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Ground Control Methods in High-Stress Ground Conditions in Civil and Mining Tunnels- Case Studies, and Benchmarking

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ABSTRACT: Extreme ground behavior in high-stress rock masses such as rockburst prone and squeezing ground conditions are encountered in a range of underground projects both in civil and mining applications. Determining the most appropriate support system in such grounds is one of the major challenges for ground control engineers because there are many contributing factors to be considered, such as the rock mass parameters, the stress condition, the type and performance of the support systems, the condition of major geological structures and the size and geometry of the underground excavation. The main characteristics and support requirements of rockburst-prone and squeezing ground conditions are critically reviewed and characteristics of support functions are discussed. Different types of energy-absorbing rock bolts and other internal and external support elements applicable for ground support in rockburst-prone and squeezing grounds are introduced. Important differences in the choice and economics of ground support strategies in high-stress ground conditions between civil tunnels and mining excavations are discussed. Ground support benchmarking data and mitigation measures for mines and civil tunnels in burst-prone and squeezing grounds conditions are briefly presented by some examples in practice. The importance of the application of shotcrete shells with yielding elements in squeezing ground conditions has been presented in detail by a simplified Convergence Confinement Method (CCM) example.

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1- Introduction

Understanding the possible ground behavior type is an essential part of stability analysis and good rock support design in underground excavations, especially in difficult and complex ground conditions. The main ground behavior types in underground excavations can be classified as follow considering the rock mass type, the stress condition, the presence of water, the condition of major geological structures, time-dependent behavior, and continuity of ground:

1. Structurally controlled failures at shallow depths and low-stress conditions, which involve a great variety of failure modes (ravelling, rock falling, etc.);
2. Stress-rock structurally controlled failure at medium depths and medium stress environment (buckling);
3. Stress-induced failure at greater depths and high-stress conditions, which may occur in two main forms:
   a. Overstressing of massive or intact rock; which takes place in the mode of spalling, popping, rockburst (strain burst, fault slip burst).
   b. Overstressing of heavily fractured rocks (where squeezing may take place).
4. Groundwater initiated failures in some rocks containing special minerals (e.g., swelling, slaking, etc.).

The main contributing factors to evaluate potential ground failure modes considering each rock mass types include:

- stress situations (in-situ stresses, groundwater pressure, induced stresses, and seismic events);
- the relative orientation of discontinuities and other geological structures to the excavation;
- size, shape, and location of the tunnel, excavation method, and sequencing.
- groundwater conditions;

Extreme ground behavior in high-stress rock masses such as rockburst prone and squeezing ground conditions are encountered in a range of underground projects both in civil and mining applications. The occurrence of such ground behavior types are difficult to predict and special design and construction measures and support requirements must be considered to control them as follow:

- Modification of the size, shape, and layout of the excavation as well as the excavation method and energy release control by improved mining methods.
- Stability improvement by relocation and/or reorientation of excavations considering geological structures (e.g., faults, folds, and weak zones).
- Ground pre-conditioning.
- Installation special and effective rock support and

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Table 1. The main characteristics and support requirements of rockburst prone and squeezing ground conditions.

Ground instability Modes	Characteristics	Support Requirements
Rockburst (brittle behavior)	Sudden/ Violent Unexpected danger potential	Immediate setting Immediate bearing Capacity High energy- absorbing capacity
Squeezing (plastic behavior)	Time-dependent High forces Large deformations Damage potential	High bearing capacity Flexibility/Yielding Sustain large deformations

Table 2. The main characteristics of conventional support elements in civil and mining projects.

Support Element	Support characteristics				
	Quick Setting	Immediate Bearing	Bearing Capacity	Flexibility/ Yielding	Deformability without Destruction
HEM steel arches	high	very high	high	medium	low
TH steel arches	high	medium	medium	very high	very high
Lattice girder	medium	medium	high	medium	medium
Rock bolt	very high	very high	medium	very high	very high
Shotcrete	very high	low	very high	low	low
Wire mesh	very high	very high	low	very high	very high
Fibre Reinforced Shotcrete	very high	low	very high	low	low

reinforcement systems, i.e., yielding systems.

There are no universal standard analyses for determining ground support requirements in underground excavations because each design is specific to the circumstances at the actual site, the ground conditions, the project-related features, and the regulations and experience. The tunnel surrounding rock mass and the excavation form an extremely complex structure. It is seldom possible, neither to acquire the accurate mechanical data of the ground and forces acting nor to theoretically determine the exact interaction of these, which makes support design for a tunnel a challenging task [1-3].

Prediction and/or evaluation of support requirements for tunnels are largely based on observations, experience, and engineering judgment of those involved in tunnel construction. Often, the estimates are backed by theoretical approaches in support design mainly include the classification systems, the ground-support interaction analysis, and the key block analysis.

There are several well-documented design schemes for ground support design. Generally, they all require the following and may need to be applied to different observed mechanisms of instability:

- Description of the rock mass and identification of likely failure mechanisms;
- Assessment of ground demand (block size, depth of failure, areal support demand, reinforcement length, force, and displacement demand, energy demand, etc.);
- Assessment of support capacity (element type, technical specifications for static and dynamic conditions, density, in situ performance, etc.);
- Design acceptance criteria (appropriate factor of safety related to excavation purpose).

In Table 1, the main characteristics and support requirements of rockburst prone and squeezing ground conditions are briefly presented. The main features of conventional support elements applicable in civil and mining projects considering support requirements in rockburst prone and squeezing ground conditions are presented in Table 2.

This paper addresses the main characteristics and support requirements of rockburst prone and squeezing ground conditions and investigates the relative performance of different ground support options. Different types of energy-absorbing rock bolts, surface supports, and yielding elements applicable for ground support in high-stress grounds are introduced. Important differences in the choice and economics of ground support strategies between civil tunnels and mining excavations discussed. Ground support benchmarking data and mitigation measures for mines and civil tunnels in rockburst prone and squeezing ground conditions are briefly presented by some examples in practice.

2- High-stress ground conditions

The stability of underground excavations, such as tunnels, caverns, and mine stopes, is mainly governed by three factors: the quality of the rock mass, the in situ rock stresses, and the size and geometry of the excavation. The essential difference between rock at depth and rock near the surface is an increase in the in situ rock stresses. The high stresses can lead to two consequences in underground excavations: large deformations in soft and weak rock masses and sudden failure in hard and massive rock masses. At high depths, the rock mass response is mainly stress-driven and conventional support measures do not adapt well to these difficult conditions [4].

The main task of rock support in shallow underground excavations is to prevent rock blocks from falling by the installation of conventional rock bolts which must be strong enough to bear the dead weight of the loosened rock block. This is called a load-controlled condition [5]. Therefore, in low in situ stress conditions, the strength of the rock bolt is more important than its deformation capacity.

The task of rock support at great depths and high in situ stress conditions is to prevent the failed rock from disintegration and the support system must be not only strong but also deformable (energy absorbent) to deal with either stress-induced rock squeezing in weak and fractured rocks or rockburst in hard and massive rocks.

3- Rock support in the burst-prone ground

As mining and underground constructions migrate to deep grounds, stress-induced rock fracturing and failure are inevitable and in some cases rocks can fail violently, releasing a large amount of seismic energy and causing damage in the form of rockburst. However, rock bursting is not confined to deep mines. Relatively shallow mines, for example in Western Australia, can also experience high stress and must address the risks associated with rock bursting.

There are many different terms to describe a rockburst in civil and mining tunnels, including seismic event, strain burst, fault-slip burst, pillar burst, etc. A rockburst is defined as “damage to an excavation in the form of stress fracturing and rock mass bulking that occurs suddenly or violently and is associated with a seismic event” [6]. The seismic event may be either remote from the damage location or the seismic event may lie directly at the damage location.

The occurrence of rock bursts is associated with stress changes after excavation. Under the triggering mechanism, a rockburst event is classified as either strain burst or fault-slip rockburst. Strainburst refers to a burst event that is directly related to stress concentration near an underground excavation boundary. After excavation, the tangential stresses in the superficial rock become elevated. In extreme cases, the stresses are so high that the rock is not capable of sustaining them. At this moment, the rock bursts out, and the elastic energy stored in the rock is released suddenly and violently.

The excavation of underground openings may also result in reductions in the normal stresses on some pre-existing faults near the openings. This in turn brings about reductions in the shear resistance of the faults and slippage may occur along them. Such fault slippage induces strain/stress waves that radiate spherically outward from the place of slippage (source). This is called a seismic event in the mining industry. When the strain waves reach the walls and roof of the underground opening, a so-called fault-slip rockburst event may be triggered. A fault-slip rockburst is usually more powerful than a strain burst and typically causes more serious damages to underground infrastructures.

Typical rockburst damage to underground excavations considering rockmass type surrounding underground excavation and dynamic loading condition includes stress-induced rock fracturing; bulking of roof and sidewalls; floor heave; shearing of rock; block ejection; and seismically induced rockfall.

Kaiser and Cai [7] categorized the main factors influencing rockburst damage and its severity into four main groups including seismic event, geology, geotechnical, and mining/tunneling (Fig.1).

The design of ground support needs to account for several uncertainties relating to loading conditions, rock mass variability, rock mass behavior, and ground support performance. When designing ground support to cater to dynamic conditions, the uncertainties are magnified due to significant gaps in our understanding of how the rock mass responds to dynamic loading as well as limitations in available design methodologies [8].

The seismic phenomena are complex, and the interaction of seismic radiation with an installed support system and the surrounding rock mass only adds to the complexity. Further difficult aspects relate to the behavior of the support components, individually and collectively, and the site variables such as quality of installation.

The general principle of ground control in rockburst-prone conditions and to mitigate the potential consequences of rockburst is the implementation of dynamic resistant ground support systems. This system transfers the dynamic energy of a rockburst event to the yielding support system to facilitate absorption and controlled deformation of rock mass while providing confinement of materials, or “helping the rock mass to support itself” [9].

There are several approaches to the selection of appropriate dynamic ground support. The deterministic approaches are based on the assessment of energy absorption capacity and include the Canadian Rockburst Support Handbook method, and the Kinetic & Potential energy calculation method [6, 10-13]. They make various assumptions about dynamic mechanisms to enable the computation of support requirements.

