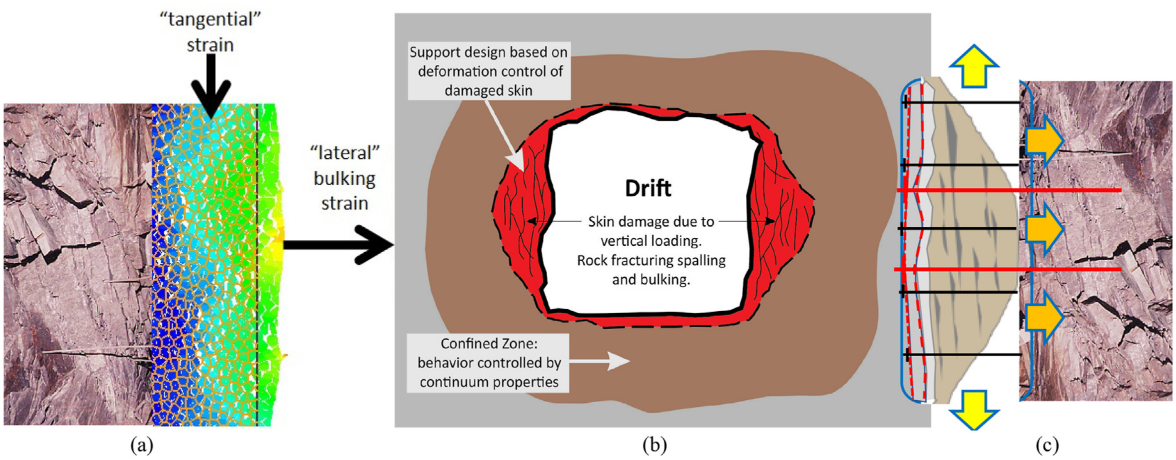


Fig. 13. (a) Bulking of stress-fractured rock causing geometric bulking as illustrated by a Voronoi model (Kaiser, 2016), (b) location of damaged skin in vertically loaded drift, and (c) 'gabion panel' of fractured rock with effective retention, reinforcement and holding capacities (Fig. 6).

