Review And Design Concept For Grouted Multi-Jacketted Friction Balancing Rock Bolt

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Abstract: Rock is under greater abutment stress and strain on the sidewall periphery of an excavation than deeper in the rock, especially in the immediate aftermath of mining. If some mechanism could be actuated where a grouted rock bolt was able to transfer excess strain energy from the highly stressed section in the sidewall along its length to the deeper part, the load along its length would be balanced or equalised through friction. The result would be increased effective rock bolt anchorage length, reduced rock yield in the sidewall, and lessened grout and/or bolt failure. The paper reviews grouted rock bolts and proposes the conceptual grouted 'Multi-jacketted Rock Bolt', as one route that could be employed in achieving frictional load balancing along the axis of the grouted rock bolt, with six variations proposed. The 'Jacketted Rock Bolt', would be an assemblage of tubular steel jackets, concentrically fitted within each other. As excavations are mined and rock bolted, friction would be generated between 'jackets' in grouted jacketted rock bolts, in response to movement in the surrounding grout and or rock mass. This would transmit frictional energy from one jacket to the other in a frictional balancing system. This is conceptual.

Index Terms: Friction, grout, grouted rock bolt, jacketted rock bolt, load, load balancing, rock bolt, stress abutment, stress-strain, Zambia.

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1 Introduction

Rock is under greater abutment stress and strain on the periphery of an excavation than deeper in the rockmass, similar to that shown in Fig. 1 (Brady and Brown, 2004). The deviatoric stress, and associated strain, is highest on the sidewall, similar to that for tangential, radial and radial stresses numerically modeled in FLAC for a 10 m diameter tunnel in Fig. 2. This is especially so in the immediate aftermath of mining. Over time, the rock in the immediate periphery of the sidewall of a tunnel or large mining excavation yields and or fails, thus, displacing the peak abutment stress deeper into the rock, like Fig. 3.

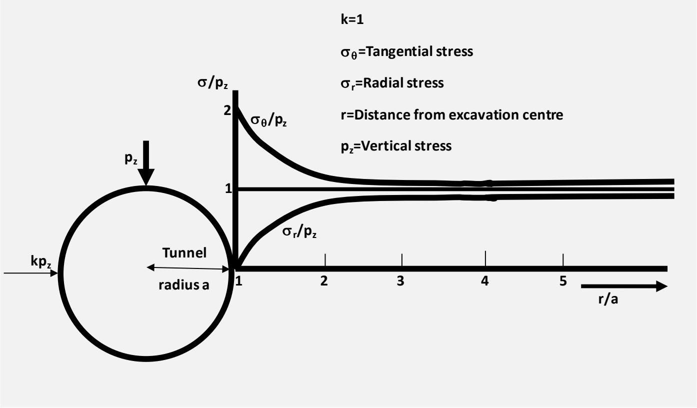

***Fig.1.** Stress redistribution around a circular tunnel (after Brady and Brown, 2004)*

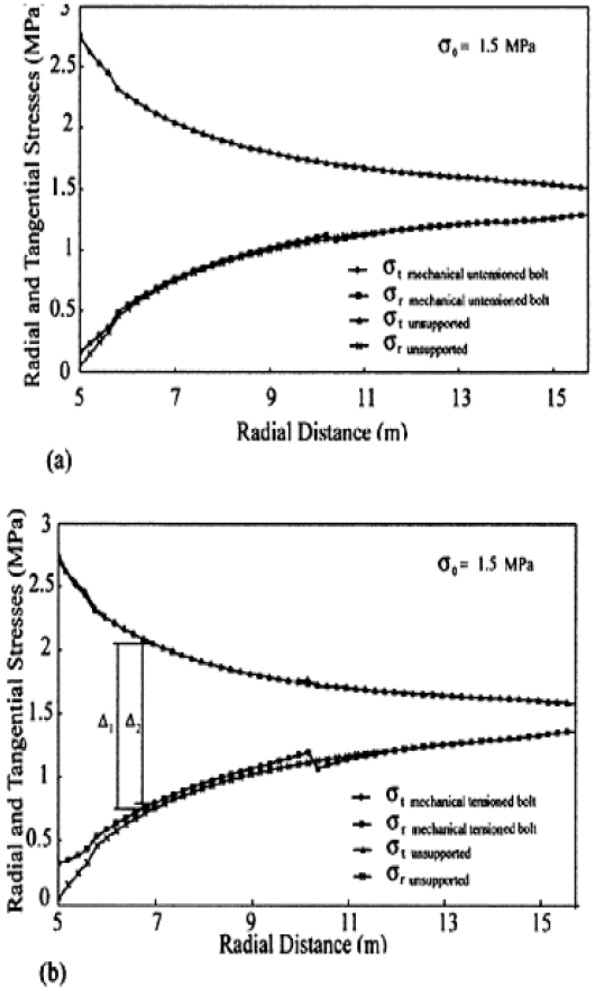

***Fig. 2.** Stress re-distribution around a 10 m diameter tunnel in reinforced and non-reinforced condition (a) untensioned bolt (b) tensioned bolt, numerically modelled by FLAC finite difference (after Fahimifar and Soroush, 2004)*

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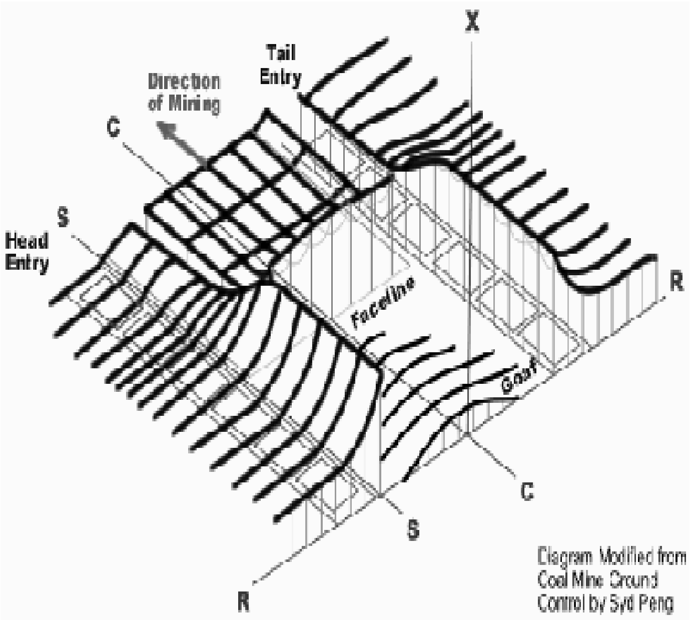