Seismic Event	Geology	Geotechnical	Mining/Tunnelling
• The magnitude of the seismic event • Distance of the seismic event and the excavations • Rate of seismic energy release • The peak particle velocity at the rockburst site (PPV)	• Insitu stress • Rock type • Beddings • The relative orientation of relevant discontinuities and other geological structures to the excavation (dykes, faults, folds and shears) • The presence of seismically active major geological structure	• Rock strength • Joint Fabric • Rock brittleness • Depth of stress fracturing or depth of failure	• Induced static and dynamic stresses • Excavation size, shape and location • Excavation method and sequencing • Mining method • Extraction ratio • Production rate • Mine stiffness • Installed rock support system and its energy-absorbing capacity • Backfill

Fig. 1. The main factors influencing rockburst damage and its severity (modified after [7]).

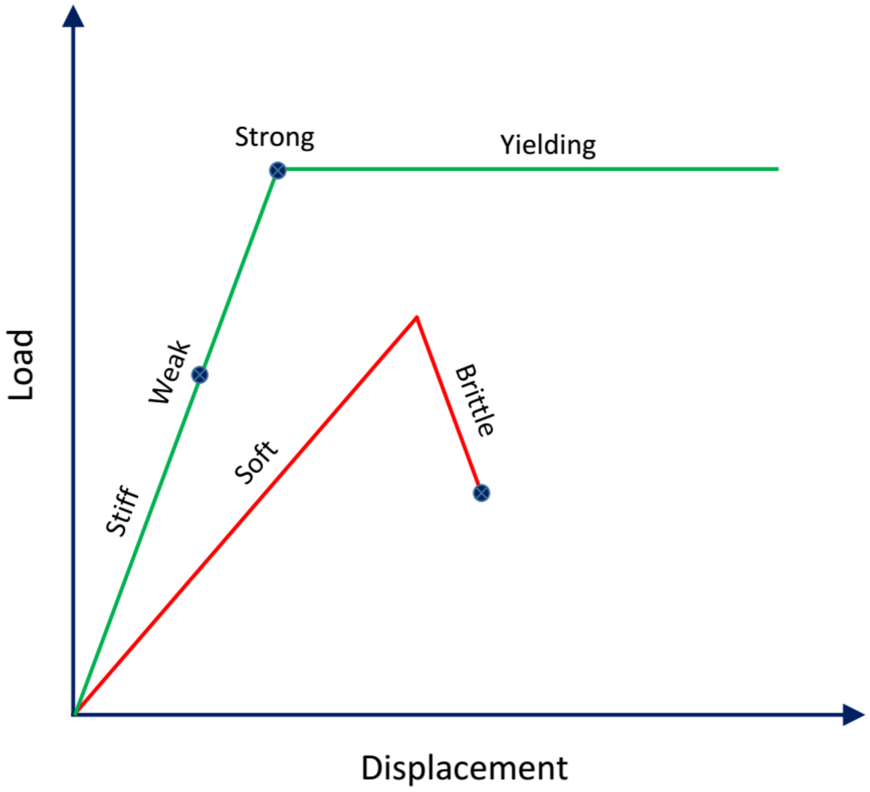


Fig. 2. Typical load-displacement behavior of support elements.

The assessment of the dynamic capacity of ground support has been the subject of intensive research during the last two decades. In particular, drop tests were developed to investigate the capacity of support elements [14, 15] while the performance of various support systems was examined by simulating rock bursts with carefully designed blasts [16-18].

In addition to simulated rockburst testing of complete ground support systems, back-calculation of support capacity from a large database of case histories comprised of 254 instances of rockburst damage from 13 hard rock mines in Australia and Canada were performed by Heal [19]. Through assessment of these case histories, Heal [19] concluded that certain excavation-specific factors contributed to the occurrence and severity of rockburst damage and were common across the different mine sites. The factors were: the stress conditions; the energy capacity of the installed ground support system; the excavation span; the presence of seismically active major geological structure; and the peak particle velocity at the rockburst site (PPV).

The objective of the site geotechnical engineer in dynamic support selection is to obtain a sufficient engineering specification for at least the following aspects of support and reinforcement:

- a load demand component;
- a displacement or elongation demand component;
- an energy dissipation demand component.

The load demand is controlled by the geometry of a failure rock volume, the displacement demand by the depth of failure and the rock mass bulking factor, and the energy demand by the volume of ejected rock and a representative ejection velocity.

The load-displacement behavior of support elements or systems can be described as stiff versus soft, strong versus weak, and brittle versus ductile (yielding), Fig.2. In the burst-prone ground, the desired properties of individual elements or support systems depend on the anticipated severity of damage inflicted by a rockburst and on the intended role of the support systems. Initially, stiff and strong support is advantageous to reinforce the rock and to prevent loosening or weakening of the rockmass near the excavation. However, if rockburst damage of major severity is anticipated, the rockmass should not only be reinforced to control the bulking process, but the holding elements must be ductile and able to yield.

The best strategy for rock support in rockburst-prone grounds is to combine softness and stiffness performances of support elements such that the support system will behave like a stiff system when stiffness is needed and change to a yielding system when softness is required [20].

Kaiser and Cai [21] summarized four functions required to provide a reliable dynamic support system for rockburst prone ground as illustrated in Fig.3:

(1) "*Reinforce* the marginally stable rockmass to strengthen it and to control the bulking process by preventing fractures from propagating and opening up";

(2) "*Retain* broken, fractured rock to prevent key block failure and unraveling";

(3) "*Hold* retaining system and reinforced rock back to the stable ground with deformation compatible support components";

(4) "*Connect* holding and retaining components to ensure system stability".

Some support components have multiple roles in terms of the four support functions but they may be strong in one aspect and weak in the others. Various support devices must be combined to form an integrated support system and to maximize their capabilities for dynamic support in rockburst prone grounds.

In Table 3, examples of typical support elements having the general characteristics noted in Fig.2, considering the required support functions in rockburst prone grounds presented.

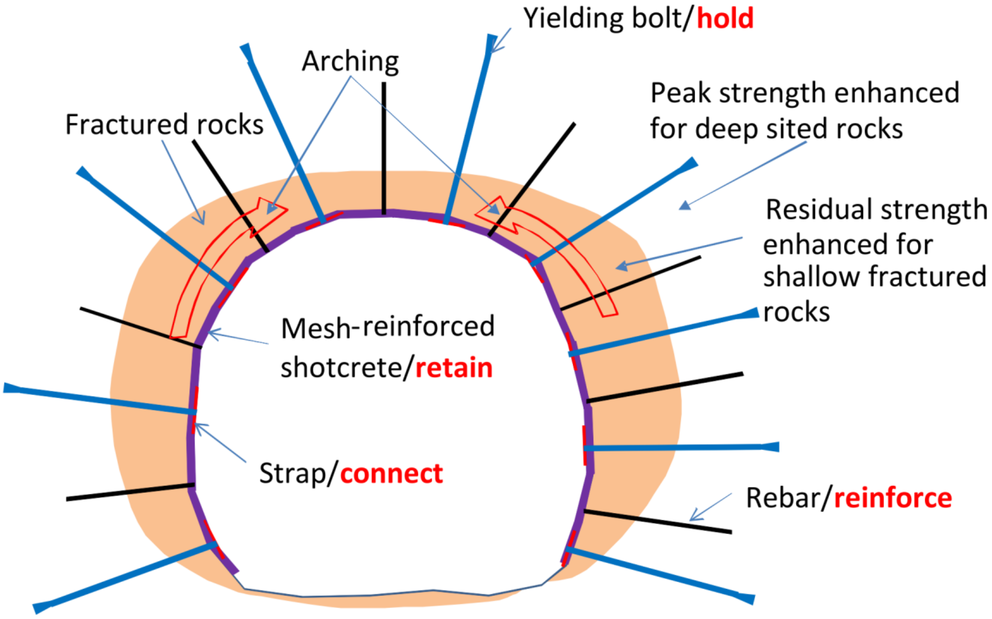


Fig. 3. Required support functions in rockburst prone ground [22].

Table 3. Characteristics of typical support elements considering support functions in rockburst prone grounds

Support characteristics	**Support functions**			
	Reinforcing	**Retaining**	**Holding**	**Connect**
Stiff	grouted rebars	shotcrete	grouted rebars	plates
Soft	-	mesh	long mechanical bolt	-
Strong	cable bolts	fiber/ mesh reinforced shotcrete	cable bolts	strong threads
Weak	thin rebars	weld mesh	Split Set bolt	threads
Brittle	grouted rebars	plain shotcrete	grouted rebars	-
Yielding (ductile)	energy-absorbing bolts	HEA mesh, chain-link mesh	yielding Swellex	straps

Table 4. Energy absorption capacities of various types of surface support (from Western Australian School of Mines static tests).

Surface Supports	**Energy absorption per unit area (kJ/m2)**	**Maximum displacement at failure (mm)**
FRS 60 mm, synthetic fibre	0.8	60
FRS 80 mm, synthetic fibre	2.2	80
FRS 110 mm, steel fibre and weld mesh embed.	7.0	120
FRS 60 mm + weld mesh over	2.1	210
FRS 80 mm + weld mesh over	3.5	210
FRS 60 mm + M85/2.7	3.2	200
FRS 60 mm + G80/4	7.3	300
FRS 80 mm + M85/2.7	4.6	200
FRS 80 mm + G80/4	8.7	300
Weldmesh 100 × 100 mm (5.6 mm wire)	1.3	210
M85/2.7 mesh (Minax high-tensile chain-link)	2.4	200
G80/4 mesh (Tecco high-tensile chain-link)	6.5	300
Woven mesh (6 mm wire) with welded double-wire on perimeter	2.0	300
High Energy Absorption (HEA) mesh	11.8	800
Woven mesh (10 mm wire)	22.5	600
*** Note: Selected surface supports must have energy and deformation capacities well over demand.**		

In the rockburst-prone ground, a support system is only as strong as its weakest link. Observations from rockburst damage have shown that the weakest link of support systems submitted to dynamic loading is often the surface support or the connection between the surface support and the reinforcement. A conservative assumption would be to use the energy absorption capacity of the surface support devices as the capacity of the overall support system [23]. Most surface support devices have an energy absorption capacity of less than 10 kJ, see Table 4.

Some miners and ground control engineers do not prefer to use shotcrete as a surface support system in burst-prone grounds because they have seen that shotcrete became part of the “fly rock” when a rockburst occurred. Early application of shotcrete on well-prepared rock surfaces (high-pressure water scaling) can inhibit rockmass dilation, reinforcing natural or mining/blasting induced fractures. This in turn can help later load transfer to rock bolts and reduce the amount of rock unraveling and therefore enhance the overall integrity of the rock mass [24]. Shotcrete can enhance the weak link between the rock bolt and mesh. From the integrated system support principle, we know that shotcrete is a very useful component in the system, and we need to use it effectively in the support system. If yielding bolts and mesh/ straps are installed over top of any applied shotcrete, the problem of “fly rock” can be resolved.

