International Journal of Mining Science and Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Partially decoupling and collar bonding of the encapsulated rebar rockbolts to improve their performance in seismic prone deep underground excavations

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ARTICLE INFO

Article history:
Received 12 May 2018
Received in revised form 14 July 2018
Accepted 7 September 2018
Available online xxxx

Keywords:
Rockbolt
Tunnel support
Collar bonding
Seismic rock support
Tunnelling

ABSTRACT

Rockbolt is widely employed all over the world as an effective ground reinforcement element in order to secure the underground workplaces. Ordinary encapsulated rebar or rebar rockbolt is most popular and commonly used as reinforcement in a ground support system because of its accessibility, cost effectiveness and easy practicability. Reinforcement elements in a seismic condition such as rock burst have to dissipate the energy release of the dynamic impact via their deformation and ultimate load capacity, knowing that the former is more important. In other words, achieving early stiff behaviour along with large deformation capacity in rockbolts are the goals for new development in rock reinforcement. Yielding rockbolts are expensive while some of them have large deformation capability with low ultimate load capacity. In this paper, modifications were made on encapsulation of rebar rockbolts to utilise it effectively as a yielding reinforcement in seismic conditions. Applying a sufficient decoupled length in the shank of rebar rockbolts which industry has regularly been using to control the bulking of the stress fractured ground, improves the deformation capacity of the bolt. Additionally, leaving a collar bonding underneath of the bearing pad and plate removes the weaknesses of the head anchorage of rockbolt. Therefore the dynamic performance of the bolt is improved by these easily applicable modifications. The behaviour and performance of encapsulated rockbolts have been discussed first, then the effects of modifications are illustrated. The proposed modification of the rebars is not only cost effective but also easy to apply in the field and improves the performance of reinforcements in seismic prone zones.

1. Introduction

To secure the underground excavation, rockbolts have extensively been used as operational reinforcement in mining and civil engineering for a long time. Various kinds of rockbolts including mechanical bolts, fully-grouted rebars, frictional bolts and energy-absorbing rockbolts are utilised every day for stabilising structures in dynamic and static loading conditions in underground mines. However, the interaction mechanism of the rock mass and the rockbolt is not understood clearly and to some extent the basis for the bolting design is still empirical or semi-empirical [1–6].

Rock reinforcement in seismic conditions has to dissipate the released energy of dynamic events. Therefore it needs specific requirements including large deformation capability and high ultimate load capacity. There are varieties of rockbolts in the industry developed for this purpose such as Split set, Swellex, Roofex, Yield-Lok, D-bolt, Cone-bolt, Garford, etc. but many of them are not available in all countries, and they need well-trained operators, certain considerations, and special installation equipment.

Different mechanisms are involved in improving the dynamic performance of the yielding bolts. Frictional bolts start to slip when the force exceeds the frictional strength of the bolt-rock interface. Slipping continues and shows larger deformation with an almost constant load in the shank of the rockbolt or with a decreasing load if the interface friction strength is reduced. Generally, this type of bolts does not have a high ultimate load capacity and even less in dynamic conditions but their advantage is the large deformability. Stretching of the shank of the bolt is another mechanism to increase its deformability similar to what is happening in D-bolts [7]. The shank of the bolt between two adjacent anchors is allowed to detach from the surrounding grout and stretch plastically to its ultimate deformation and load capacity [7,8]. Ploughing of the

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https://doi.org/10.1016/j.ijmst.2018.09.001
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anchor in the grout surrounding the bolt such as in Cone-bolts can also increase its deformability, but grout quality and its implementation need further considerations. Applying a high strength cementation grout can lead to strong anchorage of the cone, prevent it from ploughing through the cement, and result in early rupture of the bolt [7].

The rebars and threadbars are usually employed as ordinary rockbolts in underground mines all over the world. This kind of bolt wholly or partially encapsulated in cement or resin grout depending on the difference in expected performance. They are mostly used completely encapsulated in cement grout in mines as primary reinforcement in combination with surface wire mesh and shotcrete. Discontinuities opening in rock masses or ejection of a mass of rock in the tunnel wall cause local deformation and concentrated loading in the shank of the rockbolt. This phenomenon results in rupture of the bolt at the overloaded section while the rest of the rockbolt has not reached its deformation or load capacity.

The aim of this paper is to introduce an applied method of using ordinary rebar rockbolt in order to improve their capability in seismic condition. Distribution of the concentrated deformation such as a discontinuity opening along a longer length of the rockbolt (instead of a limited length) would help to increase the total deformation capacity of the rockbolt as well as prevent the local load concentration and early failure of the bolt.

In this paper, at first, the concept of energy dissipation rockbolt is discussed then the load transfer mechanisms for rebar rockbolts in mechanically end anchored and fully or partially encapsulated condition are explained. Then the critical bond length is defined. Finally, the modified rebar rockbolt presented and its role on the performance have been discussed.

2. Energy dissipation of rockbolt

The energy dissipation capacity of a rockbolt depends on its deformation capabilities along with its load bearing capacity. Rockbolts such as conventional steel rebar are strong with a high load capacity, but normally they do not have much deformation capacity due to brittle behavior of encapsulation material. These kinds of bolts are so-called strength bolts in static condition. Rockbolts such as split sets have a large capacity of deformation but they are not strong because they start to slip at a small applied load. The second type of rockbolts are so-called ductile rockbolts [8]. Additionally, hot-rolled steel rebar rockbolts show an extension in length at yield under constant load followed by strain hardening [9]. This property of hot-rolled steel rebars is also useful for increasing the energy dissipation capacity of the rebar rockbolts.