Fig. 3. *Stress redistribution and magnitude around abutments of a coal mining longwall face (after Peng, 2015)*

The two basic functions of an underground support system are to reinforce the rock mass and to secure it in place together. Heal et al (2006) were cited by Potvin (2011) as having shown from 254 rock bursts that only 30 percent of support system malfunctions were due to rock bolt failure, the majority of the rest being due to surface fixture problems (Fig. 4). Often, fully grouted rock bolts and the associated grout experience excess stress and fail close to the sidewall. At some distance within the sidewall, dependent on the excavation size and the material properties of the rock, stresses revert to the virgin stress. A grouted rock bolt could be inferred, similarly, to be under greater stress and strain on the sidewall of a tunnel than deeper into the rock.

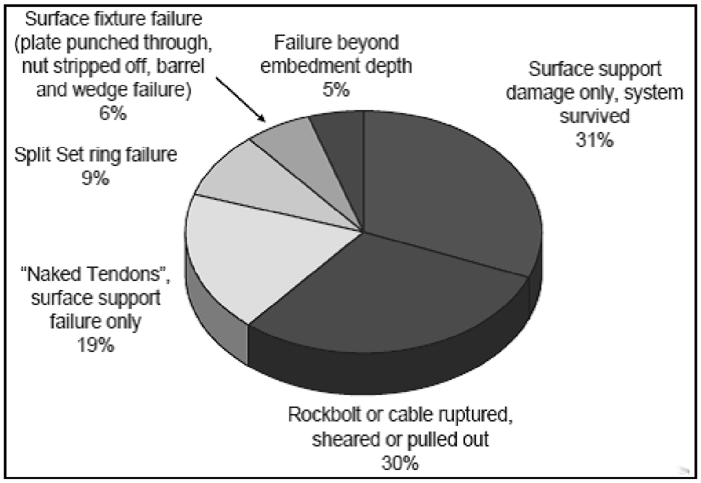


Fig. 4. *Breakdown of the components of ground support system failures from 254 rock burst damage observations (after Potvin, 2011)*

If some mechanism could be actuated where a grouted rock bolt was able to transfer strain energy from the periphery section in the sidewall along its length to the deeper part, the load imposed along it would be balanced or equalised. The result would be the elimination of localised excess stress and strain on the grout and the rock bolt, increasing the capacity of the grouted rock bolt to manage both stress and strain. The objective of this paper is to demonstrate one route that could be employed in achieving frictional load balancing along the grouted rock bolt.

2 PRINCIPLES OF ROCK BOLT LOADING AND BALANCING

2.1 Strain and Stress Distribution in and around Grouted and Friction rock bolts

Rock bolt loads can be axial, torsional, bending and/or shear (Fig. 5), with axial loading being the predominant mode in steel rock bolt failure, although combinations also drive failure, in some geological situations, particularly where jointing is present [Signer and Lewis, 1998; Signer, 2000].

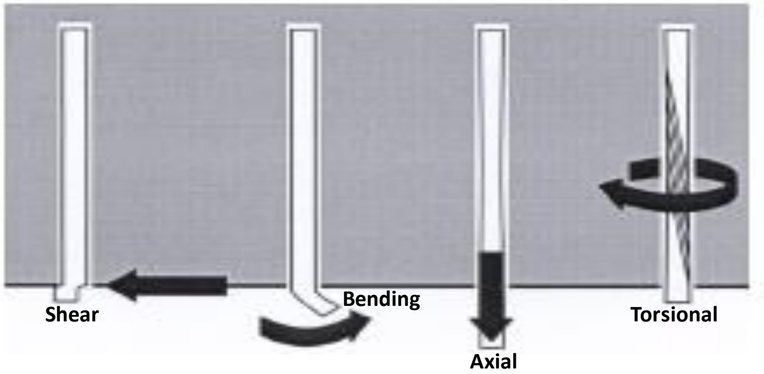


Fig. 5. *Types of roof bolt loads (after Signer, 2000)*

Hyett et al (2013) argued that the strain developed in a rock bolt comes from the torque applied by the installation drill to the bolt during installation (Active Load) and the load induced by ground movements during the life cycle of the bolt (Passive Load). Passive bolt loading caused by rock movement was due to micro- and macro-scale movements in the rock mass that are transferred to the rock bolt through the grout annulus. Depending on the state of stress around the excavation, rock movements may be either distributed or discrete, and if coaxial with the bolt, axial loading is induced. Rock movement transfers the load from surrounding rock movement to the bolt, primarily, depending on the stiffness of the grout annulus and the mechanical interlock between the grout and the profile of the rebar. Altounyan et al (2011) noted that grout annulus thickness is considered optimum up to 3.5 mm. If the rock movements are transverse to the rock bolt, shear loading results, as predicted by Radcliffe and Stateham (1980). In the Zambian Copperbelt, from the 1970s, the main type of grout used was a mixture of cement and building sand. Previously, resin grouts under the trade-name Roc Loc® had been used, but were abandoned due to forex shortages caused by political conditions then. From mining support experience underground, it was widely theorised that after the grout had hardened, the grout interacted with the rockmass around it, as mining progressed, through normal and shear stresses at the grout-rock interface. This interaction was later, in the 1980s, confirmed through strain gauge instrumentation of rock bolts around active mining faces by researchers in mines abroad, such as Serbousek and Signer (1987), Signer and Lewis