Weldmesh panels are easy to handle and are strong and stiff enough to prevent small rockfalls and the subsequent unravelling of tunnel roofs, but they cannot absorb large dynamic impacts. The welded connections are brittle and normally fail first under dynamic loading, followed by the strands when the loads further increase. High-tensile steel wire mesh (also known as high energy absorption (HEA) mesh) has been specifically designed to absorb energy from dynamic loading induced by large seismic events, but it is also suitable for application in very poor ground conditions where high convergence and squeezing ground are experienced. The HEA mesh showed good performance in rockfall and rockburst testing. Due to its strength and ductility, the mesh was able to absorb the kinetic energy thereby showing slowing down the impacting rock mass. The high strength of the mesh is required to transfer the rockburst loads to the anchors and to avoid puncturing of the mesh by the rock fragments [25, 26].

Energy absorption and maximum displacement capacities of various surface support devices are given in Table 4. All data presented in Table 4 are based on the static test results published by the Western Australian School of Mines (WASM).

An ideal type of surface support in dynamic loading conditions is one offering high stiffness at the commencement of wall deformation and then engaging its yielding capability as deformation progresses. The initial stiffness is required to minimize the extent of rock fracturing and hence rock bulking. Such capability is well displayed by fiber-reinforced shotcrete (FRS) under static conditions in moderate to high-stress environments. In dynamic conditions (rockburst-prone ground) FRS can neither sufficiently deform nor distribute the load throughout the rock bolt array. Therefore, optimal surface support in these conditions should comprise a combination of FRS and mesh [27].

Considering the extensive use of rock bolts in both civil and mining projects, in the next sections, the performance of rock bolts in high-stress conditions are presented in more detail and more common energy-absorbing rock bolts to combat high-stress induced instability problems such as rockburst and rock squeezing conditions are introduced.

3.1. Performance of rock bolts in high-stress ground conditions

Rock bolting has been widely used all over the world as an effective rock reinforcement element both in civil and mining engineering for a long period. Rock bolts can be classified according to their performance as a strong bolt, a ductile bolt, or an energy-absorbing bolt (Fig.4). Strong bolts such as fully encapsulated rebar bolt have the advantage of a high load-bearing capacity; however, it tolerates small deformations before failure, making it a strong but stiff rock bolt. Ductile bolts such as split sets can accommodate large rock deformations but their load-bearing capacity is quite low.

Rebars and Split Sets are low energy-absorbing devices and are used mainly to deal with instability problems under low or relatively low rock stress conditions. The desired type of rock bolt for rock support in high-stress rock masses should not only have a high load-bearing capacity but also

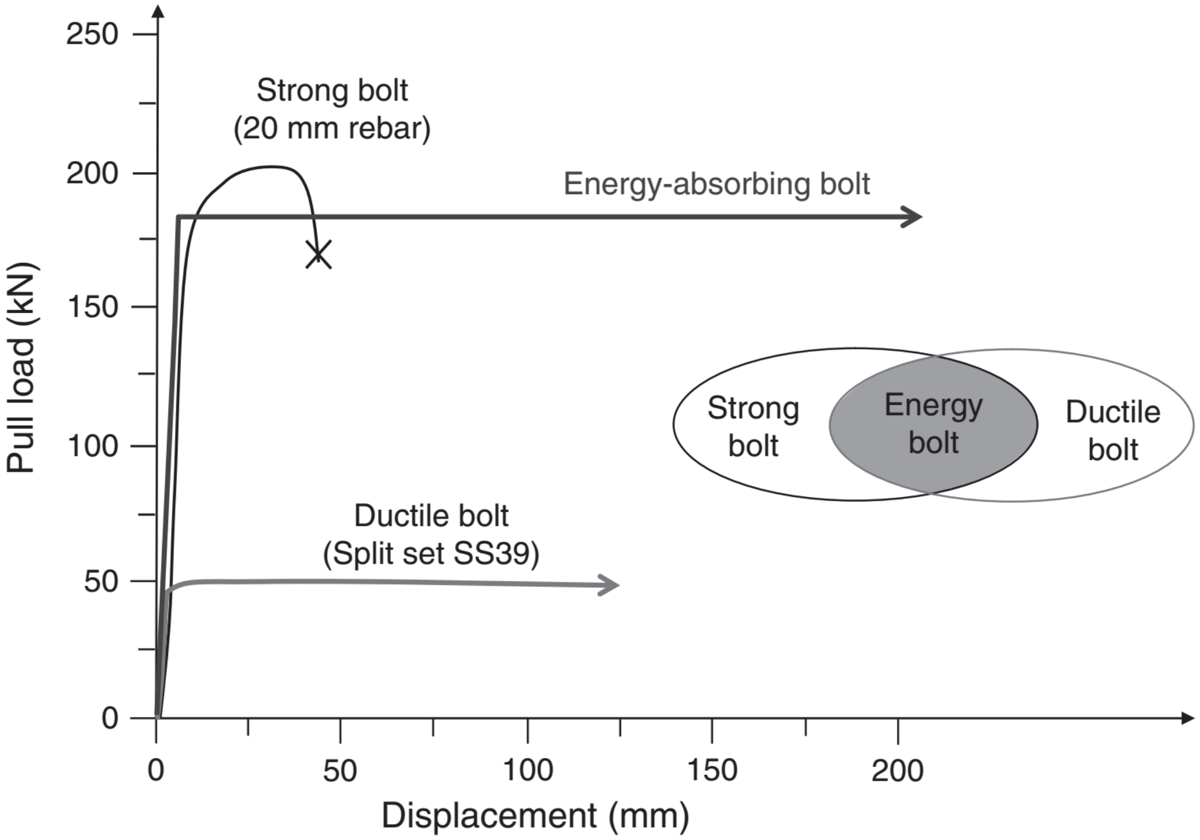


Fig. 4. Performance of rock bolts subjected to pull loading and Concept of the energy-absorbing bolt [28].

Table 5. Energy absorption mechanism of various commercially available rock bolts.

Energy-absorbing rock bolts	References	Deformation and Energy absorption mechanism
Frictional stabiliser/split set	Patented by Dr. James Scott (1973)	Slippage
Cone Bolts	[30]	Ploughing
Durabar Bolt	[31]	Bar stretching
Modified Cone Bolts	[32]	Ploughing
Roofex	[33, 34]	Slippage
Garford Solid Bolts	[35]	Bar stretching
Yield-Lok Bolts	[36]	Ploughing
D-Bolts	[37]	Bar stretching
He Bolts	[38]	Slippage
Posimix Bolt	[39]	Bar stretching
Kinloc bolt	[39]	Slippage/bar stretching
Swellex bolts	[40]	Slippage

should be able to accommodate large deformations. In other words, they should be able to absorb a large amount of energy before failure. When absorbing the same amount of energy, the bolt exhibiting the least displacement is preferred since it is more efficient in restraining rock movement. Energy-absorbing rock bolts are suitable for supporting not only the burst-prone ground but also squeezing the rock.

In massive hard rocks, energy accumulation takes place around the excavation and sudden failure modes may occur, while in thin layered or foliated rocks, large deformations and gradual failures are predicted. Opening of single extension fractures, or existing rock joints, would also cause rock dilation towards the tunnel excavation. In contrast to continuous deformations in squeezing rock, fracture/joint opening causes a local stress concentration in the rock bolt and may thus lead to premature failure of the rock bolt. In the case of hard rocks, the rock spalls and sheds pieces like onionskin behind the bolt plate, leaving a short section of the rock bolt extruded out of the rock surface. The premature failure of the rebar bolts implies that the rebar is too stiff to sustain rock dilations in high-stress rock masses.

Stiff rebar bolts, in combination with mesh or shotcrete, can control the rock bulking due to fracturing very well in hard rocks under relatively low to moderate stress conditions. When a rockburst strikes or under high-stress conditions, rebar bolts can break (usually at the threaded section) and lose their holding function but they still have their reinforcing function to some degrees. However, if yielding (energy-absorbing) bolts with straps are added to the rock support system, then a two-tiered defense system is formed. Rebar bolts (as static/stiff support) will reinforce the rock mass to ensure that it is not fracturing pre-maturely. When the rock masses do fail, the yielding (energy-absorbing) rock bolts as dynamic support will ensure that the fractured rocks are properly retained.

Masoudi et al. [29] introduced modifications on rebar rock bolts to utilize them effectively as yielding support in seismic conditions. They improved the dynamic performance of encapsulated rebar bolts by two easily applicable and cost-effective modifications including a) applying a sufficient decoupled length in the shank of rebar rock bolts which improves the deformation capacity of the bolt, and b) leaving a collar bonding underneath the bearing pad and plate which removes the weaknesses of the head anchorage of the rebar rock bolt.

3.2. Energy-absorbing rock bolts

Since 1980, extensive research and development work on yielding rock support has been conducted. Some yielding bolts have been successively developed and gradually accepted by many ground control engineers to combat high-stress-induced instability problems such as rockburst and rock squeezing conditions. The typical products are the Cone Bolt developed by COMRO, South Africa [30], the Durabar yield rock bolt invented in South Africa [31], the Modified Cone Bolt developed by Noranda, Canada [32], the Roofex yielding rock bolt produced by Atlas Copco [33, 34], the Dynamic Solid Bolt produced by Garford Dynamic Bolt in 2008 [35], the Yield-Lok Bolt developed by Jennmar [36], the D-Bolt invented in Norway [37], the He Bolt invented in China [38] and Kinloc bolt produced by DSI at the end of 2014 [39]. The terminology “energy-absorbing” is used in some literature to express the concept of the yield capacity of a rock bolt. Yield and energy-absorbing are synonyms in this paper.

As mentioned before, a yielding rock bolt can carry a high load and also accommodate significant rock displacement, and thus its energy-absorbing capacity is high. The test results show that the energy absorption of these bolts is much larger than that of all conventional bolts.

