Sustainable Lining for Underground Hard Rock Openings

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ABSTRACT

Conventional cast-in-situ concrete linings are costly, time consuming and environmentally unfriendly solutions for supporting hard rock excavations, because concrete linings are unable to utilise the inherent strength of the rock. It is well understood that rock support is the application of a reactive force to the surface of an excavation such as concrete lining for example; whereas rock reinforcement is a means of conserving or improving the overall rockmass properties from within the rockmass by techniques such as rock bolts, cable bolts and ground anchors. This rock reinforcement strategy introduced to the tunnel roof and walls is considered to be a supporting element capable of sustaining a thrust at the arch ends. However, a potential small rock wedge failure is highly probable and may occur in between rock bolts. To deal with this issue, shotcrete linings will then be introduced acting as thin "protective skin" liners to support the rock surface with performance similar to a reinforced concrete slab. As the reinforced rock arch provides the required support to the opening, this shotcrete liner will then be designed to act as permanent protection cover and to comply with structural and durability requirements. Examples referenced in this paper demonstrate that the thickness of this shotcrete liner is relatively thinner than traditional concrete lining. Due to reduction of the permanent concrete lining thickness, the total excavation volume of caverns/tunnels is also reduced. As it minimises the use of cementitious products for permanent lining construction, thus leading to reduced CO_2 emissions and lower energy.

Keywords: excavation, failure, reinforcement, rockmass, support

1 INTRODUCTION

Other than mining, many of underground openings may be used for storage, transporting personnel, conveying materials and supplies, civil facilities, etc. Based on their function and service lifetime, these openings must be "sustainably" designed with an adequate factor of safety and constructed with proper work sequence.

In terms of sustainable solutions for openings in jointed hard rock, rock reinforcement approach is one of the underground rock-support methods and strategies. Rock reinforcement is a means of conserving or improving the overall rockmass properties from within the rockmass by techniques such as rock bolts, cable bolts and ground anchors. Rock support adopting conventional cast in-situ concrete lining is an expensive and time-consuming activity for rock caverns and tunnels and is considered inefficient for supporting hard rock excavations. Also, structural concrete is a mixture of cementitious products that require heat process in manufacturing and this process exhausts a huge volume of CO_2 to atmosphere to accelerate the greenhouse effect.

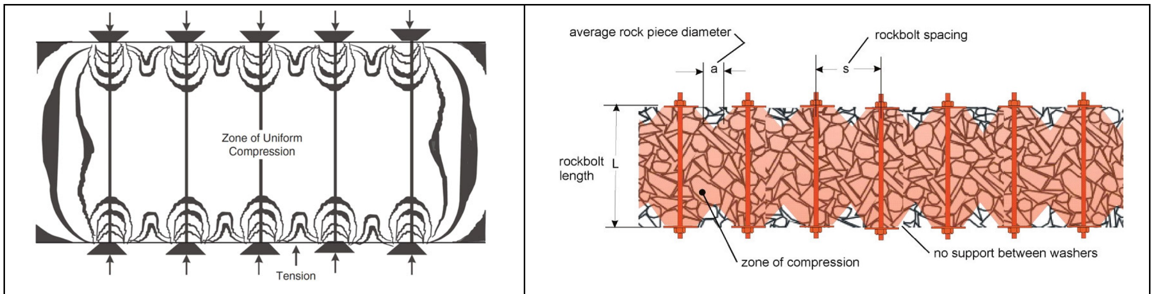
Hudson & Harrison (1997) and Kong & Garshol (2015) addressed that concrete linings are unable to utilise the inherent strength of the rock, particularly of strong rock with very poor quality of rockmass (i.e. $Q \geq 0.1$ or $GSI \geq 30$.) or better rock in terms of Q-value (Barton *et al*. 1974) or Geological Strength Index (Hoek, 1994; Hoek and Brown, 1997) respectively.

Detailed rock reinforcement design comprising rock bolts and shotcrete for underground openings has been discussed by Barrett & McCreath (1995), Uotinen (2011), and Kong & Garshol (2015). Further discussion on the constructability of shotcrete rock reinforcement from a sustainability point of view, such as less spoil generated, less cementitious products to be used for permanent lining, etc, is given in the following.