(1998) and Signer et al (2004). The normal and shear stress acting at the rock-grout contact are components of the excavation-induced stresses in the rockmass. These stresses are transmitted from the rock at the rock-grout contact through the grout to the grout-bolt contact, where they act as normal and shear stresses. These stresses induce axial load along the rock bolt. For maximum interaction with the rockmass, the rock bolt needs to be installed as early as possible after an excavation is made, so that it is already in place while mining-induced stresses and associated strain are still adjusting in the surrounding rockmass after the excavation is made. To assure this, in Zambia, mining practice does not allow mining ends beyond a few metres without rock bolt support, if rock bolt support is required by design. Australia also moved in this direction, whereby since 1997, metalliferous mining practice does not permit exposure of workers to unsupported ground, and surface support has to be installed in every face, unless demonstrated by risk assessment as unnecessary. Since then, fall of ground fatalities have reduced to 2 or less per year (Potvin, 2011). It is important to note, though, that a rock bolt is still useful, although relatively less effective, even if the installation is too late for the axial load within the bolt to be activated and maximized by initial adjustments in stress around the periphery of the excavation. Later movements in the rockmass induced by later activities such as stoping and or caving will induce axial load in the installation, enabling the rock bolt to interact more effectively with the surrounding induced stress and associated ground movements. While normal and shear stresses are emphasized, in Zambia, and other mining districts globally, these stresses act either on their own or, as described by Radcliffe and Stateham, combine with torsional and bending stresses to cause bolt or grout failure in many complex geotechnical situations. They reported a US Bureau of Mines study of 97 strain gauged resin grouted roof bolts underground which indicated strain measurements in failed rock bolts to be greatest at the centre of the bolts than at either end. The high strain at the centre was, in 30% to 45% of the bolts, sufficient to cause yield, which was theorized to be due to a combination of axial and bending action. Most of the bolts exhibited bending in the central section. None of the bolts indicated yielding at the top or bottom of the bolt. Failure of bolts due to gravity loading was ruled out, primarily, because it would not have been enough to reach the ultimate strength of the steel, and there were no horizontal bed separations in the strata. The study concluded that roof support was achieved through a combination of point suspension and resistance to vertical and horizontal stresses. Radcliffe and Stateham, citing their own work and Farmer (1975), concluded that load picked up by a grouted bolt from the surrounding rock is transmitted back to the surrounding rock within a relatively short distance, in the order of 0.2 m to 0.4 m. Work undertaken by the US Bureau of Mines (Serbousek and Signer, 1987; Signer, 1988) on 48 roof bolts grouted in rock through pull tests (Fig. 6) concluded that pull loads were not transmitted in grouted rock bolts beyond 0.6 m from the rock bolt head in elastic rock and 1.1 m for weak rock. Pull tests were thus insufficient as a test of stability beyond these distances. Hole diameter and grout type did not change the load transfer pattern, except in that gypsum was more affected by long-term creep than resin grouts. Previous work by Farmer (1975) had also suggested similarly that a pull load on a resin-grouted rock bolt would only transmit over 23 times the rock bolt diameter. Results from 28 fully resin grouted, strain-gauged roof bolts showed significant amounts of movement and loading in the bolted zone, within 2 m or less from the bolt-head, in response to the mining of nearby excavations [Signer and Lewis, 1998; Signer et al, 2004]. The anchorage length of grouted bolts was 0.56 m through mechanical interlock of the grout, with bolts mostly failing from axial and bending loads. With 0.6 m and 1.2 m grouted rock bolts, 0.56 m of bolt length was required to transfer 90% of the load from the bolt to the rock (Signer, 2000). Variations in polyester and gypsum grouts were used, without significant differences in results. The rate of load transfer was similar to an exponential curve dependent on the bolt material, grout, rock and respective interfaces. Later work done on expanded steel tube friction anchored rock bolts embedded in concrete by Aoki et al (2004), using longer friction bolts produced results (Fig. 7) similar to Serbousek and Signer (1987) (Fig. 6). The results from Aoki et al could be interpreted to mean that any elastic rock strain energy imparted to a particular section of the rock bolt would only be accommodated by that section and in the 0.6 m to 1.0 m immediately adjacent to it, similar to the conclusions reached by others [Radcliffe and Stateham (1980); Signer (1988; 2000); Serbousek and Signer (1987]. Under laboratory conditions, Fig. 7(a) shows an EST rock bolt embedded in mortar, which is very similar to a cement-building sand mortar mix used in Zambia for grouted rock bolts. The axial forces imposed by the pullout forces decayed to imperceptible between 0.8 m to 1.3m, approximately, from the collar, Fig. 7(b). Underground in the Takadayama tunnel, Japan, pullout forces decayed to insignificance between 1 m and 1.3 m, from the sidewall, Fig. 7(c). For the 16 m underground cable bolt testing, Fig. 7(e), as the face advanced, the peak of the axial force distribution was 2 to 3 m ahead of the face.

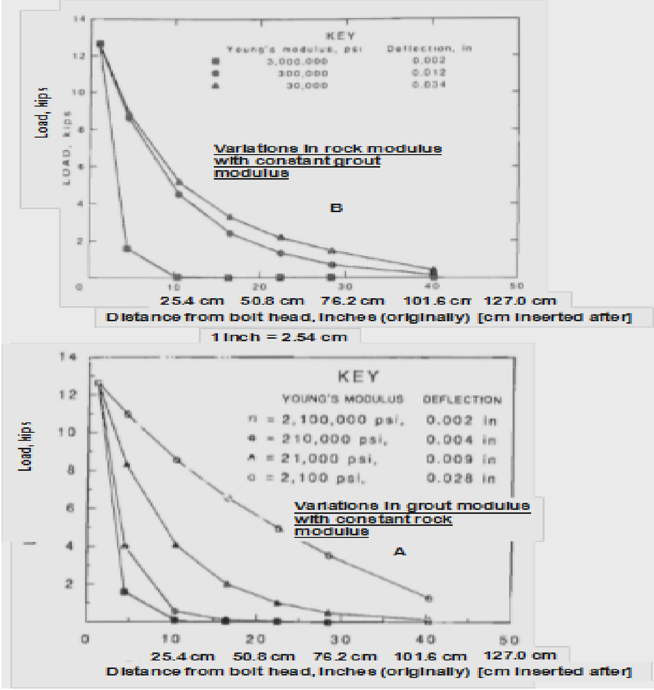
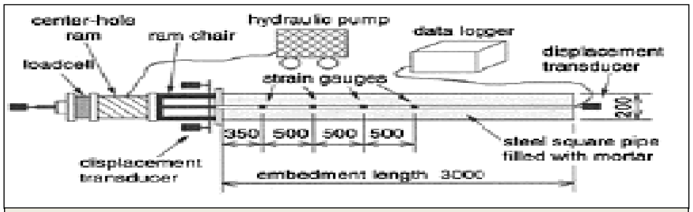