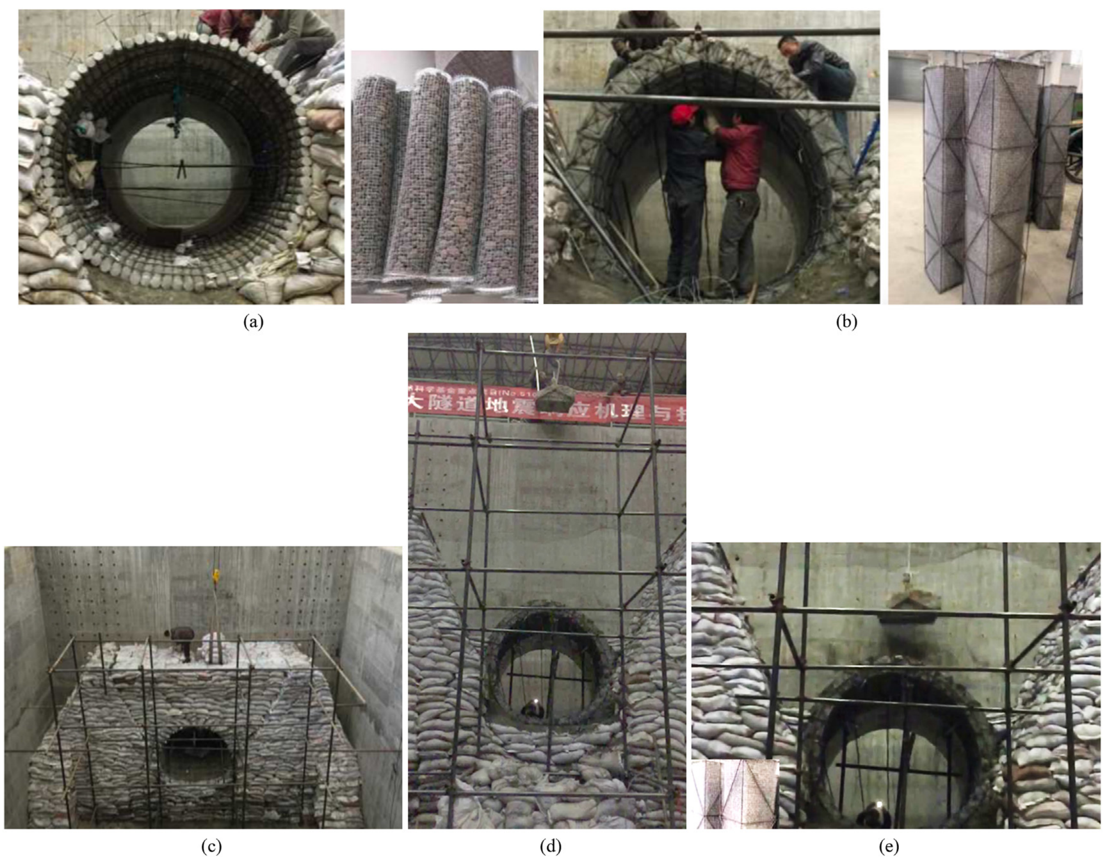


Fig. 14. Static and dynamic impact tests of 'gabion' arches at Southwest Jiaotong University by Qui (2016): (a) Gabions with circular and (b) with trapezoidal cross-sections; (c) Static loading test of gabion arch; and (d, e) Dynamic loading by drop weight.

(3) The PSM support will continue to deform until a new threshold (e.g. at 180–200 mm in illustrative example of Fig. 17) is reached and the skin either requires further PSM or becomes extensively damaged and requires repair;
(4) If no PSM was applied, the excavation would be excessively damaged once the deformation capacity of the base support is reached and rehabilitation work with removal of damaged support would be required. Repair with reinstallation of the entire support system would be required much 'earlier' (i.e. at 100–150 mm in illustrative example of Fig. 17); and
(5) With PSM, rehabilitation can either be prevented or deferred without enduring collapse as illustrated in the photographs in Fig. 17 without PSM.

Traditionally, repairs to excavations are carried out reactively. PSM represents a move toward planned maintenance with the required additional support appropriately scheduled. Significant safety benefits and cost savings were realised with the adoption of this approach. At one operation, the direct cost of PSM was approximately $2000 per meter compared with approximately

Table 3
Description of support design goals.

SLI	RMQ 1	RMQ 2	RMQ 3
1	Protection for workplace safety by containment of any loose and specific joint bounded blocks	Holding of key blocks and structurally controlled block (wedge): FS_L Sensitive to relaxation	Arch formation: retaining small block and prevention of failure of structurally controlled volumes of 'broken' rock: FS_L Sensitive to relaxation and unravelling
2	Arch formation in walls or back: Reinforcement and retention of broken rock: FS_L, FS_D and FS_E	Arch formation in walls or back: Reinforcement and retention of broken rock and structurally controlled blocks: FS_L, FS_D and FS_E	Formation of strong deformable arch in walls or back: Retention of 'broken' rock and holding of reinforced arch and structurally controlled blocks: FS_L and FS_D
3	Flexible all-round arch formation: Retention of broken rock with flexible arch or panels: FS_L, FS_D and FS_E	Flexible all-round arch formation: Retention of broken rock with flexible arch or panels: FS_L, FS_D and FS_E	Flexible all-round arch formation: Retention of broken rock with flexible arch or panels: FS_L and FS_D

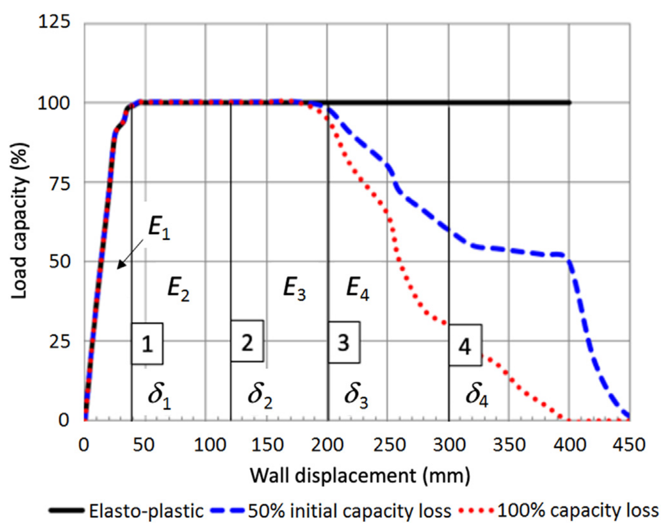


Fig. 15. Schematic support system characteristics illustrating four stages of support capacity consumption, indicated by 1–4. Energy E_1 is the energy used to deform the support from 0 to δ_1, E_2 from δ_1 to δ_2, etc.