Rockbolts have various kinds of anchoring mechanisms some of which will be discussed here after. Ordinary rockbolts are those rebars which lie in a hole entirely coupled with the rock using cement or resin encapsulation. This type of bolt shows an appropriate stiffness under loading stage of the bolt, but this kind of rockbolts have low deformation capacity due to grout brittle behavior. Specifically, a small amount of a local deformation due to a discontinuity opening overloads the related section and cause a local failure in the shank of the bolt. End anchoring or two-point anchoring of the rockbolts (using expansion shell) can increase the deformation capacity of the rockbolts by the distribution of the deformation of local expansions or discontinuity opening in the rock over the whole free length of bolts. In this case, anchor movement due to load concentration on, or creep of, the anchor point could cause loading on the bolt shank being released. Partial anchoring (having a bond length at the end of the bolt) is a way to avoid the creep but the nut and bearing plate at the head of the rockbolt do not have enough load capacity under dynamic loading conditions (or even sometimes in static conditions) [7,10,11]. Bearing face plate sometimes shows lower resistance in comparison to the rockbolt strength under the loading conditions [7,11–13]. Ductile rockbolts such as split sets accommodate large ground deformation by slippage of their cylindrical surface over the borehole's wall and have a load capacity due to the available friction in-between which usually is not high enough. Other yielding bolts such as Swellex, Cone bolt, D-bolt, Garford, etc. are not only expensive but also need special equipment to install as well as trained operators.

To sum up, ideal yielding rockbolts are those that have both high strength and large deformation capacity. The area under the curve of load-deformation of a reinforcement element during the process of loading replicates the amount of energy that the element can dissipate. As a rule, the more area under the curve that a support element has, the more energy dissipation capacity it has. Therefore increasing the deformation capacity of a rockbolt without reducing its ultimate strength will increase its energy dissipation capacity as well as increasing the ultimate strength of a bolt type without reducing its deformation capability.

3. Load transfers mechanisms in rebar rockbolts with different anchorage conditions

Primary studies on the behaviour and axial load distribution of the rockbolts under loading conditions have been started by Farmer [14]. According to literature, the axial and shear stress at the interface of the bolt–grout and the grout-rock decrease exponentially over a length of encapsulated rockbolt from the loading point to the distal end of the bolt as long as debonding has not occurred. As shown in Fig. 1, the maximum shear stress is concentrated near the surface and then rapidly decreases with moving toward depth.

An encapsulated length of a rockbolt is coupled with the surrounding ground via cement or resin encapsulation material; therefore the rockbolt is loaded due to the deformation of the ground or surrounding material. As it can be seen schematically in Fig. 2, the relative axial deformation between the rockbolt and wall of the bore hole is a result of ground deformation. The figure shows the deformation of massive rocks in the absence of discontinuities. However, the ground deformation and load distribution over the rockbolt are more complicated in such conditions [16].

3.1. Mechanically two-point anchored rockbolts

A mechanically end anchored rockbolt is anchored in a borehole at both ends of the rockbolt so it can be called a two-point anchored bolt as shown in Fig. 3. This kind of rockbolt must always have a bearing face plate on one end (head) and a mechanical anchor point such as an expansion shell on the other end of the rockbolt. In most cases, an initial pretension needs to be applied by tightening of the nut promptly after installation. The initial pretension helps to activate the rockbolt from the installation time.

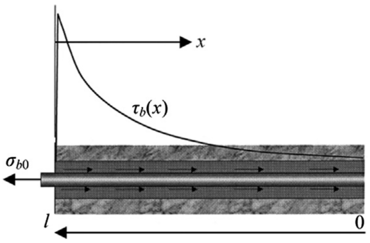

Fig. 1. Shear stress along a fully coupled rockbolt subjected to an axial load prior to decoupling (redrawn and modified after Li and Stillborg [15]).

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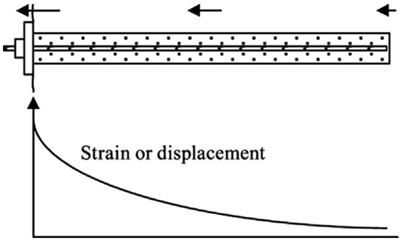

Fig. 2. Axial loading of rockbolts caused by ground deformation (modified and redrawn after Thompson, Villaescusa [16]).

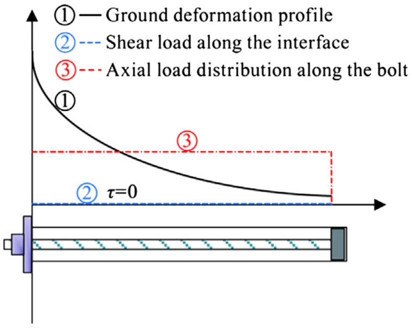

Fig. 3. Load distribution in mechanically two point anchored rockbolts (modified and redrawn after Zou [17]).

Then ground movements apply further tension in the shank of the rockbolt between the head (collar) and end (expansion shell) of it along with the loading of the support elements. The load distributes uniformly over the length of the rockbolt and all induced deformation due to ground movement or discontinuities openings cannot change the outline of the load distribution, and the load distributes over the whole length unless the rockbolt fails or is sheared off.

The strength of the bearing face plate, nut, thread, and the tightness of the end anchor, govern the load capacity of this kind of rockbolt while deformation capacity of the rockbolts depends on their material. Although these types of rebar rockbolts are produced in a broad range of load and deformation capacities, in comparison to fully grouted rockbolts, the two-point anchored rockbolts have much more deformation capacity because of distribution of the deformation over the whole length of the rockbolt.

Two-point anchored bolts have some weaknesses leading to a loss of their functionality for support the ground. Slippage of the expansion shell at the end of the bolt because of a small area of in-between contact would be a reason for releasing the load of the bolt. This phenomenon could be a result of failure due to stress concentration on an anchor point or creep of the rock under stress concentration. The other weaknesses of the mechanically end anchored rockbolts are nut and thread stripping and/or the failure of the bearing faceplate to retain the load and transfer it to the rockbolt. One of the main reasons for nut and thread stripping and the early failure of the bearing plate is the occurrence of dynamic events during which the nut can expand laterally and strip off the threads and/or the bearing plate cannot tolerate its nominal resistance. Manufacturing and non-conformance of the bearing plate and the rockbolt could be another reason for early failure. Failure of screw threaded rockbolt in the threaded part of the head of the rockbolt often occur because of the lower effective cross sectional area of the rockbolt at the roots of the screw threads.

Local weaknesses, blasting and other methods of excavation can disturb the rock mass in the wall and roof where disturbance of the rock beneath the bearing plate is another reason for unwanted unloading of the rockbolt and ruin the functionality of a support system.