Fig. 6. *United States Bureau of Mines pull test load decay in grouted steel bolts (after Serbousek and Signer, 1987)*

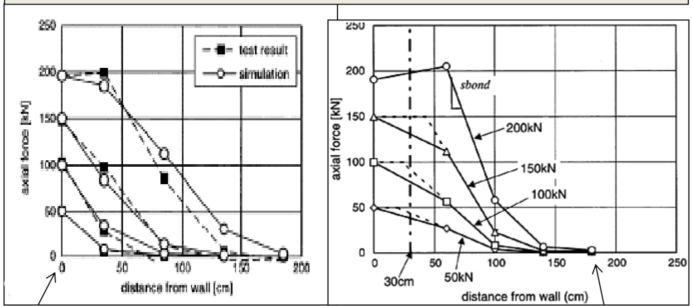
From the foregoing, the transverse strain (along the bolt axis), for example, induced by elevated vertical tangential stresses and depressed horizontal radial stresses at the collar area, which is a zone of high potential strain, would not be transmitted by the typical rigid grouted rock bolt to deeper sections, which are zones of low potential strain, Fig. 7(d). The result would be a localised excess of transverse strain at the collar zone, which would induce progressive grout failure, migrating deeper as highly stressed sections failed. A similar process would occur at discontinuities, which would cause localised failures of highly strained grout or portions of rock bolts. Friction anchored EST rock bolts showed similar results to the foregoing. In other words, the deeper and farther sections of rock bolts would provide little resistance or reaction to initial rock movement at the collar. From the work cited here in Fig. 7(e), Aoki et al concluded that for a 16 m EST cable bolt, the deepest pull out force induced axial bolt force up to 4.3 m. The results of the extensometer measurement indicated the loosened region extended up to 6 m from the tunnel wall. From the foregoing, the transverse strain (along the bolt axis), for example, induced by elevated vertical tangential stresses and depressed horizontal radial stresses at the collar area, which is a zone of high potential strain, would not be transmitted by the typical rigid grouted rock bolt to deeper sections, which are zones of low potential strain. The result would be a localised excess of transverse strain at the collar, which would induce progressive grout failure, migrating deeper as highly stressed sections failed. A similar process would occur at discontinuities, similar to the postulation from Radcliffe and Stateham by stress shearing or natural discontinuities, which would cause localised failures of highly strained grout or portions of rock bolts. In other words, the deeper and farther sections of rock bolts would provide little or no resistance or reaction to initial rock movement at the collar. Additionally, work in a slightly different context, that of varying rib geometry profile on grouted rebar rock bolts (Aziz et al, 2011), also indicated exponential loading rate decay over a distance from the bolthead, Fig. 8(a). A new development in the field of determining the stress or strain distribution called 'distributed optical sensing' which used optical fibres to gauge strain along a grouted rock bolt, shown in Fig. 8(b) [Hyett et al, 2013) appears to confirm the load exponential decay along grouted rock bolts, although the embedded length of the bolt was only 0.2 m.

2.2 Mechanism Of Load-Balancing Rock Bolts

Many rock bolt designs to accommodate macro-scale ground movements in surrounding highly-stressed rock masses have been developed. These include the Atlas Copco Roofex® (Gradnik and Doucet, 2011), the Jenmar Yield-Lok® (Wu et al, 2011), the D-Bolt® (Charette and Li, 2011), Duraset Durabar® (Erasmus et al, 2009) and Cone® bolt (Ortlepp and Stacey, 1995) to name a few (Fig. 9). These rock bolts are designed to dissipate rock mass energy without losing their integrity, thereby reducing overall rock burst damage and injuries. The Roofex® bolt was specifically designed to withstand large static and dynamic deformations under pre-specified load conditions. The Roofex® rock bolt acts as stiff support up to a preset load level before the sliding effect of the mechanical frictional system is triggered and allows rock mass movement without losing the support function [Fig. 9(a)]. In static loading conditions, the Jenmar Yield-Lok® bolt acts like a grouted rebar bolt. In dynamic loading conditions, the upset transfers the rock mass energy to the surrounding polymer coating, creating a 'ploughing effect' [Fig. 9 (b)]. The dynamic energy is dissipated by pulling the upset through the polymer and by friction between the smooth bar and the polymer coating. The D-Bolt® is a resin-grouted high-tensile strength multiple anchor rock bolt which can stretch considerably after the bolt reaches yield, for example, in macroscopic ground movement [Fig. 9(c)]. Duraset Durabar® is a grouted de-bonded rock bolt with a sinusoidal wave-like structure, with the rock bolt dissipating energy as it slides through the cement grout [Fig. 9(d)]. The Cone® bolt has an enlarged cone at the toe of the hole, which forces itself through the grout during macroscopic events, thereby dissipating energy [Fig. 9(e)].