2 OVERVIEW OF ROCK REINFORCEMENT AND REINFORCED ROCK ARCH

Lang (1961) developed one of the commonly adopted empirical design rules based on a range of laboratory, field and theoretical studies. This was used for pattern rock-bolting of permanent excavations during the construction of the Snowy Mountains Hydro-electric Scheme in Australia. These empirical design rules have been reviewed by Brown (1999) and later re-modelled by Hoek (2007) using patterned bolts to stress up aggregate in a frame model.

Based on Lang's (1961) findings [Figure 1(a)], Hoek's (2007) model demonstrated that a zone of compression is induced in the region shown in orange [Figure 1(b)]. This will provide effective reinforcement to the rockmass when the rock bolt spacing *S* is less than 3 times the average rock piece diameter, and the rock bolt length L will be approximately of 2*S* to 3*S* (particularly a rockmass with closely spaced joints). The "zone of compression" of rockmass has been treated to become isotropic in strength due to the effects of tensioned pattern bolts. An axial pre-stress is developed due to Poisson's effect of normal stress on account of the bolt's pre-tension. This pre-stress can stabilise the rock beam effectively as in the case of a pre-stressed continuous concrete beam, which agrees with the Bischoff and Smart (1997) suggested model of reinforced rock arch. If a highly compressible feature such as a fault or a clay seam, or a highly fractured rockmass crosses the compression ring, it is possible that the required compression could not effectively be developed, and that the reinforcement will be inadequate.



(a) Photoelastic stress pattern of bolting (Lang 1961)

(b) Theoretical zone of compression by bolting (Hoek 2007).

Figure 1. Illustration of “zone of compression” formed by stressed pattern bolt in media.

Bischoff & Smart (1997) and Kong & Garshol (2015) give detailed discussions on the concept of the reinforced rock arch. This concept is based on improving the strength of the rockmass at the tunnel walls by application of confining pressure via the bolts. The rock arch formed by the tunnel walls is considered to be a supporting arch capable of sustaining a thrust at the arch ends as shown in Figure 2.

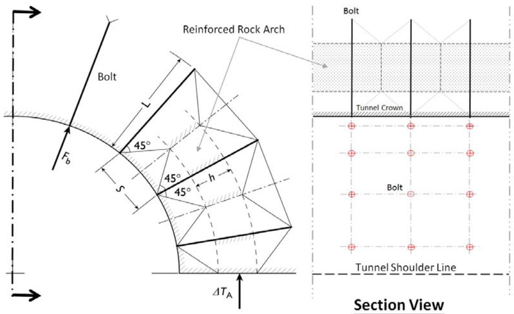


Figure 2. Geometry of tunnel bolting and rock arch thickness.

The Bischoff and Smart (1997) model showed that the thrust capacity of the rock arch is simply determined by the ratio of unconfined compressive strength to tensile strength with the provided bolt pressure. The thrust capacity of the rock arch (ΔT_A, half span of opening, in kN) is expressed as:

$$\Delta T_A = \frac{\sigma_c}{\sigma_t} \; x \; \frac{F_b}{S_2} (L - S) \qquad [1]$$

Where: ΔT_A is thrust capacity of the rock arch; h is reinforced rock arch depth; S is rock bolt spacing; L is rock bolt length; F_b is bolt force; σ_c is the unconfined compressive strength (UCS) of rockmass; and σ_t is the tensile strength of rockmass.

The thrust capacity of the rock arch (ΔT_A) can be equivalent to the Q support pressure (Barton *et al.*, 1974). According to a Mohr-Coulomb criterion, (σ_c/σ_t) can be rewritten as ‘q’:

$$q = \tan^2 (45 + \frac{Ø}{2}) \qquad [2]$$

Where ϕ is a friction angle (in degrees) of the rockmass. Based on the equations [1] and [2], the bolt length and spacing is entirely controlled by the UCS and tensile strength of the rockmass around the opening. In terms of rock strength, a stronger rockmass may require shorter bolt lengths and contrarily a weaker rockmass may need longer bolt lengths in place.