3.2. Cement/resin fully or partially encapsulated rockbolts

The length of the rebar rockbolts can be encapsulated partially or fully over their entire length. Pretension and deformation of the ground mobilise the anchorage strength, but the anchorage force and axial mobilised stress are not uniform over the encapsulated length of the rockbolt. Previous studies and experiments show that when tension is applied to the head of the rockbolt, it is transferred to the initial anchorage point at the proximal end of the bond length through the shank of the rockbolt [18]. Anchorage resistance is mobilised in the first segment of the bond length and passes to the following segments by further deformation of the bolt until the anchorage strength is reached. Therefore, in the case of using an infinitely stiff plate the maximum anchorage force (and axial induced load in the shank of the rockbolt) is on the first grouting point and decreases toward the end of the bolt (Fig. 4). It worth mentioning that in the case of using a flexible bearing plate, the distribution of the axial load and shear stress should be similar to those in Fig. 5 with differences in the position of the peak which is closer to the tunnel wall, and returning the axial load to a certain amount larger than zero, depend on the capacity and stiffness of the bearing plate [9].

The summation of the mobilised anchorage strength over the segments (elements) of the encapsulated length of the rebar rockbolt determines the anchoring force. The axial load distribution over the bond length is not uniform, and also it is governed by ground deformation to which it shows a similar pattern. Extending the ground deformation and increasing the induced load can result in stress above the strength of the rockbolt.

Fully encapsulated rockbolts sometimes can be utilised without a bearing face plate; in this condition, the pattern of the load distribution will change to zero tension at the proximal end (head) of the rockbolt. Due to lack of initial pretension, the rockbolt load is only induced by rockmass deformation. Depending on the ground movement and differential deformation there is a separation line of induced shear and consequently induced tension. The actual pattern of the induced tension is very complicated and difficult to determine. Stress adjustment induces more displacement near the collar in comparison to deeper parts in the borehole and this differential movement between two points induces shear stress over the bolt-grout interface. Induced shear applies the axial load in the shank of the bolt. Shear stress near the head (collar) is in the opposite direction to that of the shear stress near the distal (far) end. Therefore, there is a separation line in-between which can be seen in Fig. 5. The schematic profiles of the ground deformation,

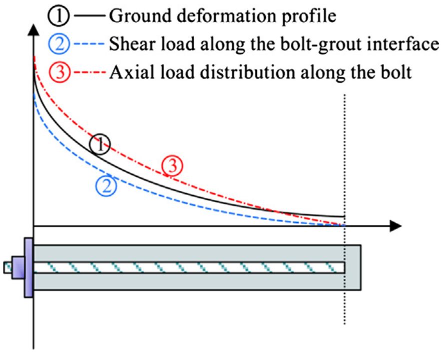

Fig. 4. Load distribution in fully grouted bolts with bearing plate in uniform media (modified and redrawn after Zou [17]).

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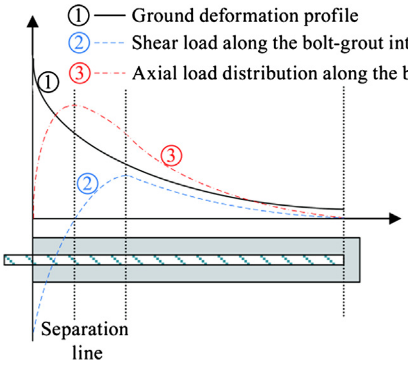

Fig. 5. Stress distribution in fully grouted bolts without bearing plate in uniform media (modified and redrawn after Li and Stillborg [15], Zou [17]).

induced shear stress along the bolt-grout (or grout-rock) interface, and the induced axial load along the shank of the bolt are illustrated in this figure. The tension in a rockbolt as well as mobilised anchorage achieve maximum values at the separation line and go to zero at both ends. Shear force, as it has been mentioned, is zero at the separation line and is in the opposite direction on each side of it. With developing the deformation, the separation line is displaced and normally goes toward the end of the borehole.

Fully-grouted rebar rockbolt shows the highest load bearing capacity of the conventional rockbolts if the failure occurs in the shank of the bolt. The capacity is highest in shear and pull loading conditions, although it does not have much deformation capacity. In other words, the fully-encapsulated rebar rockbolts are characterised as strong but stiff rockbolts which may not suit in seismic prone zones [7].

The presence of an active discontinuity in ground causes a local change in loading around the discontinuity in the shank of the bolt because of the opening of the discontinuity. Due to the involvement of the bolt and surrounding encapsulation material, the displacement cannot distribute over the length of the bolt. Consequently, the axial load in the shank of the bolt rises (Fig. 6). Loading can increase gradually because of the progressive opening of discontinuity and lead to a local failure in the shank of the bolt, in the case of the bolt strength being exceeded.

The partially encapsulated rebar rockbolts are those that have a bond length at the distal end of the rockbolts and the rest of the bolts are completely decoupled from the surrounding grout or are free of the encapsulation material. The termination arrangement of this type is similar to mechanically end anchored type of rockbolts or fully grouted rebar rockbolts. This kind of rockbolt needs to have the termination elements to be able to contain the surface movement of the ground and transfer it to the shank of the bolt. The major portion of induced deformation distributes over the grout-free section of the bolt (free length). Therefore, this kind of rockbolt can tolerate more deformation than the fully grouted kind. The axial load distribution in the free length is constant as there is no shear stress at the interface to transfer the load to the bolt segments. The distribution of the load over the bond length is similar to that of the fully encapsulated rockbolts. The axial load in the bond length is the difference of applied load to the bolt and mobilised anchorage force as shown in Fig. 7.

It is worth mentioning that the real load/stress distribution along a partially encapsulated rockbolt has some differences over the bond length. Stress concentration at the beginning of the proximal end of the bonding length could overcome the strength of the anchorage resistance of the bolt-cement or cement-ground interface, and transfer the load to the following segments (Fig. 8). As a matter of fact, if there was some friction along the shank of the rockbolt in the grout-free section, then the axial load in this part would not be horizontal and would have a small inclination toward the end of the bolt while the pattern of the load distribution over the bond length would be the same.

Partially encapsulated resin/cement rockbolts should have enough bond length in the stable zone at depth to be able to secure the opening effectively. Due to the stress concentration on the proximal end of the bonded length, decoupling of the bolt-cement interface could occur. Under a load increasing condition, decoupling could develop progressively. Therefore, it has to be ensured that the remaining part of the bond length is enough or has adequate strength to avoid a failure.