Energy absorption and deformation mechanisms of various commercially available yielding rock bolts are presented in Table 5. Yielding rock bolts accommodate rock dilation and absorb energies via ploughing of the anchor in

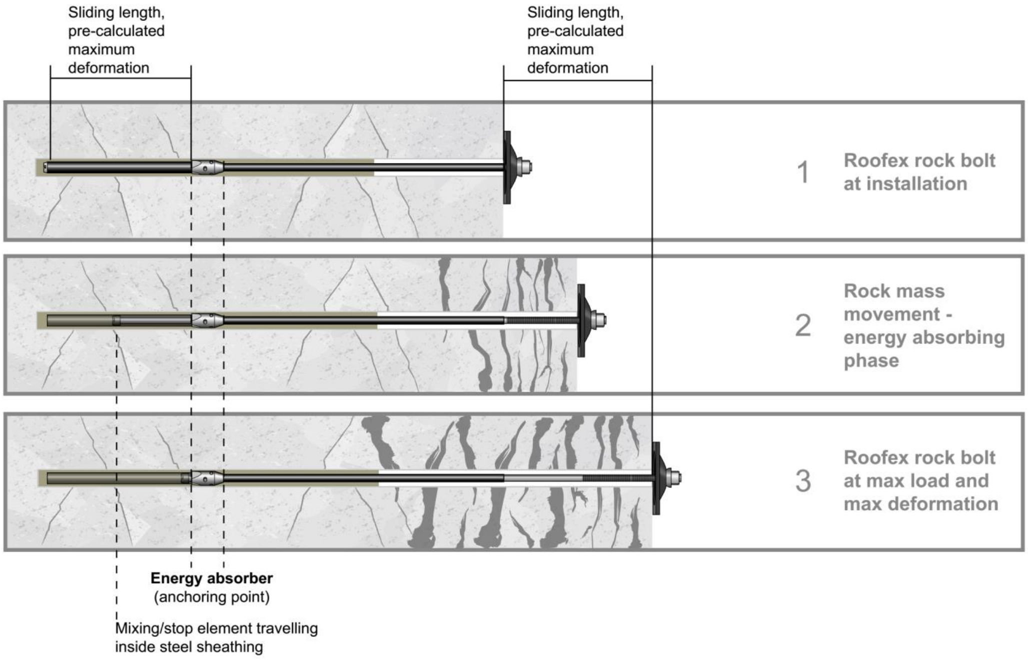


Fig. 5. The working principle of the Roofex rock bolts, deformation, and energy absorption mechanism.

Table 6. Demand–capacity based rock bolt selection (modified after [41]).

Ground demand		Reinforcement selection	
Surface displacement (mm)	Energy (kJ/m2)	Recommended rock bolts	Capacity category
<50	<5	Expansion shell rock bolt, Resin/cement grouted rebar	Low/stiff
50-100	5-15	Split set, Swellex, Roofex	Medium
100-200	15-25	D-Bolt, Conebolt, Roofex, Yield-Lok	High
200-300	25-35	Conebolt, D-Bolt	Very high
>300	>35	Conebolt, Garford	Extremely high

the grout, through slippage of the bolt shank through the anchor/grout, or stretching of the steel bolt.

All above mentioned energy-absorbing rock bolts are two-point anchored in boreholes except D-bolt which is multi-point anchored in a fully grouted borehole.

Efforts were made to usefully bonded and debonded threadbare for dynamic rock support [25]. Differently from the other rock bolts described above, threadbare absorb energies by partially or fully mobilizing the strength and deformation capacities of the bolted steel.

Notably, displacement is a quantity that should be restrained by the support system rather than to which the support system should adapt. To absorb a given amount of energy, the smaller the displacement of the bolt is, the better the support effect is. Thus, the energy absorption per unit displacement is an appropriate parameter to evaluate the performance of a rock bolt.

The working principle of the Roofex rock bolts as an energy absorbent (yielding) rock bolt and its deformation and energy absorption mechanism have been illustrated schematically in Fig.5.

Typical Load- Displacement behavior of different types of rock bolts subjected to pull loading is illustrated in Figure 6. Considering load capacity, displacement capacity, and energy absorption capacity, rock bolts were classified into 5 categories including strong bolts, ductile bolts, moderate energy-absorbing bolts, high energy-absorbing bolts, and very high energy-absorbing bolts as illustrated in Fig.6. Considering rock bolts' energy absorption capacities illustrated in Figure 6, suitable rock bolt type selection for various ground demand categories is proposed in Table 6. This table could be used as an initial guideline to narrow the choices, and it is evident that complementary studies such as dynamic tests are required for detail design [41].

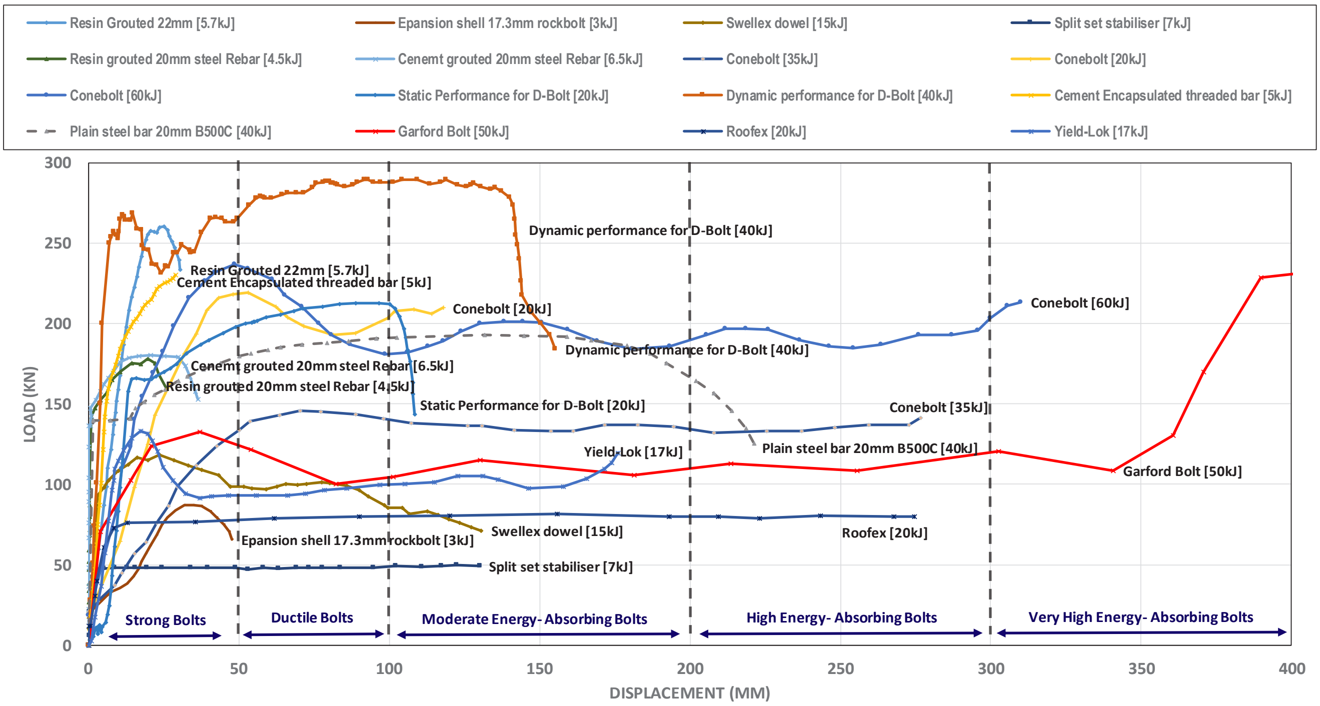


Fig. 6. Load- Displacement behavior of different types of rock bolts (modified after [41]).

3.3. Ground control methods in the rockburst-prone ground in mining and civil tunnels, case studies

In this section, case studies are presented to describe examples of ground control methods in rockburst-prone ground conditions. Information describing the current practices for ground control at several high-stress underground mines and civil tunnels is also presented.

Data from mines with stress-driven failure and current ground support practices are presented in Table 7. The strength to stress ratio presented in this table only considers in situ stresses. Based on benchmarking information, mines with high-stress-to-strength ratios and therefore strong seismicity rating, tend to employ a combination of fiber-reinforced shotcrete (FRS) and mesh as external support devices, and energy-absorbing rock bolts as internal support elements. Development trending perpendicular to in high-stress mining, environments should have some level of dynamic support. For mines that are rockburst-prone, the face should be meshed for all development trending perpendicular to .

Data for civil tunnels in burst-prone grounds and applied mitigation measures are presented in Table 8. Based on benchmarking information, the main mitigation measures and support devices in civil tunnels with rockburst hazard include de-stressing blasting, reduced blasting length and/or optimization of the drilling scheme, steel ribs, fiber-reinforced shotcrete, rock bolting, and sequential excavation.

4- Support under large deformation and squeezing rock conditions

The term "squeezing rock" originates from the pioneering days of tunnelling in the Alps. Terzaghi [42] provides one of the earliest and scientific descriptions of squeezing rock behavior concerning tunneling as follows: "Squeezing rock slowly advances into the tunnel without perceptible volume increase. Prerequisite of the squeeze is a high percentage of microscopic and sub-microscopic particles of micaceous minerals or clay minerals with a low swelling capacity."

Aydan [43] provided a general description of squeezing in rocks from the phenomenological point of view by distinguishing between three failure mechanisms:

- Complete shear failure: generally observed in continuous ductile rock masses or masses with widely spaced discontinuities.
- Buckling failure: This type of failure being generally observed in metamorphic rocks and thinly bedded ductile sedimentary rocks.
- Shearing and sliding failure: Generally observed in relatively thickly bedded sedimentary rocks.

Large deformations refer to squeezing pose a considerable challenge in the construction and maintenance of underground excavations in rock. Squeezing conditions imply a reduction in the cross-sectional area of excavation.

Squeezing conditions are encountered in both civil tunnels and mining drives in poor quality or weak rock but

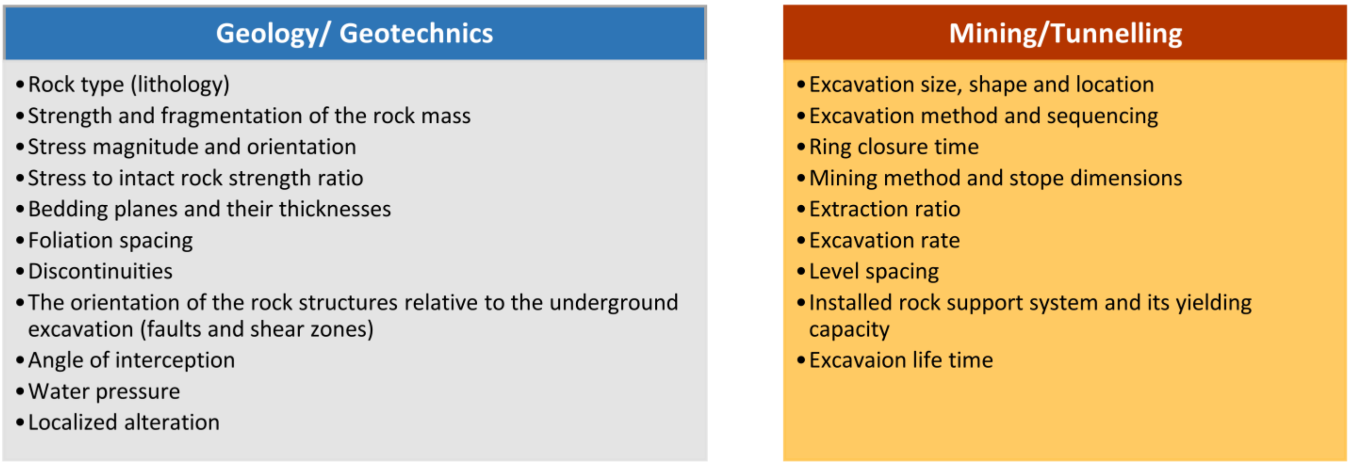
Table 7. Ground support benchmarking data for mines in the burst-prone ground (modified after [44]).