$20,000 per meter for rehabilitation. Furthermore, substantially more value accrued to PSM compared with repair due to the reduction in unscheduled production interruptions.

For the implementation of PSM, the following methodology is recommended:

(1) Recognise changes in load (deformation, energy) as mining progresses by repeated digital displacement monitoring.
(2) Develop a deformation-based TARPs for PSM. Separate TARPs are required for footprint and infrastructure. For infrastructure, the TARP must consider the function of the excavation, criticality to production, and life span. Deformation thresholds will be typically lower than those for the footprint. This is due to the importance of the facility and the generally difficult access which may require longer periods to fully implement PSM. Specialised equipment may have to be developed to ensure ease of PSM installation, i.e. to minimize disruptions.

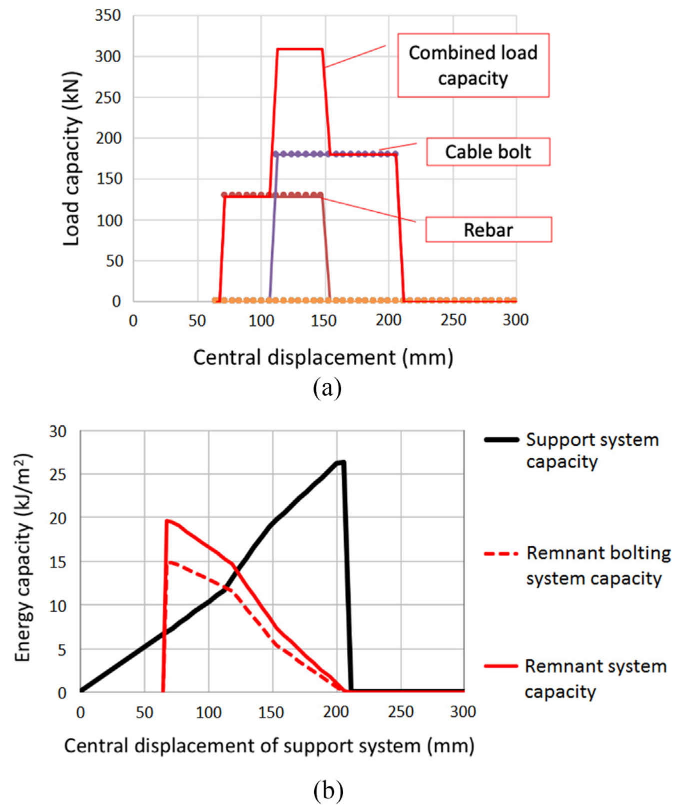


Fig. 16. Schematic load and energy capacity of a support system consisting of rebar and cable bolts: (a) Load capacity evolution, and (b) Energy capacity (black) and remnant capacity (red) (Cai and Kaiser, 2018).

(3) Continue measurements of deformations and install PSM support accordingly in an orderly and safe manner. Thus, the design must respect that, at any point of the support's life, the remnant support capacity is less than the installed capacity. In other words, the actual factor of safety *FS* is gradually lowered by mining-induced displacements. From a safety perspective, it is not of interest what the capacity of the support was at time of installation, but that the current *FS* demonstrates that there is sufficient capacity available when needed. Particularly in yielding and brittle fractured ground, the design must account for displacement and deformation-based consumption of support capacity.

5. Conclusions

A growth in deep underground mining is anticipated to satisfy increasing metal demands. Though deep mining is not new, the scale of production from depths exceeding 1000 m is. Depth and scale combined present a risk to construction and production schedules and ultimately to the value proposition, particularly in caving operations.

Infrastructure excavations and production development are the largest investments in many underground operations. Managing these assets are key to successful operations. The need for good management increases with depth as the rock mass responds to mining-induced deformations. Deeper excavations are more vulnerable to mining-induced demands than those at shallower depths as the rock behaviour changes from joint controlled wedge type failures to brittle failure and bulking of the rock mass. The approach to design and excavation management must reflect this change.