If a ground movement such as concentrated deformation of the discontinuity opening or ejection of a mass locates in the free length of the rock bolt (Fig. 9), the imposed deformation is distributed over the whole of the free length and just an increase in the load level

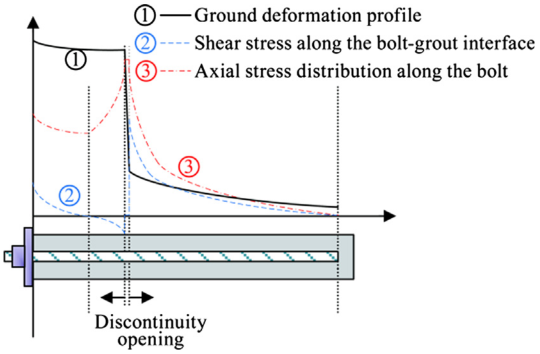

Fig. 6. Stress distribution in fully grouted bolts with bearing plate under effect of a discontinuity.

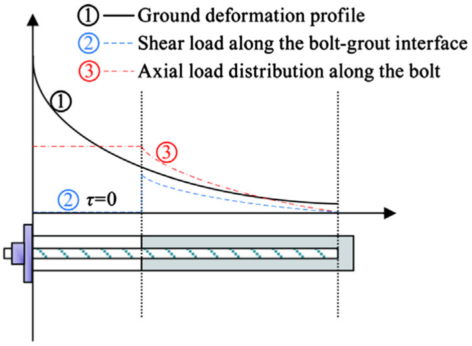

Fig. 7. Load distribution in partially grouted bolts with bearing plate in uniform media (redrawn and modified after Li and Stillborg [15], Zou [17]).

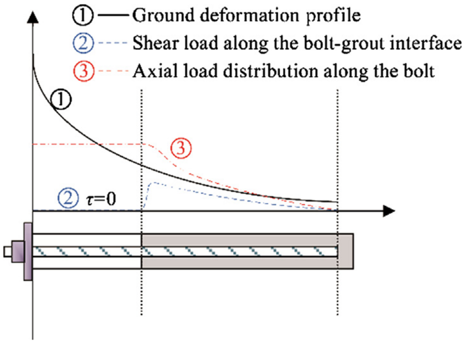

Fig. 8. Realistic load distribution in partially grouted bolts with bearing plate in uniform media (modified and redrawn after Li and Stillborg [15], Zou [17]).

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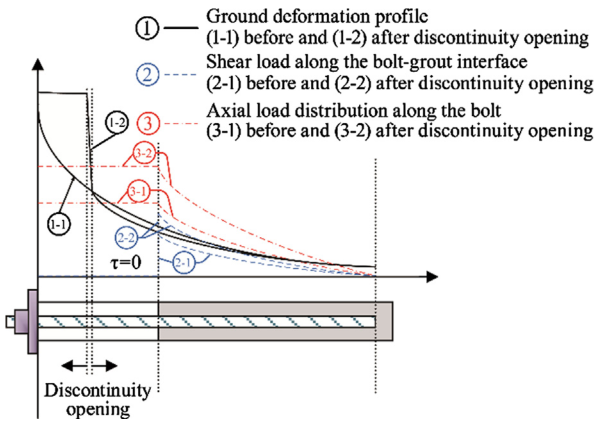

Fig. 9. Load distribution in partially grouted bolts with an active discontinuity in free length (redrawn and modified after Li and Stillborg [15], Zou [17]).

occurs. The exception is when the total deformation is large enough for the rebar to reach failure. On the other hand, if the concentrated deformation locates in bond length of the rockbolt, the load distribution over the bond length is similar to what was explained for fully encapsulated rockbolts. It is worth mentioning that the initial pre-tension and induced tension of the ground movement are superimposed together [17] as shown in Fig. 9.

Although the weakness of the two-point anchored rockbolts at the end anchoring part is removed, the termination arrangements (head) weaknesses, the early failure of bearing plate and nut, nut and thread stripping, or failure in the threaded part, especially in seismic conditions, still remain unsolved.

4. Concept of rockbolt Critical Bond Length (CBL)

The length of the encapsulation in rockbolt reinforcements plays a crucial role in bolt performance. The reinforcements have to be able to transfer the applied load to the ground. The Bond length is the end part of the rockbolt which has the function of transferring the applied load to the stable ground at depth. Loads increase after installation of a reinforcement element in parallel with the progress of the excavation. Advances in faces or benches, change in geometry, time dependent behaviour of the surrounding ground, the setting time or other property of the grout material if applicable, pretension or applying an external load, dynamic seismic events, failure of other elements, changes in underground water level, etc. are the main factors for increasing the load on the reinforcement element. In all cases, bond length has the role of transferring the load to the ground, so it is necessary that a particular part of it lies in the stable ground. Therefore, the length should be adequate to sustain the load of the unstable and pass it to the far end of the bolt where its bonding or anchoring system is located.

In the case of partially encapsulated reinforcement, bond length in stable ground should be enough to carry the total applied load and to be able to transfer it to the ground. If the bond length was not long enough, it could not tolerate the load, and then the interface of the bolt - grout or the grout-rock would probably be decoupled. The minimum bond length of rockbolt in stable ground should be more than the critical bond length. The Critical Bond Length (CBL) is the maximum length of embedment for which the failure of the rockbolt will happen at the interface; greater embedment length causes the failure to occur in the shank (in the case of overloading). In other words, if the embedment length is less than the CBL, failure of the rockbolt will occur at the interface in the case of overloading. This indicates non-employment of the ultimate strength capacity of the rockbolt. If the embedment length is greater than the CBL, the failure will occur in the shank of the rockbolt [19]. If the bond length is less than CBL, then the load-displacement behaviour of the rockbolt failure would be similar to that of the cement grout. Otherwise, it is governed by the behaviour of the material of the bolt (steel) itself and shows the adequacy of the bond length. Fig. 10 schematically compares these two behaviours and failure modes.