Mine	Strength: stress ratio	Seismicity	Surface support	Rock bolts	Bolt spacing, m	Other supports
Mine A (Australia)	1.2-2.6	Moderate	75 mm FRS+ weld mesh to 1.8 m from the floor	2.4 m D-bolt	1.0 × 1.5	Face meshed for drives sub-parallel to σ1
Mine B (Ghana)	0.5-1.4	Strong	75 mm FRS+ weld mesh to floor	2.4 m Garford dynamic bolt	1.2 × 1.2	Face meshed
Mine C (Canada)	3.3-4.2	Strong	Mesh 1.8 m from the floor	2.4 m Kinloc bolt	1.1 × 1.1	Closure pillar mining sequence
Mine D (New Zealand)	0.6-1.8	Strong	50–75 mm FRS+ weld mesh to floor	2.4 m D-bolt	1.4 × 1.1	Face meshed, cable bolts and mesh straps
Mine E (Canada)	2.9-5.8	Minor	Weldmesh to 2 m from the floor	2.4 m debonded resin bolts	1.3 × 1.2	-
Mine F (Australia)	1.8-5.3	-	60 mm FRS+ weld mesh	2.4 m Garford dynamic bolts	1.5 × 1.4	-
Mine G (Australia)	1.4-1.9	Strong	75 mm FRS+ mesh to floor	3 m debonded resin bolts	1.4 × 1.5	Face meshing where required

Table 8. Ground support benchmarking data and mitigation measures for civil tunnels in the burst-prone ground.

Tunnel	Reference	Hazard	Mitigation Measures
Furka Base railway tunnel [Switzerland]	[45]	Rock bursts similar to slabbing in coarse homogeneous granite. The maximum overburden measures approx. 1500 m.	rb; srb+sh (dry mix); fbr (f/c)
Vereina railway Tunnel [Switzerland]	[46]	Rock bursts in extremely hard and tough amphibolites. The maximum overburden measures approx. 1500 m.	rb; srb+sh (wet mix); fbr (f/c)
Maule hydroelectric tunnel (D~8m), [Chile]	[47]	Heavy rockburst during full-face excavation in hard grain-diorite	sp; bl; rb+sh
Campegno roadway tunnel (D ~12m), [Italy]	[48]	Highly anisotropic stress conditions (k≈0.3), with principal stress, inclined, parallel to the surface slope. Occasional rockburst in rhyolitic- orphyric rock mass during full-face excavation.	dh; sp(f); bl; srb+sh
Gotthard Base Tunnel [Switzerland]	[49]	In the bedded, heavily jointed gneisses in the MFS Faido, rock bursts or events similar to rockburst have been recorded in various tunnel drives of the MFS. These occurred in 75% of the cases in the face in the first three hours after a blast and were noticed in the form of vibration, cracking sounds, and spalling from the face. Preventive measures at the face against rockburst danger in MFS Faido included partial-face excavation, arched face, a wedge of material as an obstruction in front of the face, face sealing, and bolting. Special temporary support measures could be used, e.g. Swellex or yielding Swellex rock bolts or flexible steel arches to resist dynamic loading in rockburst. The most important measure, however, was the change from the originally intended and practiced full face excavation to an advanced top heading followed by excavation of the bench and the invert. This greatly reduced the danger to the miners from spalling and ruptures from the face due to stress release and rockburst. Despite about 1000 smaller rock bursts (mostly at the tunnel face) and some 10 larger rock bursts no accidents or injuries due to rock bursts occurred.	rb; ssrb+sh; se

Note: **bl**=reduced blasting length and/or optimization of the drilling scheme; **dh**=de-stressing blasting; **fbr (f/c)** = pre-consolidation by cemented/resin fibreglass (face/contour); **rb** = radial bolting; **sh**=shotcrete (fibre-reinforced or with steel mesh); **sp**=spiling in advancement; **srb**=steel ribs; **ssrb**=sliding steel ribs; **se**= sequential excavation.



Geology/ Geotechnics

- Rock type (lithology)
- Strength and fragmentation of the rock mass
- Stress magnitude and orientation
- Stress to intact rock strength ratio
- Bedding planes and their thicknesses
- Foliation spacing
- Discontinuities
- The orientation of the rock structures relative to the underground excavation (faults and shear zones)
- Angle of interception
- Water pressure
- Localized alteration

Mining/Tunnelling

- Excavation size, shape and location
- Excavation method and sequencing
- Ring closure time
- Mining method and stope dimensions
- Extraction ratio
- Excavation rate
- Level spacing
- Installed rock support system and its yielding capacity
- Excavaion life time

Fig. 7. The main factors influencing squeezing damages and severity in underground excavation.

also structurally defined rock masses. Weak rock masses behave differently from stronger rock masses when subjected to tangential stresses, and show significant time-dependent deformation behavior under high-stress conditions. In weak rock masses such as shale and phyllite, when the strength is less than the induced tangential stresses along the tunnel periphery, gradual formation of micro-cracks along the schistosity or foliation plane will take place. Thus, a viscoplastic zone of micro-fractured rock mass is generated deep into the walls.

From worldwide experience in tunnelling in squeezing rock, the following empirical facts concluded:

- Large long-term deformations or large long-term rock pressures only occur in rocks of low strength and high deformability. A pronounced creep capacity is an important prerequisite for the occurrence of this type of rock pressure.
- The rock pressure decreases with increasing rock deformation.
- The existence of groundwater or high pore pressures aids the development of rock pressure and rock deformation.

The main factors influencing squeezing (large deformations) damages and severity in underground excavations are illustrated in Fig.7. For the assessment of squeezing potential, all known factors must be considered and their relative influences must be established: if no quantitative assessment is possible then at least a qualitative description should be attempted.

There are important differences in the choice and economics of ground support strategies for squeezing rock conditions between civil tunnels and mining excavations. In civil tunnels, we have access to a range of effective support systems that can arguably manage ground deformation during and after the construction phase of tunnelling such as steel arches or ductile tunnel linings with yielding elements. The use of some of these systems in a mining environment, however, is prohibitively expensive and would involve considerable delays in development and production mining. Other important differences between civil and mining projects in squeezing rock conditions include the service life of excavations, desired rate of advancement, and convergence tolerance limits. In civil tunnels, the tolerance for deformation is low, and strain greater than 10% considered an extreme squeezing problem, while in mining excavations, large deformation can occur and closure greater than 2 m (40% strain) categorized as heavy squeezing ground.

From the viewpoint of a lifetime, all underground excavations can be classified into three main groups including:

- *Short-term excavations:* with a lifetime of less than 1-3 years, such as crosscuts, ore drives, temporary excavations, and exploration galleries.
- *Medium-term excavations:* with a lifetime of more than 3–10 years, e.g. level accesses, ventilation drifts.
- *Long-term excavations:* with a lifetime of more than 10 years, e.g. main accesses, declines, ramps, shafts. All civil tunnels could be categorized as long-term excavations.

4.1. Mining projects in squeezing rock conditions

For mining in squeezing ground condition, maintaining excavations open and operational is difficult and often results in considerable investment in rock reinforcement and support but also in time-consuming and sometimes hazardous scaling and rehabilitation operations. Large deformations are a major concern during the construction and maintenance of underground mining excavations.

The selection of ground support systems for squeezing conditions in mining drives is more often than not, a reactive process. As the level of squeezing increases mines are forced to explore different alternatives that can mitigate the resulting deformations [50].

Several mines have also explored the use of mesh embedded in between two layers of shotcrete or fiber create. This results in a stiff system that provides support at relatively small-scale deformations. Unfortunately, shotcrete will crack at low-level deformation. Consequently, several mines experiencing squeezing rock conditions are moving away

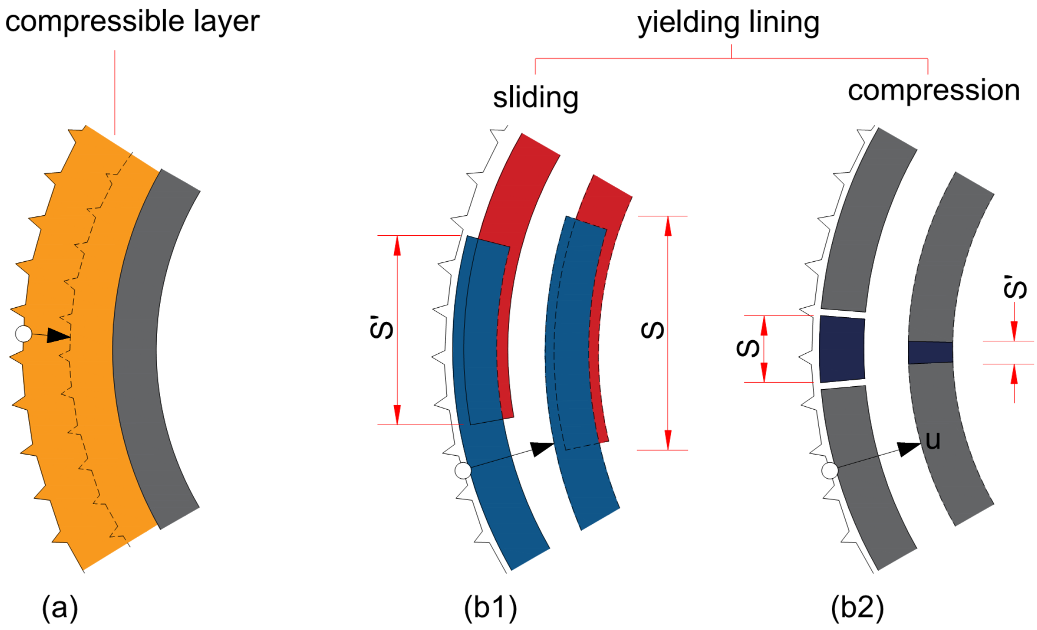


Fig. 8. Basic types of flexible support in civil tunnels.

from this support practice as it results in disproportionate and difficult rehabilitation. Another problem associated with shotcrete embedded mesh, which is more ductile than fiber creates, is the outside layer of shotcrete failing in large slabs. Australian mines, currently operating in squeezing rock conditions, favor the use of fiber-reinforced shotcrete, installed "in-cycle", and then applying mesh on top. The resulting surface support system, which keeps the rock mass together, is initially stiff until the shotcrete cracks and then acts as a soft system with the mesh containing the large shotcrete plates produced by the excessive wall deformation. The main drawback of this surface support system is its high cost. This, however, can become acceptable if it can be demonstrated that it can significantly reduce rehabilitation work.