Comparing the Eq. (1) to Q-bolt length equation [i.e. $L_{Q\text{-}system}$ = 2 + (0.15B/ESR), as shown in Barton *et al.* 1974], it is hard to get agreement or a close relationship to determine the design bolt length using both approaches. For most cases when adopting closer bolt spacing, the estimated bolt length using Eq. (1) is shorter than the Q-bolt length. Contrarily in a wider bolt spacing arrangement, the estimated bolt length using Eq. (1) is longer than the Q-bolt length. With confidence of more than 40 years’ practical experience using the Q-system and the above findings of the bolt length relationship, it is recommended the design bolt length should be determined using both approaches, whichever longer bolt length is estimated.

3 DESIGN OF SHOTCRETE LINER WITH ROCK REINFORCEMENT CONSIDERATIONS

With the effect of tensioned pattern rock bolts forming a reinforced rock arch, shotcrete lining for underground openings can be considered as a thin shell liner. It is called “Shotcrete Rock Reinforcement” (SRR). For this thin shell shotcrete liner, six failure modes have been described by Barrett & McCreath (1995) comprising adhesive, flexural, shear, punching, compressive and tensile failures as illustrated in Figure 3. Key findings from their study revealed that falling block tests indicated the most likely failure modes would be adhesive, shear and punching.

Lang (1961), Bischoff and Smart (1997) and Hoek (2007) concluded that a possible contribution load acting on the shotcrete liner between bolts would be considered a pyramid shaped wedge, i.e. for the worst case scenario in highly fractured rockmass, it is 45° projected from the base plate of the rock bolt (see Figure 4 for illustration). Bischoff and Smart's model specified that the rockbolt base plate size will be one of the key elements in controlling the size of potential failure wedge forming between bolts.

Barrett & McCreath (1995), Uotinen (2011), and Kong & Garshol (2015) gave full discussion on the design checks against adhesive, flexure, shear and punching failures of shotcrete liners using Eurocode 2 (BSI, 2004); and Christine *et al.* (2017) has also conducted a revisited shotcrete support design in blocky ground. Discussion on the design of shotcrete layers is not given in this paper (refer to the captioned references).

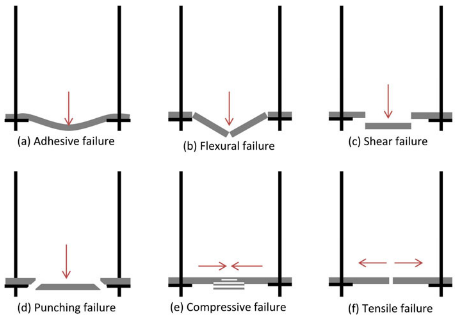


Figure 3. Failure modes of shotcrete between rock bolts (excerpted from Kong & Garshol, 2015).

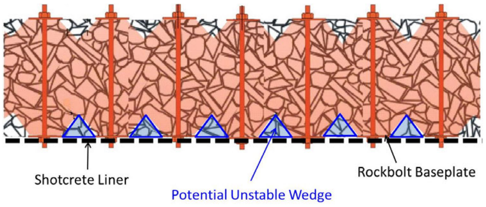


Figure 4. Schematic layout of SRR support measure.

4 ENGINEERING RESPONSE OF SRR AND DEFORMATION OF OPENINGS

Kong (2108) carried out a study using SRR approach to investigate a range of rockmass qualities from Q = 0.1 to Q = 10, with rock strength (UCS) of 70 MPa, and with the underground opening span as 24 m, at 14.8 m in height with rock cover of 45 m. The results of the findings of his investigation is summarised in Table 1.

The result of Phase² models show that all six models are stable at the opening and no yielded bolt and shotcrete liner are found. In different rockmass qualities, a boundary deformation of the opening is modelled ranging from 3.5 mm (in Q10 model) to 70 mm (in Q0.1 model). A percentage ratio of boundary deformation to the span of opening varies from 0.015% (in Q10 model) to less than 0.292% (in Q0.1 model). A summary of the model results is presented in Table 1.