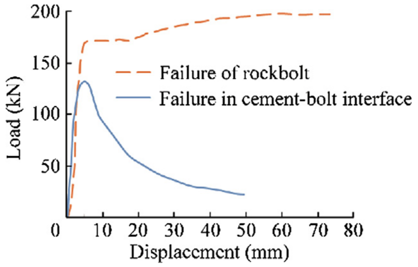

Fig. 10. Load-Displacement behaviour of a rockbolt under overloading condition (modified after Li, Kristjansson [19]).

Experiments on 20 mm diameter rebars show that the critical cement encapsulated bond length is between 25 cm and 36 cm for water to cement ratios of 0.40 to 0.50 (UCS of 37 to 28 MPa) [19].

5. Rebar rockbolt modifications to enhance the dynamic energy absorption

Fully grouted rebar rockbolt is the most common type of reinforcement systems in civil and mining projects. Due to rebar rockbolt popularity, its installation technology significantly developed and well trained among tunnel practitioners. The low deformation capacity of fully grouted rebar rockbolts is their main shortcoming for efficient use in seismic conditions. To overcome this shortcoming, the partial encapsulation of rockbolt at both ends were recommended. Preventing the bonding at the middle of rockbolt could be easily carried out by covering the bolt with a piece of pipe in the middle part as shown in Fig. 11. In this section, proposed modifications in order to increase the energy absorption capacity of rockbolts. The proposed modifications will remarkably increase the deformation and consequently energy dissipation capacity of the rebar rockbolts.

A photo of the proposed modification rockbolt is shown in Fig. 11. The rockbolt is divided into four parts consisting: (a) "main bond length", (b) "free length" which is free of contact with grout, (c) "collar bond length", and (d) "outer length" which is the same as in ordinary rockbolts. These components along with effect of modifications is illustrated as follows.

5.1. Main Bond Length (MBL)

A particular length at the distal end side of the rockbolt is considered as the "main bond length". Since this part has the function of transferring the induced load to the ground, its length should be at least as long as the Critical Bond Length (CBL). Due to uncertainties in the ground, some extra length has to be considered to increase the factor of safety. As a rule of thumb, the additional length could be considered as 50–100% of the CBL as shown in Eq. (1).

$$\mathrm{MBL} = \mathrm{SF} \times \mathrm{CBL} \tag{1}$$

$$\mathrm{SF} = \text{Safety Factor} \approx (1.50 \text{ to } 2.00) \tag{2}$$

Therefore, at first, the CBL will be verified by laboratory or insitu tests. In addition to CBL, some extra length should be considered for the factor of safety which is determined by engineering

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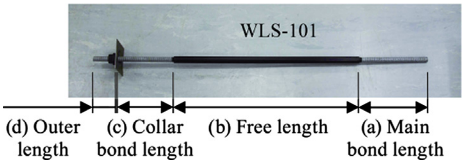

Fig. 11. Components of proposed modification rebar rockbolt.

procedures. Insitu testing for evaluation of the CBL is more reliable than laboratory testing, and in the latter case, the factor of safety should be considered higher. Although with progress in excavation the reliable CBL could be adjusted based on site specific conditions.

5.2. Free length

Covering a particular length of a rockbolt with a piece of smooth pipe, such as PVC pipe, with an appropriate inside allowance prevents the surrounding grout contacting the bolt. Thus, rockbolt can freely move axially inside the smooth pipe. Therefore, this part can be considered as free length, or free of contact that allocates more deformation due to ductile behavior of steel rebar. In other words, the free length on the middle of the rockbolt plays a vital role to distribute the applied axial deformation on the rockbolt originated from discontinuity opening, wedge movement, movement of a volume of rock due to seismic activity, etc. over the free length. The concentrated deformation in fully grouted rockbolt could lead to a failure due to lack of deformation capacity.

To cover a rockbolt at free length, the smooth pipe can be installed with sealing material on both ends such as heat shrink sleeve or crimp fitting. In most cases, whole length sealing is not required, since the cement grout cannot penetrate the pipe and the bolt will not be coupled with the surrounding grout. The cement grout might infiltrate into the pipe or at worst, there might be a small amount of grout intrusion, but this will not bind the rockbolt to the surrounding encapsulation material. Therefore, the pipe acts as an element for decoupling the rockbolt from the surrounding material and allows the applied deformation to be distributed over the free length. It should be ensured that the dislocation of the pipe does not occur during the installation of the rock bolt in the borehole (Fig. 12).

5.3. Collar bond length

As it has been shown in Section 3.1 and 3.2, a rockbolt likely fails from the termination arrangement. Weaknesses in bearing plate, nut, threading, bearing pad, or the fractured rock underneath the bearing plate or pad, lead the rockbolt to malfunction or early failure. Even local failure of the rockbolts causes the failure of neighbouring bolts and gradual development of the support failure to the entire support system.

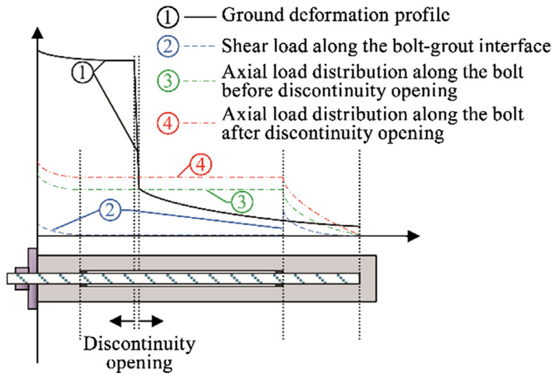

Fig. 12. Load distribution in partially decoupled rebar rockbolts with bearing plate under effect of a discontinuity.

Routine practices such as making the bearing pad perpendicular to the rockbolt, using an extra bearing plate and nut, etc. not only result in additional costs and complexity of the application, but also they cannot remove all of these weaknesses. The only way by which removing all weaknesses is viable is the application of a collar bonding. Collar bonding is the coupling of rockbolt to the surrounding rock and can also couple to surface support. Mobilising the anchorage force in this part in addition to the resistance of the bearing plate and nut can form an appropriate terminating arrangement and involved with the surface support and rock to contain the surface movement of the rock and transfer the load to the rockbolt at depth. Then, the main bond length can transfer the load to the ground. To be in safe side, the collar bond length can be considered as same length as critical bond length. As it has been explained, the collar length determination itself has not an accurate calculation. The reason for employing the collar bond length is uncertainty of the strength of the bearing plate and nut, strength of the ground around the collar and beneath of the bearing plate, and so on. Due to such uncertainty using such a collar bond length by the length of the critical bond length would be an appropriate way to avoid misfunctioning of the bolts. The method to determine the critical bond length is explained in Section 4. The method can be employed both in lab or field.