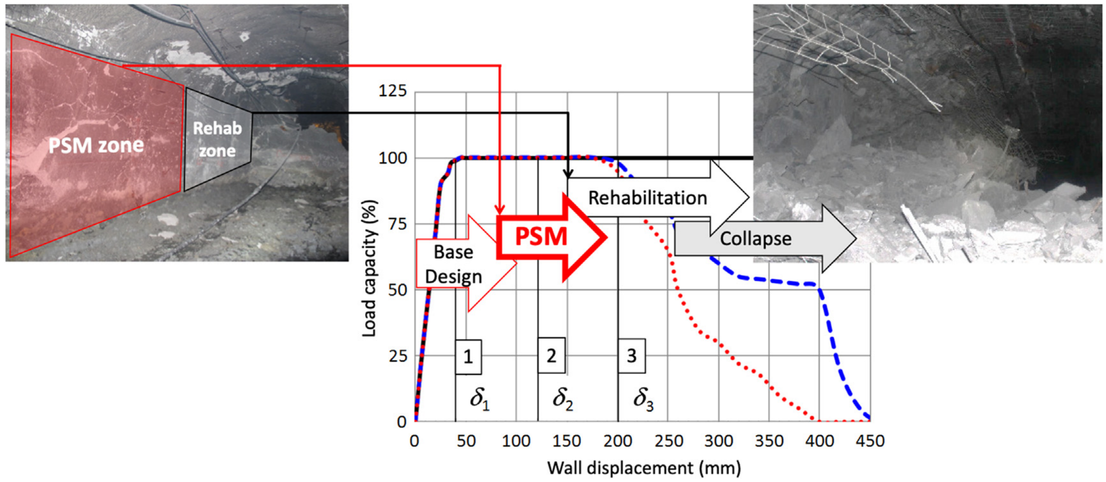


Fig. 17. Illustration of support system capacity consumption and range of applicability of base design, PSM, and support rehabilitation (photos: Courtesy DMLZ at Grasberg Mine, PT Freeport Indonesia (2017) and R. Bewick).

Excavations need to remain functional during their operating life and thus, ground control becomes central to good asset management. An outcome of deeper mining is increased deformation of the wall of an excavation often resulting in a skin of failed and bulked rock that must be managed during the life of the excavation by the installation of an appropriate support system. This system must be able to deal with the imposed deformation, load, and energy demands. For this purpose, the accepted wisdom of helping the rock mass support itself has evolved into the concept of 'gabion panel' support. These 'gabion panels' are formed by a combination of rock bolts, cable bolts, and robust areal support that with the bulked damaged skin forms a deformable self-supporting arch or wall panel. The effectiveness of gabion support has been demonstrated at a major caving operation where the system has substantially reduced damage and contained local strainbursts of local magnitude up to $M = 2$.

An equally important factor in excavation management is to appreciate that support capacity is consumed by mining-induced deformations, and that it is important to maintain this capacity to ensure long-term excavation functionally. This can be achieved in a cost-effective manner by installing supplementary support during PSM. To be cost effective, the PSM support must be installed prior to the occurrence of significant damage in order to avoid repair or rehabilitation costs and associated delays. Thus, there is a need for planned support maintenance. New technologies, such as LiDAR, provide the deformation information that determines when additional support is required.

In summary, deeper mining requires a robust process to manage major assets, i.e. the excavations. Ground control utilising deformation-based design principles is a cornerstone of the proposed process. The damaged rock that can occur around the excavations is used in combination with bolts, screen, and shotcrete to form deformable gabion panels. These gabion panels provide an effective means for enhancing stability. The consumption of support by on-going mining-induced deformation is measured and system performance is monitored. Planned support maintenance is used to maintain the design capacity and maintain excavation functionality.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The efforts of many individuals and their supporting companies including PT Freeport Indonesia and Newcrest deserve to be thankfully acknowledged. The list is too long to name all contributors, but we wish to especially thank Matt Sullivan (PT Freeport Indonesia), Jared De Ross (Newcrest, Australia), and Drs Ming Cai (Laurentian University, Canada) and Wenge Qiu (Southwest Jiaotong University, China) for their contributions. This work was also facilitated by financial support from NSERC (Canada's Natural Sciences and Engineering Research Council) and ORF (Ontario Research Fund).

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