In theory, this magnitude of deformation is less than the EC2 (BSI, 2004) or AS3600 (SAL, 2018) requirements of 'span/250'. In one of the examples, a 62 m span Norwegian Olympic Ice Hockey Cavern (Barton *et al.,* 1994) adopted rock reinforcement techniques and reported that the cavern roof deformation of about 10 mm was recorded for the section of rock quality Q = 1, and the final shotcrete liner thickness was 50 mm.

For a range of different rockmass qualities, the results of SRR with numerical modelling are in close agreement to Mahar *et al*. (1975) and the Hoek *et al.* (2000) study which collected various rules of thumb from a variety of sources and included them in their monograph. These empirical rules of thumb prescribe that the shotcrete thickness for underground openings in jointed rockmasses and under various in-situ stress conditions, range from 25 mm to 100 mm.

Table 1: SRR calculated values (shotcrete) and Phase² model results (excerpted from Kong, 2018).

Model ID	Shotcrete Thickness (mm)	Phase² Results			SRR Calculated Shotcrete Capacity	
		Max. Shear Force (MN)	Max. Bending Moment (kNm)	Max. Boundary Deformation (mm)	Permissible Shear Force (MN)	Permissible Bending Moment (kNm)
Q10	77	0.047	1.0	3.5	0.280	4.816
Q5	57	0.028	2.0	17	0.185	2.674
Q2.5	59	0.024	0.787	26	0.17	2.861
Q1	39	0.013	0.339	32	0.097	1.266
Q0.4	27	0.012	0.336	57	0.057	0.612
Q0.1	25	0.017	0.247	70	0.042	0.525

5 CONSTRUCTABILITY OF SRR AND CASE EXAMPLES

5.1 Durability of Rock Bolts

Regarding the durability of permanent rock bolts with single corrosion protection of hot-dip galvanised high-yield or mild steel bars, an allowance for generalised corrosion of 2 mm sacrificial thickness on the radius is to be made (GEO, 1984). Hence the determination of design working load of bolts should be considered as based on a bolt diameter minus 4 mm. Where grout is used, a minimum cover of 6 mm should be provided to the bolt (GEO, 1984). However, Pells & Bertuzzi (1999) suggested a minimum grout cover to the bolt should be 10mm. The free length of the bolt should also consist of grout, grease-filled sheathe, or other suitable protection method.

SINTEF (1999 & 2000) undertook evaluation of the accelerated corrosion tests for the CT-Bolt (one of the commercially available self-anchorage rockbolts) which is coated with a specific combination of hot-dip galvanising, zinc phosphate and powder coating. The evaluation showed that the bolt is capable to sustain lifetimes up to 150 years. This treatment gives unique protection against corrosion and wear and tear. Singapore's Jurong Hydrocarbon Storage Caverns used the CT-Bolt as a permanent rock reinforcement measure.

5.2 Waterproofing

One of the structural integrity problems presented at cavern/tunnel permanent linings is water seepage. Commonly, sheet waterproofing membrane is adopted in cast in-situ concrete lining for caverns/tunnels. In view of the physical nature of permanent shotcrete lining, it is possible to use spray-applied waterproofing membrane. Su (2013) found that spray-applied waterproofing membrane demonstrated that there is sufficient and reliable tensile and shear strength at the shotcrete-membrane interface to prevent water permeating through cracks and seeping along the interface in such a way that it could load the permanent lining (i.e. the permanent shotcrete liner) directly. ITAtech (2013) gave further guidance on the design for spray-applied waterproofing membranes for underground structures. As reported by Wallis (2007) and Garshol & Lacerda (2007), a 30-year old Chekka highway tunnel north of Beirut was experiencing water ingress through cracks in the existing concrete lining. Tunnel lining repair works without demolition of the existing lining had been carried out successfully using spray-applied waterproofing membrane with a 4 cm thick finish of steel-fibre reinforced shotcrete.