5.4. Outer length

The outer or external length is a part of the rockbolt which stays out of a bore hole. Bearing plate and underneath pad, nut, possibly centraliser and bevelling washers, and protection cap, are placed in this part of the rockbolt. The outer length should be long enough to contain all designed facilities. This length for conventional rockbolts is 10–15 cm. It is noteworthy that longer outer length would reduce the effective span of the opening and this problem could result in extra costs.

5.5. Static and dynamic test results on partially encapsulated rockbolts

Laboratory experiments have been performed by Western Australian School of Mines via a dynamic testing facility on 20 mm threadbars [11]. The results were compared with previous attempts on similar rebars under static loading condition. Dynamic tests have been carried out by dropping a loading mass attached to a rockbolt cast in grout within thick wall steel pipe, into a pit. The rockbolts were assembled with the proposed configuration (a = 1 m main bond length, b = 1.6 m free length, and c = 25 cm collar bond length) and compared with the fully grouted configuration. The mechanical properties of this type of rebar rockbolts are: average yield force = 165 kN, average tensile strength = 191 kN, and average elongation capacity = 21%.

Typical results of three combinations of embedment and loading conditions of the rebar rockbolts is illustrated in Fig. 13 for comparison. The fully grouted rockbolts are stiff and take up the load quickly, but they do not allocate much deformation. As it can be seen in Fig. 13 they can tolerate about 30 mm deformation in the static loading condition. Under dynamic conditions, the fully grouted rockbolts showed higher strength, higher energy dissipation capacity (about 10–15 kJ), and higher deformation capacity (60–70 mm). As it was predicted, the proposed configuration increases the deformation capacity of this type of rockbolt to more than 100 mm as well as their energy dissipation capacity to more than 20 kJ.

Additionally, it has been found that the rebar rockbolts show higher strength under dynamic impact. Although the ultimate

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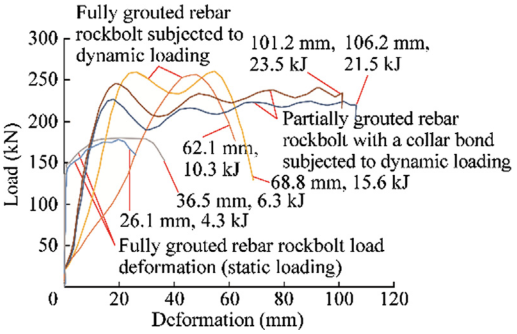

Fig. 13. Different combination of embedment and loading condition of the rebar rockbolts (Data from [11,20]).

strength of the rebar rockbolts in the static loading condition is about 191 kN, the strength increases up to 250 kN under dynamic impact so that the higher strength increases the energy dissipation capacity of rebar rockbolts.

The results show that both deformation capacity and energy dissipation capacity of rebar rockbolts would be improved by applying the suggested modifications.

5.6. Field experiment results on partially encapsulated rockbolts

Field experiments have been carried out in order to evaluate the rebar rockbolts' behaviour under seismic condition produced by blasting. Due to uncertainty in location and time of natural seismic events, blasting is used to produce the seismic wave. Nine rockbolts installed in a tunnel as shown in Fig. 14 which was completely removed by backward excavation. The tunnel was an access pilot to the top-heading of a cavern in order to be excavated top to down.

The rebar rockbolts behaviour monitored in the 6 m × 6 m pilot tunnel of the 16 m × 27 m × 161 m cavern as illustrated in this section. The pilot was excavated by drill & Blast to the roof level of the cavern by 12.5% upward inclination as an access tunnel. Top heading of the cavern horizontally excavated by drill & blast by 6 m height and 16 m span in two stages of a horizontal pilot and enlargement to the final span by slash blasting. Excavation in bench was continued in every 3 m depth of bench blasting. The support system of the roof and wall has been installed simultaneously. As shown in Fig. 14 three arrays of monitoring have been carried out in chainages of 15.0 m (array 1), 30.0 m (array 2), and 45.0 m (array 3). In each array, three rebar rockbolts with the length of 4 m equipped with deformometre to monitor the deformation over different segments of each rockbolt. The borehole loadcells installed on the bolt to measure the load along the shank of the rebars.

Each rockbolt was hot-rolled steel rebar that shows an extension in length at yield under constant load followed by strain hardening. Rebar specification consists: yield strength/ultimate strength = 400/600 MPa, diameter = 20 mm, average yield force of the bolt = 130 kN, average ultimate strength = 190 kN, average elongation capacity = 6%, length = 4 m. The suggested modification have done with: (a) main bond length = 1.50 m, (b) free length = 1.70 m, (c) collar bond length = 0.50 m, and (d) outer length = 0.30 m. The dislocation of pipe monitored visually because one end was close to the collar and the distance was monitored visually and measured by a tape.

The load in the shank of the rockbolt was measured with a borehole load cell at the proximal end of the free length and deformation was measured in borehole and surrounding rock by multiple borehole deformometres in sections of the surface to the depth of 0.50 m (0.0–0.5 m), 0.5–2.2 m, and 2.2–3.7 m. 0.3 m of each bolt stayed out of the borehole for bearing pad, plate, nut, and initial tightening of the bolt. The proposed deformometre as sketched in Fig. 15 is a wire strain gauges like material. Increase in length of wire leads in change of its electrical resistance and output voltage of the readout unit calibrated for the instrument. The wire was covered by a smooth pipe to protect it from encapsulation material.

A geodetic target was also installed adjacent to the head of each rockbolt to monitor the surface movement of the bolt head. Results of the geodetic point data were used for calculation of absolute displacement of each point in the borehole. The instruments recordings were carried out on a daily basis plus recording after each blasting. The recorded results of the monitoring for three of the rockbolts (array No.3 ch: 45 m), including displacement and load variation over a period of 100 days are depicted in Figs. 16–21 and illustrated herewith. The presented results in these figures clearly depict the ground behaviour, deformation profile in surrounding ground that transfer to the rockbolt, and respected loading of the rockbolts. Combining each pair of graphs result in finding the load deformation behaviour of the each rockbolt including total deformation and energy absorption capacity.