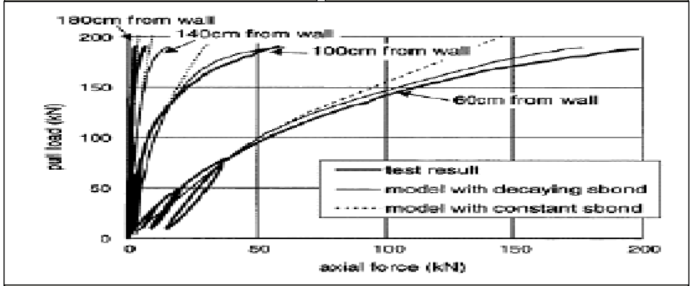


(a) Laboratory test rig of full-scale pull test of 3 m mortar embedded EST rock bolt

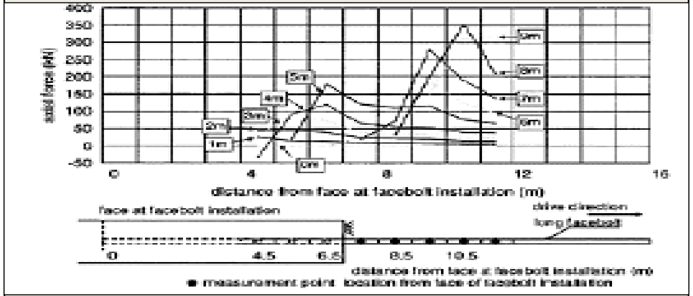


(b) Comparison of pull load – axial force of numerical modelling FLAC results with actual physical strain gauge test results on 3 m EST rock bolt embedded in mortar obtained from laboratory test rig in (a) (decaying sbond model)

(c) Axial force distribution of in-situ pull tests of 4 m long EST rock bolts at Takadayama Railway Tunnel, Japan

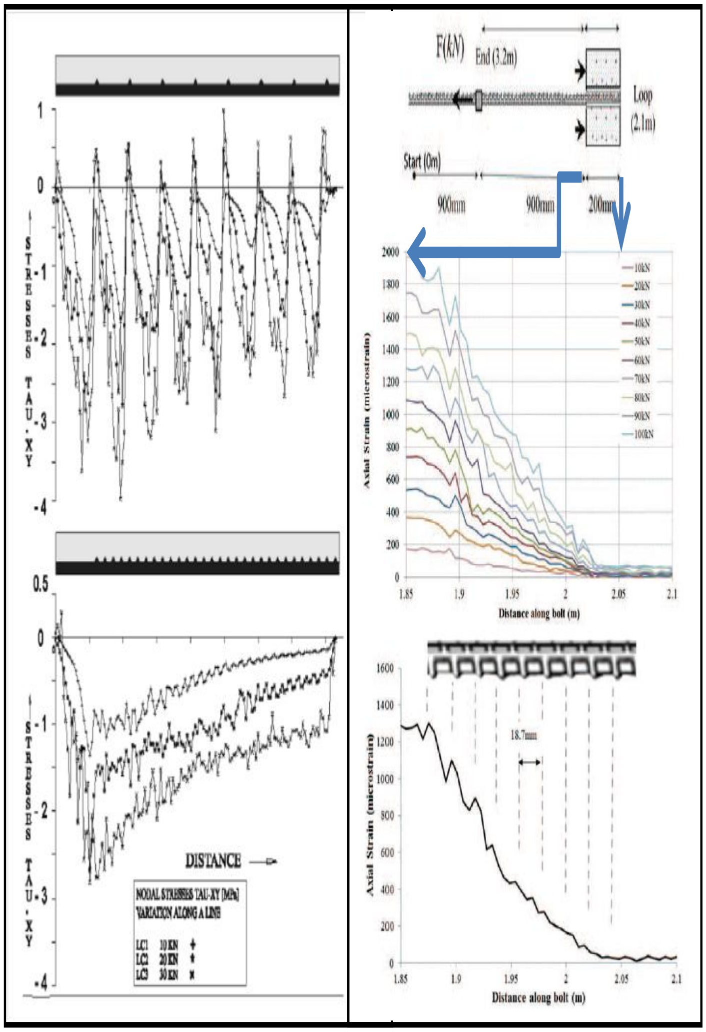


(d) Relationship of pull load vs axial force in situ tests on 4 m long EST rock bolts at Takadayama Railway Tunnel, Japan



(e) EST rock bolt axial force distribution with advancing tunnel face at Takadayama Railway Tunnel, Japan

***Fig. 7**. Japanese laboratory and underground in-situ results for load distribution in expanded steel tube friction bolts (after Aoki et al, 2004)*