In addition to spray-applied waterproofing membranes, modern concrete technology (ACI, 2016) has proven that permeability-reducing admixtures such as crystalline products (CP) and hydrophobic pore blocker(s) (HPBs) are capable of improving water absorption and permeability effectively if they are added to concrete. Some permeability-reducing admixtures (e.g. CP and HPBs) report to have two distinct actions. The first is a reaction of the hydrophobic compounds with hydrating cement phases, modifying the cement paste matrix and changing the surface tension of the capillary surfaces, reducing the capillary movement of water through the concrete mass. The second action of the HPB is reported to collect in the capillaries forming a physical plug, blocking the capillary system and preventing further water entry (Ramachandran, 1995; Aldred, 1988).

These permeability-reducing admixtures in concrete have been reported to resist water penetration (with coefficient of permeability less than 1×10^{-12} m/s) against hydrostatic pressure (British Board of Agrément, 2006 and ACI, 2016). Shotcrete treated with some permeability-reducing admixtures (e.g. CP) has been used successfully for rehabilitation of the Ohio's National Road Bikeway Tunnel (Penetron, 2013). The tunnel was reported to have water leakage and a dangerous ice build-up, which threatened use of the tunnel.

5.3 Fireproofing

Without a doubt, rock is a very fire-resistant material and hence there are insignificant fire-induced effects to tensioned rock bolts that would cause the loss of reinforced rock arches. Only an element of the rock bolt head needs to be provided with fire proofing cover. With reference to Eurocode 2 (BSI, 2004) for example, a minimum shotcrete cover of 70 mm to steel reinforcement should be provided to avoid falling-off of concrete (or shotcrete) in the latter stage of fire exposure. Thus, the schematic illustration of shotcrete fire protection cover to the rock bolt head is shown in Figure 5.

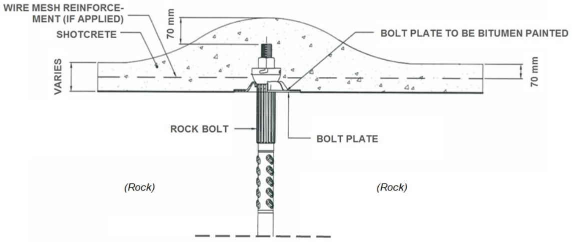


Figure 5. Schematic illustration of shotcrete fire protection cover to rock bolt head.

In case of fire, spalling of shotcrete can be prevented by adding polypropylene micro fibres to the shotcrete mix as an additional fire protection layer. The effect is achieved by melting of the fibres at low temperature, leaving open channels in the concrete that will allow steam to evacuate without building internal splitting pressure within the concrete.

5.4 Reduction in Excavation Volume

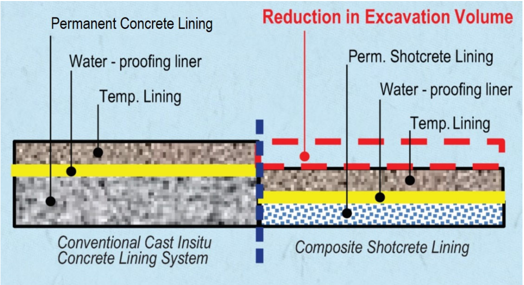


Figure 6. Illustration of cost saving and less excavation by using shotcrete rock reinforcement.

For the SRR support and construction method, the use of rockbolt and shotcrete in lieu of in-situ concrete as secondary (permanent) lining is adopted. This means that the excavation envelope (i.e. volume) can be reduced by about 10% (depending upon the cavern/tunnel size and length) (see Figure 6 above), and concrete volume reduced by up to 50% due to the required thickness of the permanent shotcrete liner being much thinner than the structural concrete lining support. With less use of cementitious products, this leads to a reduction in the carbon footprint. As shotcrete can be sprayed any time after excavation, there is no need to erect formwork, pour concrete and strip shutters, which gives program advantages as well.

5.5 Case Examples of Using SRR

Over the past 30 years, a number of underground excavation projects have adopted rock reinforcement with shotcrete liners for ground support. A list of selected projects using SRR is summarised in Table 2.

Table 2: Selected case examples using SRR.