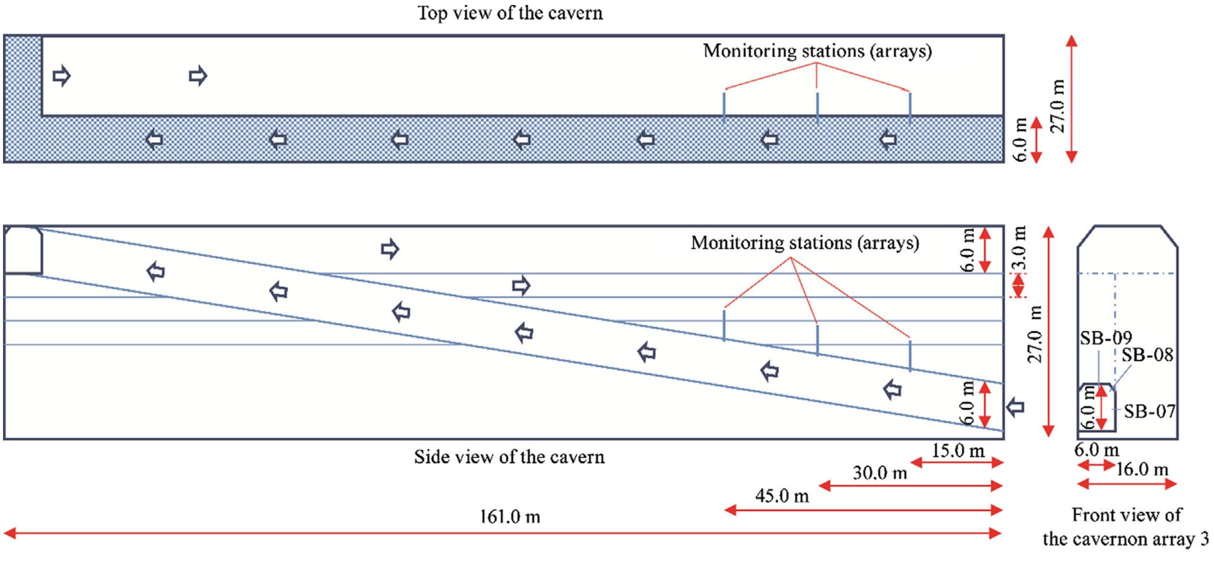

Fig. 14. Different views of the cavern including the tunnel under study.

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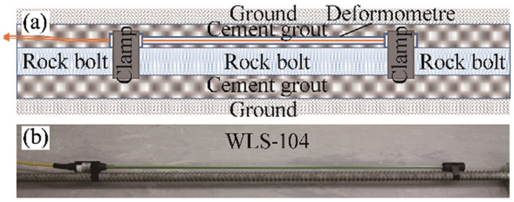

Fig. 15. Deformometre to measure the large deformation along a rockbolt: schematic view (a) and photo of installed set sample (b).

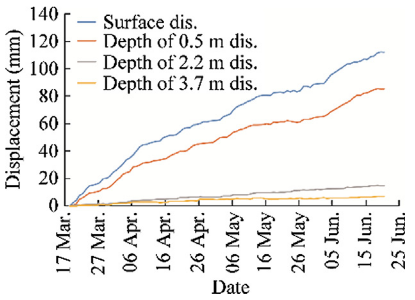

Fig. 16. Displacements monitoring results at different distances from rockbolt head No. 7.

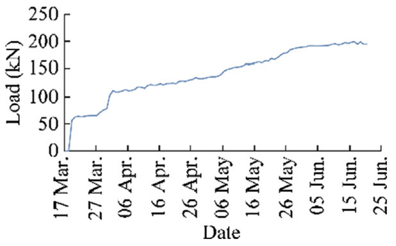

Fig. 17. Load monitoring in the shank of rockbolt No. 7.

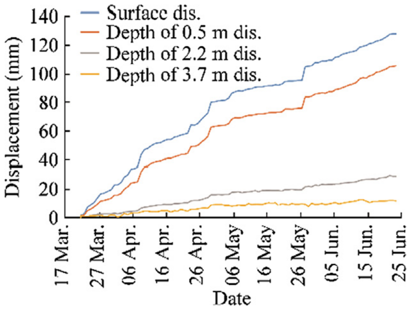

Fig. 18. Displacements monitoring results at different distances from rockbolt head No. 8.

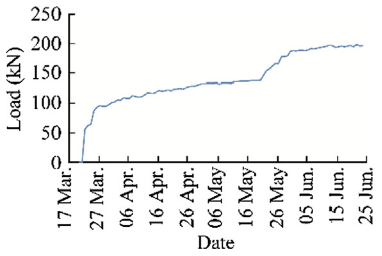

Fig. 19. Load monitoring in the shank of rockbolt No. 8.

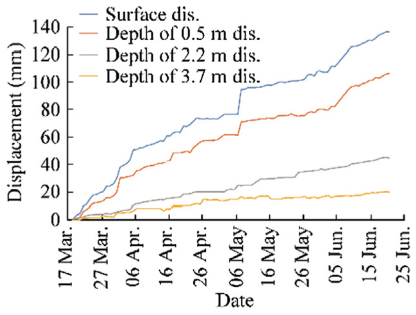

Fig. 20. Displacements monitoring results at different distances from rockbolt head No. 9.

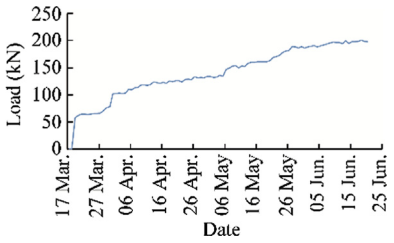

Fig. 21. Load monitoring in the shank of rockbolt No. 9.

As shown in Figs. 16 and 17, the rockbolt No.7 which is installed at the wall of array 3 was able to tolerate about 112 mm of deformation to reach to the final loading capacity, the rockbolt No. 8 (Figs. 18 and 19) installed at the corner was able to tolerate about 128 mm, and the rockbolt No. 9 (Figs. 20 and 21) installed at the roof was able to tolerate about 137 mm.