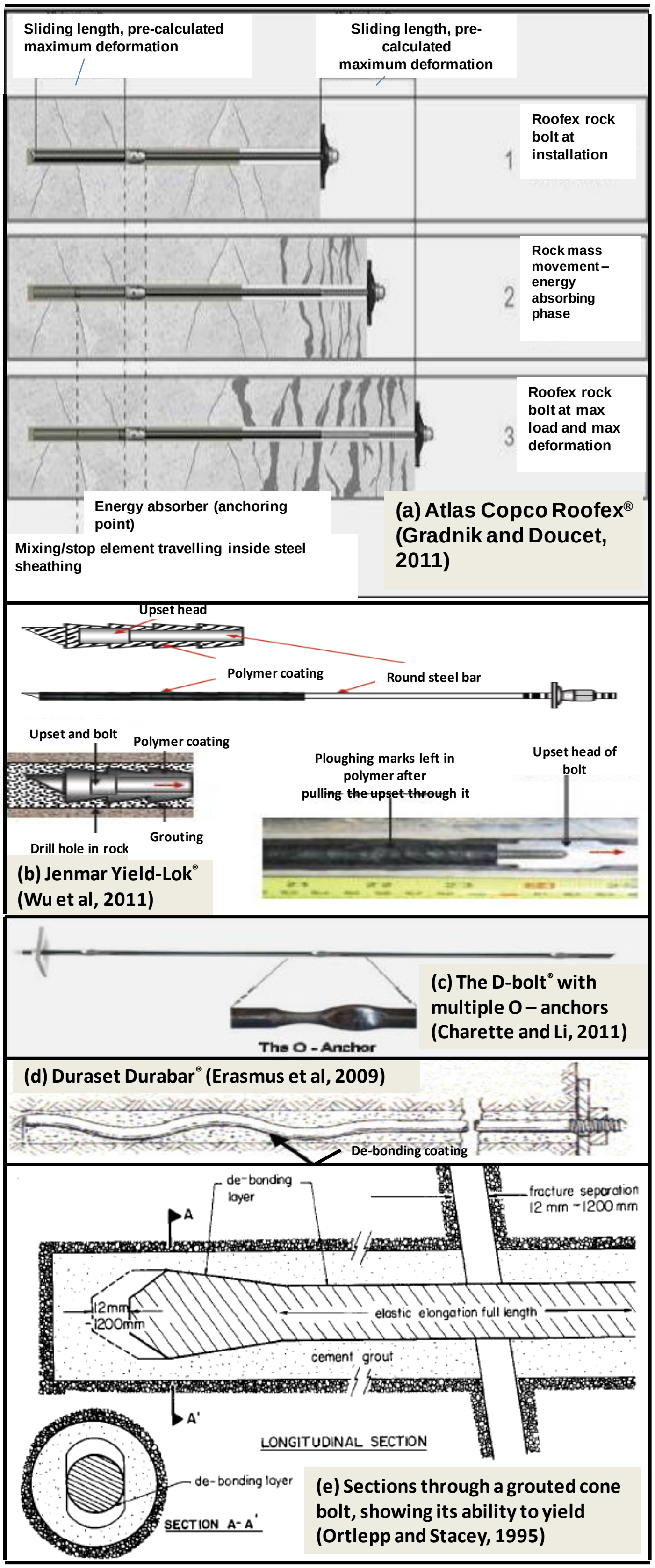


(a): Numerical modelling of axial stress developed on bolts of two different spaced profiles (after Aziz et al, 2011)

(b): Detailed axial strain profile for the grouted section of the bolt [1.85 m to 2.05 m along the fibre optic (total of 0.2 m grouted rebar)]; Upper: change in strain profile with applied axial load. Lower: Detailed variation axial load at 70 kN) related to the rib geometry.) Undulations being due to the rib prolife on the bolt (after Hyett et al, 2013)

Fig. 8. *Results of numerical stress modelling and fibre optic axial strain measurement (Aziz et al, 2011; Hyett et al, 2013)*

In a review, Charette and Hill (2011) analysed basic static and dynamic loading data of six grouted rock bolt types capable of long term support (Fig. 10). They concluded that the rebar and D-Bolt had a higher static load performance, while the Hybrid, MCB cone, Yield Lok®, D-Bolt® and Roofex® provided large deformation capacities at various loading levels. The MCB33 cone is best coupled with rebar reinforcement, while the Hybrid, D-Bolt® and Yield Lok® are designed to be used as single pass reinforcement bolts. Laboratory testing appeared to show that rebar and MCB cone bolt worked best together, at bolt displacements of less than 25 mm, while a dynamic event exceeding 7 kJ occurring would fail fully-grouted rebars (displacement larger than 25 mm). Thereafter, only the MCB cone bolt is able to provide static support.



(a) Atlas Copco Roofex® (Gradnik and Doucet, 2011)

(b) Jenmar Yield-Lok® (Wu et al, 2011)

(c) The D-bolt® with multiple O – anchors (Charette and Li, 2011)

(d) Duraset Durabar® (Erasmus et al, 2009)

(e) Sections through a grouted cone bolt, showing its ability to yield (Ortlepp and Stacey, 1995)

Fig. 9. *Commercial rock mass energy dissipating rock bolts used for static and dynamic situations*

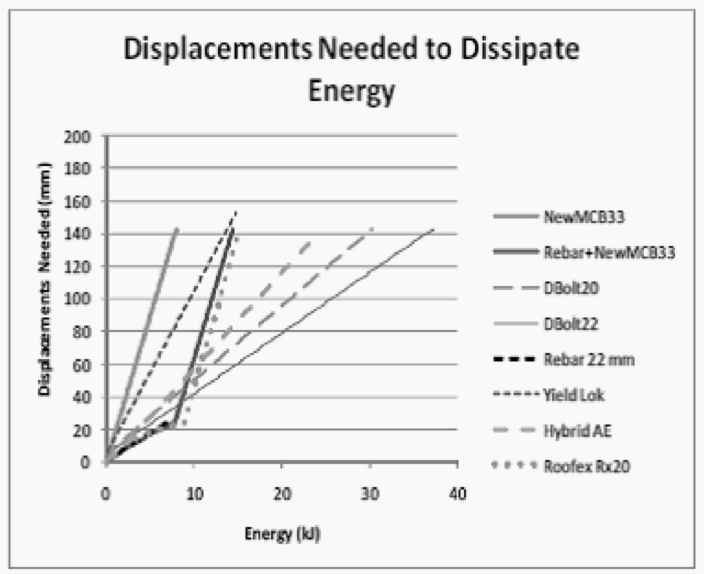


Fig. 10. *Displacement vs energy for various grouted reinforcement bolts (after Charette and Hill, 2011)*

3 PROPOSED JACKETTED LOAD BALANCING METHOD

The function of the jacketted rock bolts proposed here would be to balance the stress and strain, imposed by surrounding rock on grout and/or grouted rock bolts. If the high strain energy in the excavation periphery were to be accommodated over the whole length of a grouted rock bolt to the toe by a load balancing rock bolt, localised strain and stress excess would be mitigated. The low shear stress induced in the minimal strain zone in the deepest toe part of the grouted drill-hole would be increased, while that at the collar of the hole would be reduced. The result would be equitably distributed average shear stress on the rock bolt. The likelihood of grout or grout-rock or grout-bolt or rock bolt failure would be significantly reduced thus increasing the effectiveness of the grouted rock bolt. The overall effect of the load-balancing rock bolt would be to increase the effective anchorage length, especially with longer rock bolts.

3.1 Rock Bolt Construction

The load balancing rock bolt can be constructed as follows (Chileshe, 1992; 1996; 2012). The design, referred to here as the 'Jacketted Rock Bolt', would be an assemblage of concentrically tubular steel jackets [Figs. 11(a) and 11(b)]. Each jacket would be 0.6 m to 1.1 m in length, and would be fitted within each other. The jackets would overlap by, say, 0.2-0.4 m, thus forming a total length and diameter compatible with a typical rock bolt hole. The tightly or spirally or groove-fitted or lined or indented overlaps would provide friction between jackets and thus transmit energy from one jacket to the other in a frictional balancing system. The capacity to slip is essential. The entire jacketted assembly would be grouted into the drill hole or simply in force-fitted direct contact with the rock.