Recently High Energy Absorption (HEA) meshes as external support devices have been specifically developed for application in very poor ground conditions where high convergence and squeezing ground are experienced.

Data from mines with squeezing ground conditions and ground support practices are presented in Table 9. Based on benchmarking information presented in Table 9 and reviewing ground support strategies used to control large-scale rock mass deformation under squeezing conditions in Australian and Canadian hard rock mines, it is evident that an effective support system makes use of both reinforcement elements and surface support. Case studies have shown that ductile surface support is an essential part of a successful ground support system in squeezing conditions. A difference between the two countries is the higher use of fiber-reinforced shotcrete in Australian mines, with Canadian mines using mesh.

4.2. Civil projects in squeezing rock conditions

There are two basic concepts for dealing with squeezing ground conditions in civil tunnels [51]. According to the so-called "resistance principle", a practically rigid lining is adopted, which is dimensioned for the expected rock pressure. In the case of high rock pressures, this solution is not feasible. The so-called "yielding principle" is based upon the observation that rock pressure decreases with increasing deformation. By installing a flexible lining, rock pressure is reduced to a structurally manageable value. An adequate over-profile and suitable detailing of the temporary lining will permit the non-damaging occurrence of rock deformations, thereby maintaining the desired clearance from the minimum line of excavation. The rock load reducing the effect of flexible supports has been known since the first decades of the 20th century. Major progress was made in 1932 with the introduction of sliding connections by Toussaint-Heintzmann (TH).

Generally, there are two technical solutions for accommodating large deformation without any structural damage to the support as illustrated in Fig.8 including:

- Arranging a compressible layer between the extrados of a stiff lining and the excavation boundary (Fig.8-a);
- Installation of a yielding lining in contact with the rock face (Fig.8-b).

Table 9. Ground support benchmarking data for mines in squeezing ground (modified after [44, 52-59]).

Mine	Strength: stress ratio	Foliation spacing (mm)	Squeezing Rating	Surface support	Rock bolts	Bolt spacing (m)	Other supports
Hartebeestfonte (S. Africa)	1.7	10-100	Very severe	-	2.2m smooth bars	-	-
Henty (Australia)	0.1-1.5	5-10	Severe-extreme severe	Φ5.6mm weld mesh	1.8-2.4m friction bolts	1.2×1.2	Cable bolts
Creighton (Canada)	0.4-0.7	-	Severe	#4 gauge galvanized mesh	46mm friction bolts	1.1×1.4	-
Peak (Australia)	<0.15	-	Minor	100mm thick plain shotcrete	2.4m debonded cables	1.3×1.8	Strap
Kristineberg (Sweden)	0.2-0.5 m damage depth		Moderate damage	Shotcrete	Rebar and D-bolt	1.0×1.0	-
Lapa (Canada)	0.1-1.2	1-100	Severe-extreme severe	Φ4.1mm galvanized weld mesh	Resin rebar, split set	1.9×2.3	Φ33mm, 2.0m hybrid bolt
LaRonde (Canada)	0.4-1.2	50-200	Severe-very severe	Weld mesh	Hybrid bolts	0.8×0.8	-
Maggie Hayes (Australia)	0.3-0.5	100-200	Moderate	50-75mm FRS + weld mesh	2.4m split sets and 5m cable bolts Φ45	1.3×1.5	5m twin strands cable bolts
Black Swan (Canada)	0.5-0.7	50-100	Severe	75mm FRS + weld mesh	1.8-2.1 split sets Φ43	1.0×1.0	0.9m stubby bolt
Agnew (Canada)	0.3	50-500	Minor-severe	50-75mm FRS + weld mesh	2.4m split sets and debonded cable bolts	1.4×1.4	-
Perseverance (Canada)	0.5-0.8	10-20	Very-extreme severe	75mm FRS + weld mesh + 50mm FRS	Omega (swellex) bolts	1.3×1.2	2.4m friction bolts
Mine A (Australia)	1.2–2.6	-	Severe	50 mm FRS+ weld mesh to floor	2.4 m hybrid bolt	1.1×1.4	Cable bolts and straps
Mine B (Ghana)	0.5–2.2	-	Severe	Weld mesh	2.4 m friction bolts and cement-grouted solid bar bolts	1.2×1.2	Cable bolts
Mine C (Canada)	0.5–1.6	-	Severe	Weldmesh to 0.6 m from the floor	2.3 m solid bar resin bolts, 2.0 m hybrid bolt	0.9×0.9	Cable bolts 2m spacing and mesh straps
Mine D (New Zealand)	1.2	-	Severe	50 mm FRS and weld mesh to 1.5 m from floor	2.4 m grouted DCS	1.0×1.0	Face bolted and meshed
Mine E (Canada)	0.9–1.4	-	Severe	Weldmesh to 0.6 m from the floor	2.0 m split sets, 2.3 m solid bar, 2.0 m hybrid bolt	1.2×1.2	Mesh straps
Mine F (Australia)	0.6–1.8	-	Severe	50–75 mm FRS+ weld mesh to floor	2.4 m D-bolt	1.4×1.1	Cable bolts and straps

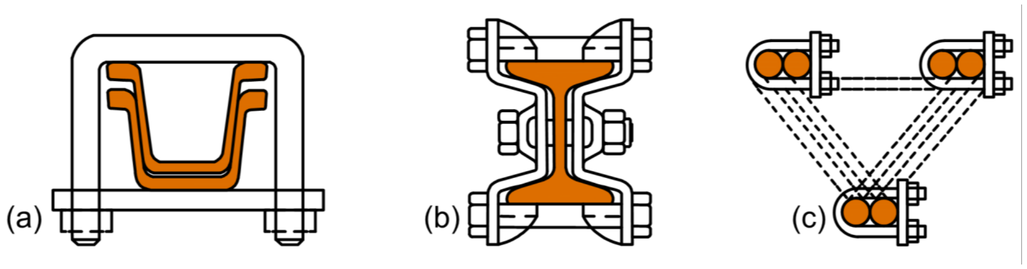


Fig. 9. Sliding connections of (a) top hat section steel sets; (b) H section steel sets and (c) lattice girders.

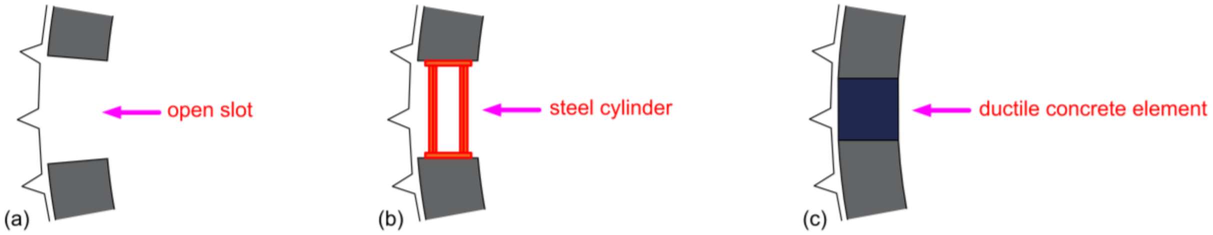


Fig. 10. Shotcrete shell with (a) open slots; (b) steel cylinders; and (c) ductile concrete elements.

The first solution (compressible layer) is practical in the case of slow and prolonged deformations during the service life of a tunnel.

In the second solution (yielding lining), the initial lining deforms with the rock and is efficient in the case of large deformations. The yielding lining could be sliding steel sets (Fig.8-b1) or inserting deformable elements into the shotcrete slots (Fig.8-b2).

The basic design parameters of yielding support are the deformability, in Fig.8-b, the number and the yielding load of the flexible joints. The first two parameters are selected based on the radial convergence that must occur to reduce loading (for a circular tunnel cross-section, $n.\Delta S = 2\pi u$).

Depending on the strength and the structure of the rock mass, block detachment or loosening of an extended zone above the crown may occur - particularly when considering the larger deformations taking place with yielding support. The yield load of the joints must, therefore, fulfill two criteria: it must be, (i), lower than the design load of the lining segments or the steel ribs but, (ii), higher than the resistance needed for safety against loosening. If the resistance of the flexible joints is not high enough, the support starts to yield under the weight of the rock [60]. Hoek et al. [61] indicated that a low yield load (e.g., 50 kPa) does not ensure safety against loosening.

Steel sets applied in squeezing ground have usually a top hat cross-section and are connected by friction loops (Fig. 9-a) offering a sliding resistance of up to 600 kN/set (4 loops x 150 kN) utilizing thus the high bearing capacity of TH ribs (TH-ribs successfully were applied in tunnels with up to 10% convergence). Occasionally, H cross-section ribs (Fig. 9-b) are also used. Lattice girders with sliding overlapping bars (Fig.9-c) have even been proposed although their contribution to the support resistance is negligible (very low buckling load of the bars).

A shell made of shotcrete can, due to the brittleness of the material, accommodate only small deformations without damage (maximum 1-2% convergence). Leaving longitudinal slots open in a shotcrete shell was a method used for dealing with high rock pressures in conventionally driven alpine tunnels in the 1970s (Fig.10-a). In this case, the high compressive strength of the shotcrete is not utilized, and its statical function degenerates to that of large anchor plates.

Compressible elements incorporated into the slots of the shell increase safety by utilizing the shotcrete during the deformation stage (Fig.11). For this purpose, so-called “Lining Stress Controllers (LSC)” have been developed, and were applied first in the Galgenberg Tunnel [62]. They consist of steel cylinders that are loaded in the axial direction (Fig.10-b), and which buckle in stages and shorten up to 200 mm at a load of 150 - 250 kN, thereby limiting the stress in the shotcrete shell.