Country	Project	Year	Cavern Size and Details
Norway	Olympic Ice Hockey Cavern	1994	▪ 62 m span Norwegian Olympic Ice Hockey Cavern, 25-50m ground cover (Barton *et al.,* 1994). ▪ Alternate 6m long Ø25mm rockbolt and 12m long twin-stranded cable bolt (Ø12.5mm) at 2.5m and 5m centre-to-centre; 50-100mm thick permanent shotcrete lining.
Hong Kong	Saltwater Service Reservoir Caverns	2009	▪ Cavern size with 17m span, 15m high, min. ground cover 45m, (Chung, 2011). ▪ 3mm thick of spray-on waterproof membrane with permanent steel fibre shotcrete liner applied to the cavern roof.
Singapore	Jurong Hydrocarbon Storage Caverns	2012	▪ Cavern size typically 20m wide, 27m high constructed below sea level. (Zhou *et al*., 2017). ▪ 4.4m long CT-bolts with steel fibre shotcrete liner of 60mm – 140mm in thickness.

6 DISCUSSIONS AND CONCLUSIONS

As discussed by Kong (2018), in most of the cases the design of rock bolt support for underground hard rock openings overlooks the rock bolt's function acting as reinforcement to form an in-situ rock arch. This rock arch that is formed by application of confining pressure via the bolts, utilises the inherent strength of the rock to support the rock load above the opening. With confidence of more than 40 years' practical experience using the Q-system, the support rock load using Q support load is feasible for the SRR approach. As the rock bolts have been designed to support the required rock load, the shotcrete lining may only be designed to retain a potential wedge load forming in between bolts.

Shotcrete linings (with or without reinforcement) can be designed in accordance with the available design codes and standards such as AS3600 (SAL, 2018) or Eurocode 2 (BSI, 2004) by considering thin "protective/supportive skin" liners to support the rock surface between rock bolts with performance similar to a reinforced concrete slab. Attention is drawn to the fact that the shotcrete liner cannot prevent deformation from taking place, especially in high stress environments, but it can assist in controlling deformation, particularly when used in combination with rockbolts, dowels or cables. Nevertheless, shotcrete support becomes very effective after rock bolt installations are carried out. Therefore, the approach of SRR with the patterned rock bolts and high-quality shotcrete provides one of the most stabilisation measures for underground openings.

The SRR approach may give an optimised solution in the thickness of shotcrete liner as a permanent structure for hard rock underground openings. In terms of constructability, as referred to in ITA (2010), a minimum of 60 mm thickness is recommended for permanent lining.

In evidence of accelerated corrosion tests, rock bolts with a combination of hot-dip galvanising, zinc phosphate, and powder coating has indicated lifetimes up to 150 years. Carbon steel bolts, cement grouted in an open-ended plastic sheath are acceptable for 100-year design life in which cement grout is considered to be part of the corrosion protection, if it is within a plastic sheath. Hence, the durability of rock bolts with design lifetime of 100 years, which complies with the Eurocode 0 (BSI, 2005), is feasible.

Composite shotcrete liner sandwiched with spray-applied waterproofing membrane or the use of permeability-reducing admixtures in the shotcrete mix are able to provide a one-piece waterproofing structural liner to prevent water permeating through cracks and seeping along the interface of the permanent cavern/tunnel lining.

Modern shotcrete technology reveals that the durability of shotcrete is governed by the same parameters as cast in-situ concrete. For quality and workmanship control to shotcrete, it is possible to follow the Specification for Tunnelling (BTS & ICE, 2010). In the case of fire, spalling of shotcrete can be prevented by adding polypropylene micro fibres to the concrete mix. The effect is achieved by melting of the fibres at low temperature, leaving open channels in the concrete that will allow steam to evacuate without building internal splitting pressure within the concrete.

It is concluded that the SRR for underground excavations, particularly of large span caverns constructed in non-squeezing hard rock media is able to provide sustainable and cost-effective solutions. Cost-wise, SRR reduces in construction time and resources that no formwork or rebar fixing are required for permanent lining, and less excavation volume is required. In addition, due to the reduction of the permanent concrete lining thickness, the total excavation volume of caverns/tunnels is also reduced. As it minimises the use of cementitious products for permanent lining construction, it leads to reduced CO_2 emissions and lower embodied energy.

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