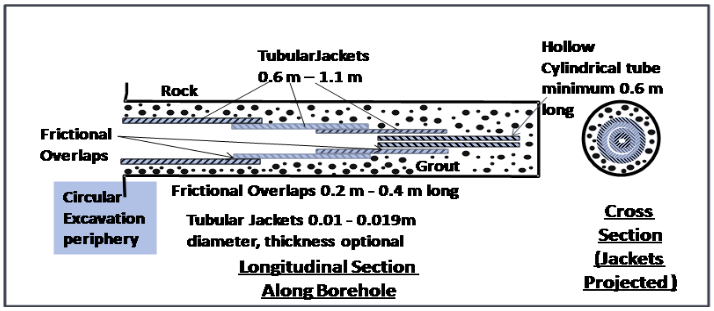


Fig. 11(a). *Jacketted Rock Bolt Type 1*

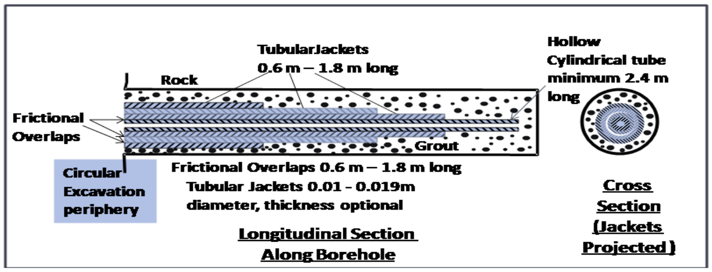


Fig. 11(b). Jacketted Rock Bolt Type 2

Alternatively, to accommodate extreme cases of gross deformation, such as rock-bursts, the innermost tube can be replaced with a similarly sized solid rod [Fig. 11(c) and 8(d)] of a length that allows extension, even protrusion out of the hole [Figs. 11(e) and 11(f)]. Other variations based on the basic principle of frictional energy transfer can be made.

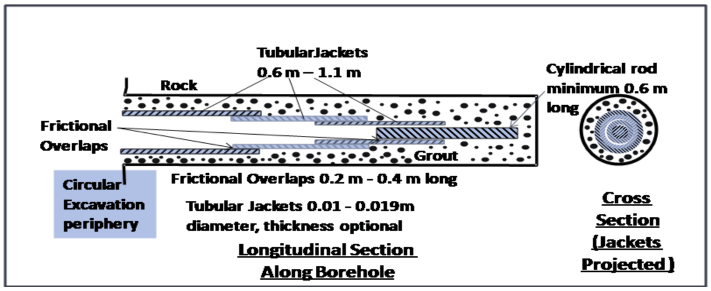


Fig. 11(c). *Jacketted Rock Bolt Type 3*

3.2 Strain Energy Transmission By Frictional Overlap And Slip System

The Jacketted Rock Bolt designs would work on the principle that the greater part of shear stress induced on any

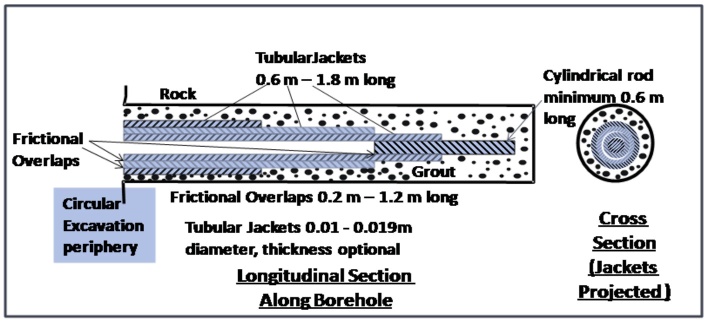


Fig. 11(d). *Jacketted Rock Bolt Type 4*

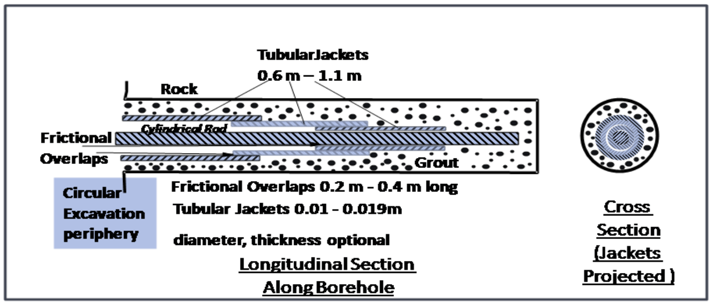


Fig. 11(e). *Jacketted Rock Bolt Type 5*

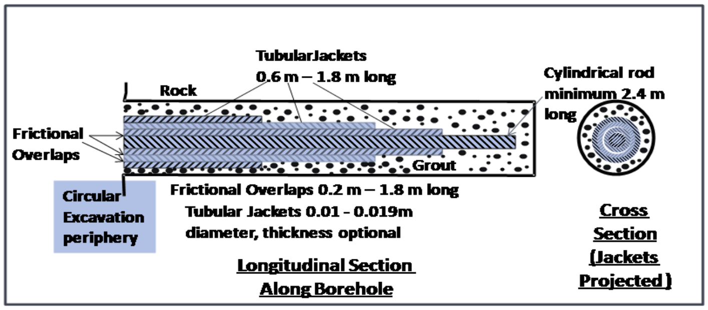


Fig. 11(f)*. Jacketted Rock Bolt Type 6*

jacket of the assembly by the rock would be capable of transmitting through the frictional overlaps to adjacent jackets in a kind of domino-effect. Hence, the assemblage would balance the differing shear stresses on the various jackets, unless slip took place. Such slip would then allow the rock bolt to continue working effectively even after major ground movements. The load balancing would be very effective in both continuous and discontinuous rock masses. The frictional properties of the jacket-to-jacket contact would be designed to allow slip at the frictional overlaps before that of the grout-bolt contact. This would permit any slip to be accommodated over the various frictional overlaps. This would also allow yield in both rock and rock bolt without damaging the continued effectiveness of the assemblage or that of the grout, even where the grout was damaged in localised positions. Varying the contact surface area of the frictional overlaps or their polishing or lubrication can do this.