Further progress in this field has been made recently with the introduction of beam-shaped High Deformable Concrete (HiDCon) elements composed of a mixture of cement, steel fibers, and hollow glass particles [63, 64], Fig.10-c. The

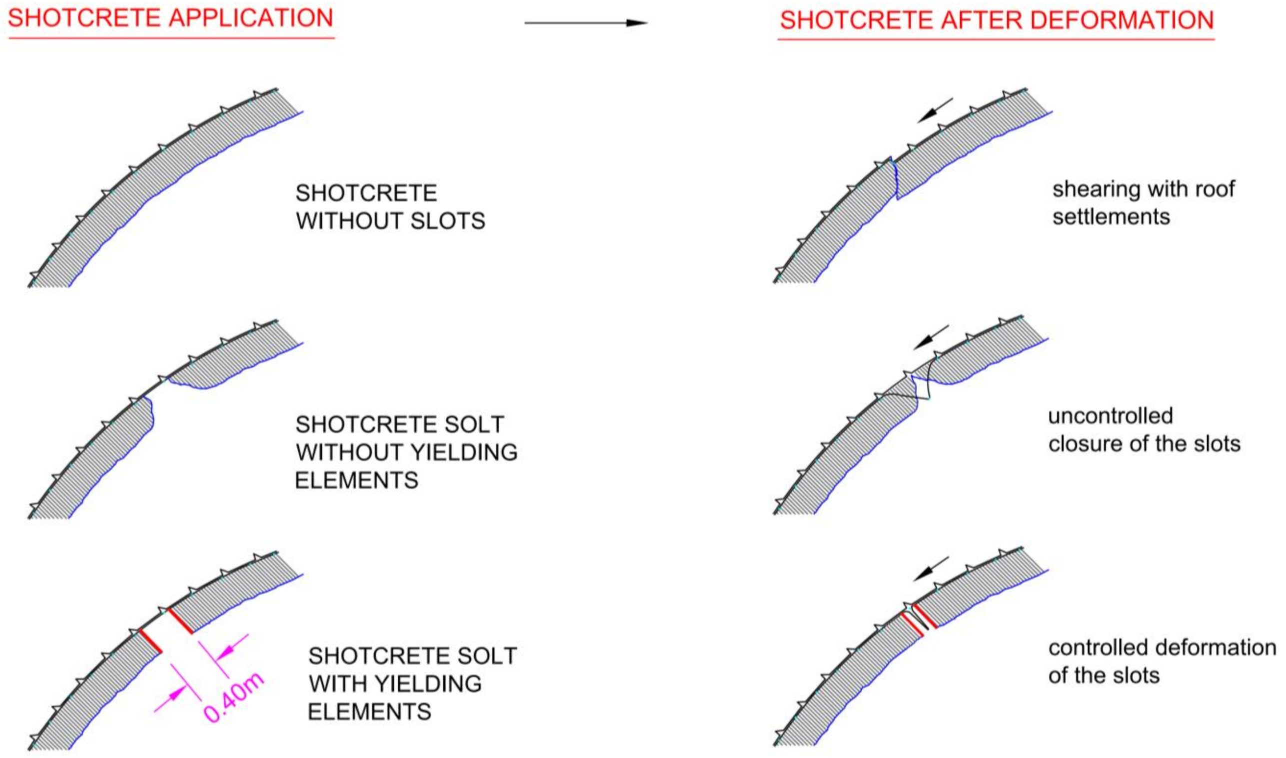


Fig. 11. Deformation of shotcrete shell with and without open slots.

glass particles increase the void fraction of the mixture and collapse at predetermined compressive stress, thereby providing the desired deformability. The elements yield up to 50% in a ductile manner, while the yield strength depends on the composition of the mixture and can be adapted to specific project conditions and ranges from 4 to 18 MPa.

The Lining Stress Controllers (LSC) have been incorporated into the slots of the shotcrete shell in the Galgenberg Tunnel (Austria), in the Semmering base tunnel (Austria), and the Gotthard Base Tunnel (Switzerland), Fig.12, and successfully controlled large deformations during passing high squeezing ground conditions.

The High Deformable Concrete (HiDCon) elements have been applied successfully in the Saint Martin la Porte access tunnel of the Lyon Turin Ferroviaire (France), Fig.13, and in the Lötschberg Base Tunnel (Switzerland).

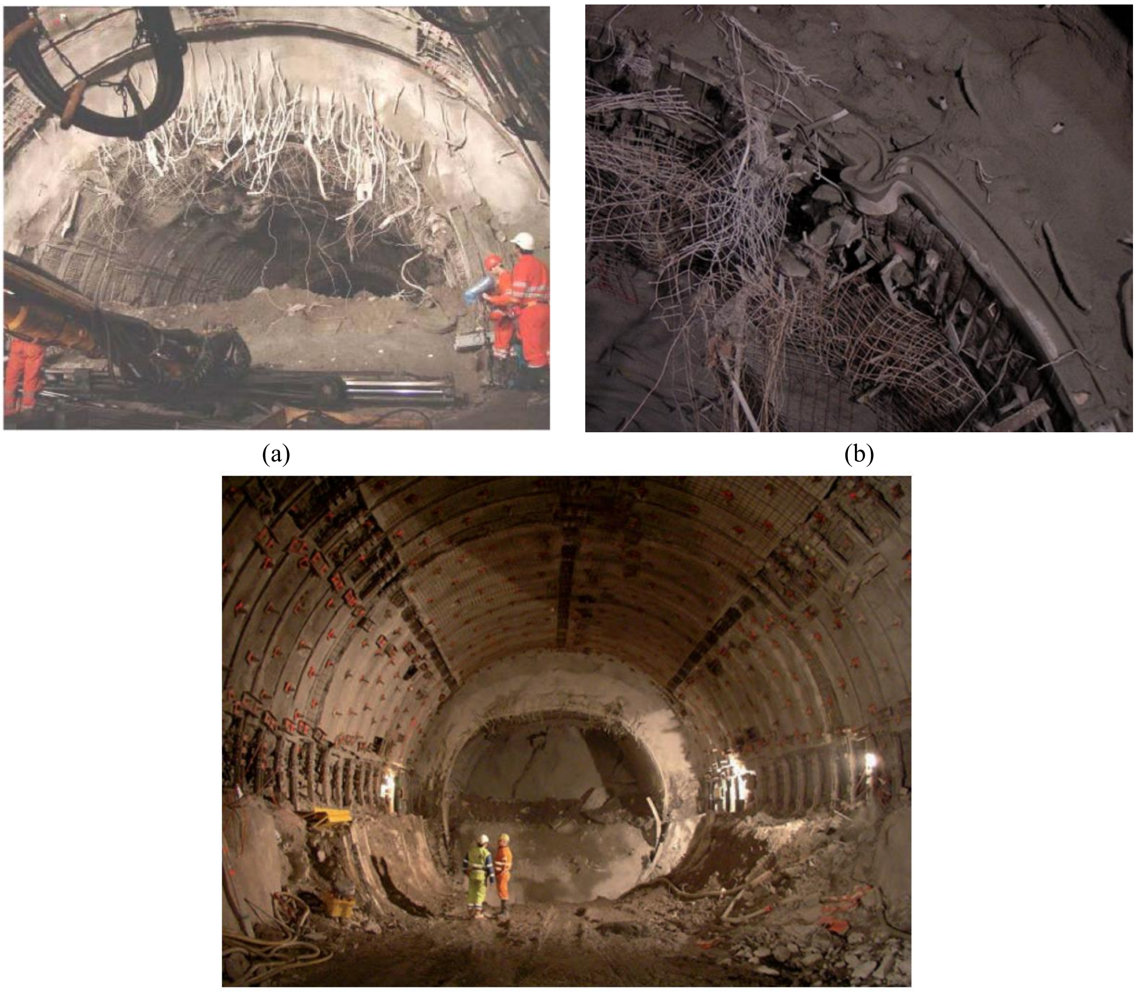
In Fig.14, a simplified Convergence Confinement Method (CCM) example of a shotcrete shell with and without yielding elements and an elastic and a plastic Ground Characteristic Curves (GCC) and a Longitudinal Displacement Profile (LDP) are illustrated. In Figure 14 it is evident that the Support Characteristic Curve (SCC) of the shotcrete shell without any yielding element does not reach the point of equilibrium. The consequence is a failure of the support and a collapse of the tunnel. The additional application of yielding elements in the shotcrete shell allows the support construction to absorb more deformation. In this case, the SCC reaches the state of equilibrium. In this example, yielding elements with 3 load stages of 600, 700, and 1000 kN and deformation of 70, 60, and 50 mm respectively have been considered.

Typical applications of the convergence confinement method are deep tunnels and squeezing ground conditions where time-dependent displacements play a major role.

Data from civil tunnels with squeezing ground conditions and applied mitigation measures are presented in Table 10. Based on benchmarking information, the main mitigation measures in civil tunnels with squeezing hazards include over-excavation, dividing the shotcrete liner into several segments, and installing yielding elements (LSC, HiDCon elements, …) between the segments in connection with yielding steel arch couplings and rock bolting.

5- Conclusions

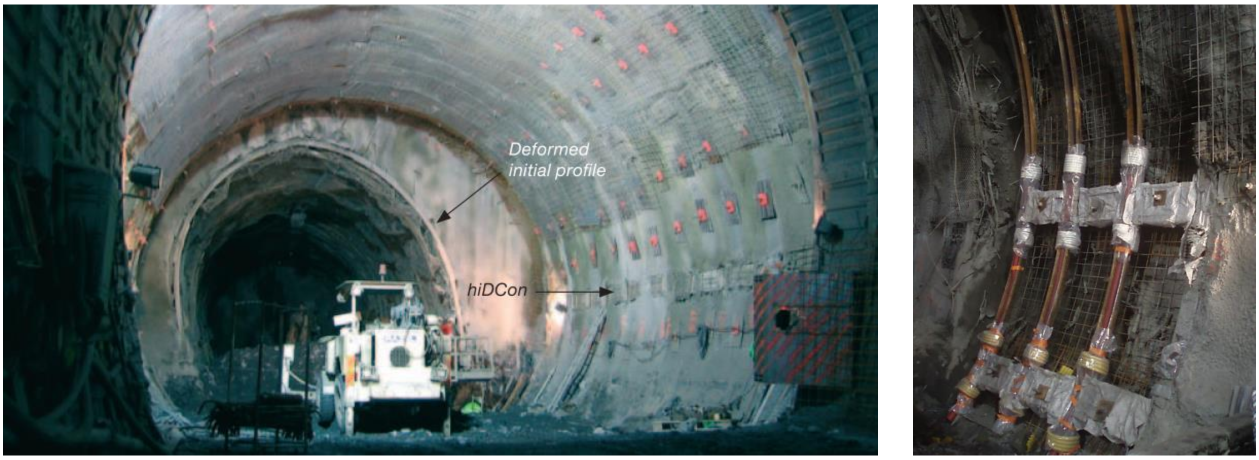
The tunnelling industry and its customers want safe tunnels, both during construction and operation. But they also want optimized tunnels from a life cycle cost perspective. The balance of achieving these two major goals is an interesting challenge and requires the industry to develop and improve. This paper has tried to outline some areas in which improvements in rock support systems may have a good effect on the result. Nowadays, by equipment and material development and increasing our knowledge and understanding of ground behavior, more complex and difficult ground conditions can be managed and more advanced support systems can be used to control the ground



(a) (b)

(c)

Fig. 12. (a) Destruction of support system by squeezing rock mass before installation of yielding elements; (b) close view of buckled HEM 180 arch with "suitcase fold"; and (c) Enlarged tunnel section and installation of LSC elements into the shotcrete slots and between TH bell profile steel sets with an old, smaller and deformed initial profile in the background in the Gotthard Base Tunnel, Switzerland.



(a) (b)

Fig. 13. Yielding support with HiDCon elements incorporated in the shotcrete lining and between TH bell profile steel sets with yielding couplings in the Saint Martin La Porte access tunnel in the (a) enlarged tunnel section with an old, smaller, and deformed initial profile in the background; and (b) a close view of installation detail of HiDCon elements

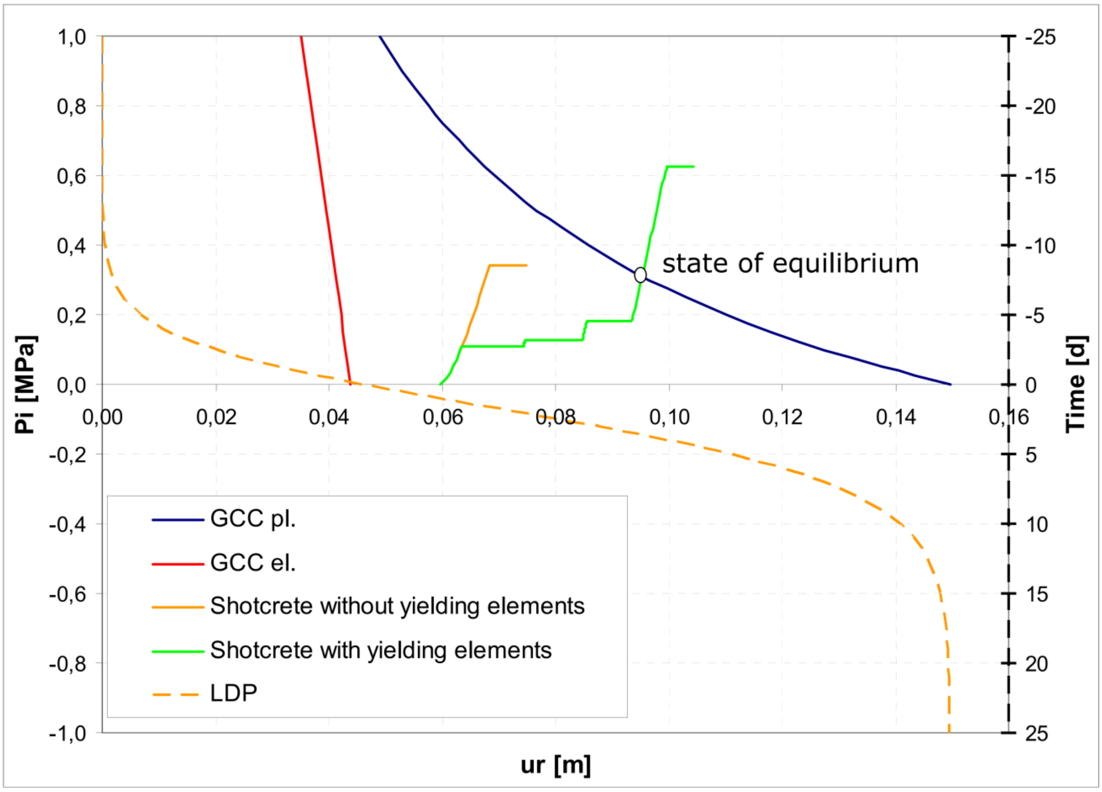


Fig. 14. A simplified CCM example of a shotcrete shell with and without yielding elements.

behavior in underground excavations under high in-situ stress conditions. The high stresses can lead to two consequences in underground excavations: rock squeezing in soft and weak rock masses and rockburst in hard and brittle rock masses.

Rock stabilization can be achieved by installing internal support devices, like bolts, within the rock mass, or by applying external support devices or structures, such as steel sets, shotcrete, and mesh, on rock surfaces. Internal support devices are integrated into the rock and make it stronger, while external support devices/structures provide support on the surface. In the case of rockburst-prone and squeezing ground conditions, both internal and external support devices should be capable of absorbing a good amount of the released strain energy to avoid premature failure of the support system instead of simply equilibrating the ground load because the ground load is not constant, rather it is correlated with the deformation. In mining engineering, people have put significant effort into developing energy-absorbing rock bolts in the past three decades (such as Cone Bolt, the Durabar yield rock bolt, the Modified Cone Bolt, the Roofex yielding rock bolt, the Dynamic Solid Bolt, the Yield-Lok Bolt, the D-Bolt, the He Bolt and Kinloc bolt). Energy-absorbing rock bolts with high load capacities are the ideal rock bolts for rock support, particularly in high-stress rock masses. Little work has been done to develop external energy-absorbing and yielding support structures in mining engineering, mainly because permanent external support structures are not widely used in underground mines.

On the other hand, significant advances have been made in the development of external energy-absorbing support devices or structures in civil engineering. Two technical options in squeezing ground conditions that have demonstrated the ability to maintain flexibility in the primary lining and to accommodate deformations without significant damage are Lining Stress Controller (LSC) and High Deformable Concrete (HiDCon) elements. They both can be installed in the gaps of a shotcrete lining and between steel sets with yielding couplings. Some efforts have been made by researchers to make rock bolts energy absorbent by adding deformable elements under the bolt plate but, in general, internal energy-absorbing support devices have not been widely used in civil engineering.

Table 10. Ground support benchmarking data and mitigation measures for civil tunnels in squeezing ground.

Tunnel	Reference	Hazard	Mitigation Measures
Tauern Tunnel [Austria]	[62, 65]	The Tauern-Tunnel intersects the foliation perpendicularly to the strike, and the cross-cuts are thus parallel to the foliation. In the Tauern Tunnel, the convergence was larger in the cross-cuts than in the main tunnel. A low-cost solution of dividing the shotcrete liner into several segments and leaving gaps between the segments in connection with yielding steel arch couplings was first applied in the Tauern tunnel by Rabcewicz (1973).	rb; ssrb+shd; ovx
Arlberg Tunnel [Austria]	[62, 65]	The Arlberg tunnel strikes sub-parallel to the foliation and faults, convergences in the order of several decimeters were common. In the cross-cuts, with similar size cross-sections, the convergences were of the order of several centimeters. The maximum overburden measures approx. 1000 m and the geology mainly consists of mica schist, feldspathic gneiss, and phyllite.	rb; ssrb+shd; ovx
Karawanken Tunnel [Austria]	[62, 65]	A low-cost solution of dividing the shotcrete liner into several segments and leaving gaps between the segments in connection with yielding steel arch couplings was applied.	rb; ssrb+shd; ovx
Furka Base railway tunnel [Switzerland]	[45]	Large deformations in squeezing rocks. Deformations could be stopped in squeezing ground by simply changing from a horseshoe to an elliptical profile shape.	rb; srb+sh (dry mix); fbr (f/c); ovx
Inntal Tunnel [Austria]	[66]	Sever squeezing during crossing an approx. 2000 m wide fault zones.	rb; ssrb+shd; ovx
Galgenberg Tunnel [Austria]	[66]	Severe squeezing when crossing a very heterogeneous fault zone (consisted of mainly sheared greenschist, platy greenschist, an intercalated fault gouge, and sheared graphitic phyllite).	rb (regroutable); ssrb+shd (LSC); ovx
Vereina railway Tunnel [Switzerland]	[46]	Heavy squeezing in horizontally or sub-horizontally bedded gneiss's.	rb; ssrb+sh (wet mix); fbr (f/c)
Yacamboo hydroelectric tunnel, [Venezuela]	[67]	Extreme squeezing behavior in very low strength graphitic phyllite at depths of up to 1200m	ovx; ssrb+shd; ovx
Semmering base tunnel [Austria]	[68]	Heavy squeezing during crossing a weak phyllitic rock mass section and the lining was severely damaged, requiring considerable repairs.	rb; ssrb+shd (LSC); ovx
Lötschberg Base Tunnel [Switzerland]	[69]	In a zone of highly squeezing rock with a great height of overburden, it was necessary to install HiDCon beam elements over a tunnel length of 180 meters.	rb; ssrb+shd (HiDCon); ovx
Stranger Tunnel [Western Austria]	[70]	The parallelism of schistosity planes and fault zones to the tunnel alignment resulted in long-lasting large deformations. During the heading excavation, a remarkable uplift of the heading invert of up to 1.5 m was observed.	rb; ssrb+shd; ovx
S.Martin La Porte Adit (D~10m) to the Base tunnel of the railway link Lyon-Turin [France]	[71-72]	In the zone crossing carboniferous black schist, an extremely severe squeezing condition during full face excavation (measured convergences up to 2m, which required re-shaping)	fbr (f/c); rb; ssrb+shd (HiDCon); ovx
Drisko's twin tube highway tunnel (D~12.5m), [Greece]	[48]	A severe squeezing condition during bench excavation in silty-flysch with a frequent band of highly tectonized rock mass, requiring additional stabilizing measures and frequent re-shaping.	dr; srb+rb+sh; ca; ovx
Gotthard Base Tunnel [Switzerland]	[73]	In the fault zones of the MFS Faido, but also in their extended borders, heavy squeezing rock was encountered associated with large deformations. The maximum rock overlay was about 2300 m.	rb; ssrb+shd (LSC); ovx; se

Note: **ca**=long cable anchor; **dr**=drainages in advancement; **fbr (f/c)** = pre-consolidation by cemented/resin fibreglass (face/contour); **ovx**= over-excavation; **rb** = radial bolting; **sh**=shotcrete (fibre-reinforced or with steel mesh); **shd**= shotcrete with deformable elements or gaps; **srb**=steel ribs; **ssrb**=sliding steel ribs; **se**= sequential excavation.

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