3.3 Ideal Operating Environment Of Jacketted Rock Bolt Systems

The kind of load balancing rock bolt described above would work especially well where applied environmental stress increased after installation. This could be when the rock bolts came under the influence of abutment stresses or experienced further development-related or time-dependent rock stress and strain. Load balancing would also allow weak grouts such as cement to compete with resin grouts that are 30 times tougher (Pralle and Karol, 1966). The longer the assemblage the longer the zone over which the excess strain in the sidewall could be accommodated.

4 DISCUSSIONS

Over the years, additional new work [Jalalifar, 2011; Aziz et al, 2011] indicates that the exact distribution of the axial load along grouted rock bolts is not completely settled. Hyett et al (2013) used sophisticated fibre optic sensors to confirm the strain and stress exponential decay from collar to 0.2 m. Consequently, whatever the case, the need for balancing the axial load from the higher strain zones at the borehole collar to the lower strain zones at the toe is needed. The engineering options available in terms of the frictional overlaps are not entirely clear, until actual prototype production. Without a prototype or instrumentation at this stage, the discussion is qualitative. Typically, the rockmass is in equilibrium of natural forces before any excavation takes place. When an excavation takes place the equilibrium of forces is disturbed. The support for the rock is removed, and the forces redistribute around the excavation in order to establish a new equilibrium. The time taken to establish the new equilibrium varies from instantaneous for perfectly elastic material to years for time dependent creep-prone materials. Empirically, for many rock masses around tunnel excavations in the Copperbelt of Zambia, most of the ground deformation in response to an excavation takes place within weeks. Such deformation is greatest in the immediate periphery and progressively reduces to virgin in-situ stress level within a distance, from the sidewall, of 5 or 6 times the excavation radii [Brady and Brown, 2004], Fig. 1. As stated earlier, results from 28 fully resin grouted, strain-gauged roof bolts showed significant amounts of movement and loading in the bolted zone, within 2 m or less from the bolt-head, in response to the mining of nearby excavations [Signer and Lewis, 1998; Signer et al, 2004]. This is the rock movement which the grouted jacketed rock bolt would interact with. The magnitude of the mining induced deformation is very important in activating and inducing axial load in a grouted rock bolt which is placed in a borehole in the periphery of the excavation. In the aftermath of the installation, the grout around the rock bolt hardens either quickly or slowly dependent on the nature of the material. In the case of cement grout, which is either a mixture of building sand-and-Portland cement or cement with building and concrete sands, 48 hrs to a week is sufficient to create a grout material capable of interacting with the surrounding rockmass, as well as the rock bolt itself. Other systems include resinous and chemical grouts. At the simplest level, each grouted tubular jacket, as postulated in this paper, can be viewed as operating in the same medium (the grout) but in differing stress and strain environments caused by abutment stress in the surrounding periphery rocks, varying from the highest stress and strain at the borehole collar to the lowest along the diametral axis to the toe of the hole. Each jacket would respond accordingly to the stress and strain environment around it, through the surrounding grout. Since they reflect different loads, balancing between jackets could only be achieved through the frictional overlaps by equilibrium, or by alternating slip-and-grip to accommodate the strain energy. In the Zambian underground mining environment, empirical observations are that where the rock surrounding an excavation fails, the greatest damage is in the immediate periphery. As the rock in the immediate periphery fails either the progressive failure stops of its own accord as equitable stress distribution predominates creating an harmonic hole, dependent on the shape of the excavation and the principal stress ratio in the surrounding rockmass, or progressively the failure envelope advances deeper into the rockmass, until at some point, the excavation fills up completely with broken rock. In some situations, the scenario described is irresistible and cannot be stopped. In most situations, passive and or active support at the earliest possible stage after mining may arrest or diminish ground failure. With active support, which became extremely popular in Zambia in the 1970s, such as grouted wire rope ‘rock bolting’, installation at the earliest was considered critical so that the rock bolt would interact with the ground movements generated in the rockmass in the immediate aftermath of excavation. If there was delay, resulting in installation of the rock bolts in ‘relaxed’ ground, movements would not be as restrained, it was theorised. Widespread introduction of cement grouted rock bolting, either on its own as primary support or supplemented with subsequent passive wiremesh/lacing, steel and or timber support, made a very substantial difference in the economics and safety of ground support, and resulted in the elimination or reduction of expensive steel set support and reduction of ground failure in the Zambian Copperbelt mines. Affordability, in the forex constrained period of 1975 to Year 2000, was also a driving issue in that previous situations requiring expensive steel sets could be handled with relatively inexpensive grouted rock bolting. Consequently, any further improvements of the effectiveness of the efficacy and efficiency of the grouted rock bolt, would contribute significantly to ground control safety in the Zambian Copperbelt mines, which even at present relies on the grouted rock bolts, de-strained wire rope bolts and cable bolts as the mainstay of ground support programmes.

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6 CONCLUSIONS

Firstly, from literature review, deviatoric stress and strain are greatest at the excavation periphery, declining deeper into the rock mass until at some distance the magnitude reaches the pre-mining status. Rock bolt designs have to recognise this variation in stress, and associated strain. Secondly, in light of the foregoing, present designs of rock bolts attempt to accommodate micro- and macro- movements in the rock in two ways:

- Rigid bolts with either cone, sinusoidal or o-shaped designs which stretch, while retaining integrity, in response to static and dynamic stresses; and
- Multiple-member assemblies, parts of which anchor and act like grouted rebar, while other parts slide in response to macro-scale dynamic stresses.

Thirdly, conceptually, a mechanism is demonstrated in the paper whereby excess stress and strain, as identified by the first conclusion, at the sidewall of an excavation is transferable through shear stress from one concentric jacket to the next, to deeper sections of the rock, by using a frictional balancing Multi-Jacketted Rock Bolt. The deeper sections being under greater confinement are able to accommodate the transferred stress and strain without excessive strain and failure. To start with, this would increase the effective anchorage depth of the rock bolt. Additionally, the elimination of localised excess stress on sections of the grout and/or rock bolt would allow relatively weaker grouts and bolts to be used. The rockmass in the immediate surround of an excavation would be able to yield less and with lessened unraveling, thereby re-distributing excess strain energy at the sidewall deeper into the rock.

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