In order to investigate the load and deformation capacity, and estimate the energy dissipation capacity of the rockbolt, deformations and loads measured at the same times in each pair of graphs were extracted and depicted in Fig. 22. The distribution of the displacement along each rockbolts and the energy absorption of each one are varies, although in comparison with full encapsulated rebar rockbolt it is evident that total energy absorption capacity of all of the bolts increased considerably [21].

As it can be seen in Figs. 16–21 during the period of study, the rockbolt No. 7 at wall has experienced about 112 mm of deformation from which about 97 mm is related to the free and collar bond length (from surface to the depth of 2.2 m). The rockbolt No. 8 has tolerated about 128 mm of deformation. Where 99 mm of the deformation occurred from the surface to the beginning of the main bond length (0.0–2.2 m). The rockbolt No. 9 at the roof has experienced about 137 mm from which about 67% of it tolerated along free length and collar bonding length. Generally, most portion of the deformation were tolerated by the free length in all cases. Since this type of rockbolt does not have much elongation capacity, the results show significant improvement in rebar rockbolt deformability.

Comparison of the results of the available load in the shank of the rockbolt with the applied deformation shows consistency in the whole range of monitoring except between 130 kN and 190 kN, which is around the yielding load of the rockbolt to the ultimate failure point. In this range, the load pattern differs from the deformation pattern because it is in the plastic zone of the rockbolt material. This behaviour shows that some part of the yielding of the rockbolt occurs under dynamic impact, then recovers to elastic range in the following stable condition. This impact load increase (impact ultimate strength) could reach to 20–30% higher than its static ultimate strength. Determining this portion of the jumping in load of the shank of the rockbolt needs continuous dynamic mon-

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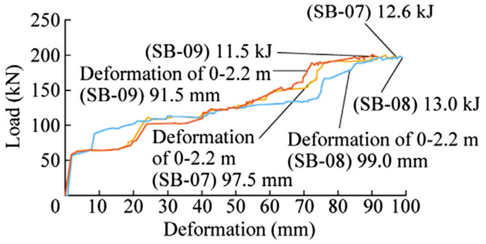

Fig. 22. Changes of load versus deformation of the modified rebar rockbolt.

itoring of the rockbolt during the impact that has not been carried out before in field. The field experiments shows that the continious dynamic monitoring can be achieved using proposed deformometre (Fig. 15).

The practical experiments also show that the deformation capacity and energy dissipation capacity or steel rebars improve with partially encapsulation of rebar rockbolts.

6. Discussion on modified rebar rockbolt performance in seismic prone zones

The rebar rockbolts are frequently used in underground mining to control the bulking of the stress fractured ground even in seismic conditions. The seismic prone ground needs considerations to avoid the violent collapse of the wall or roof. Improving the rebars rockbolts, promote the entire rock support system and results in an effective safe workplace.

Modified rebar rockbolts in comparison with frictional rockbolts show much higher strength, specifically in seismic conditions. They are able to tolerate more load even compared with this ultimate strength in static condition due to their involvement with the ground through anchoring system compared to frictional contact.

A suitable ground support system in the seismic prone zones should have enough resistance as an integrated system. The capacity of the support system is governed by the weakest link in reinforcement or surface support. Having the collar bonding prevents the rockbolt to be the weakest link by removing all weaknesses in heading anchorage of the rockbolt. The low resistance of the bearing plate, nut, thread, and loose surface rock cover with the resistance of the coupled collar length so that the ultimate strength of the head anchorage goes much higher than the strength of the shank of the rockbolt.

The free length or decoupled part of the rebar increases the deformability of the rockbolt and prevents any local failure due to concentrated deformation which leads to rockbolt failure. The debonded part of the rockbolt is an important part of it so that many discontinuity opening or ejection of a volume of rock locate in this depth. Without the free length in this part, early rupture of the rebars likely occurs or there are high risk of the support failure.

Considering that proposed rockbolt modification is an easy and low cost practice with high performance in seismic prone zones and significant improvement in the capacity of the deformation, avoids early failure, improves head anchorage, not leaving a weak link in reinforcement, connecting elements, and terminating arrangement, while rockbolts have enough strength in the anchorage.

7. Conclusions

The rockbolt is a vital element of a rock support system in underground mining. Rockbolts tolerate the contained load by the surface support and have to have enough length to be able to transfer it to the stable ground at depth while being not too long because of economic reasons and implementation limitations. The bond length in the stable zone has the role of load transfer to the ground. Therefore uncertainty of the bond length dimension should be minimised. Previous experiments show that there is a critical embedment length for rockbolts in different situations that the designer has to take this into considerations.

In this research with modifications applied on ordinary rebar rockbolts improves their performance in a rock support system specifically in seismic conditions. Considering a free length in the middle of the bolt by a piece of smooth pipe over the rockbolt to decouple it from surrounded cement material, allow the rockbolt to be able to absorb more ground deformation than conventional full encapsulation.

Collar bonding underneath of the bearing pad and plate, improve the head anchorage of the bolt and avoid any early failure in this part due to pre-existing rock breakage under the bearing pads, low resistance of bearing plates, the possibly lower ultimate strength of the threaded part, etc. The proposed length for collar bonding is the same length as critical bond length.

The main bond length that transfers the applied load to the surrounding ground should be conservatively considered. Therefore, laboratory or preferably on-site testing is required to evaluate the CBL which is the minimum length of the bonded part that the bonding resistance is more than the ultimate strength capacity of the shank of the rebar. Applying an engineering factor of safety to the CBL leads the designers to consider an appropriate main bond length.

The field experiments shows that the dynamic continious monitoring of large deformation of rockbolts in seismic prone grounds can be achieved by proposed deformometre.

Prior to a rockbolt project, an on-site test plan to determine the optimised practical critical bond length for minimising the risk of support failure is recommended. Monitoring and observations will assist the engineers to modify the whole system along with the progress. Since this type of rebars are always available and frequently employed in ground support systems along with other types of rockbolts and support elements, these modifications will improve the performance of the whole ground support system.

Acknowledgements

The authors would like to acknowledge funding organisations, Curtin International Postgraduate Scholarship (CIPRS)/Department of Mining and Metallurgy Scholarship, and the Mining Education Australia (MEA), Collaborative Research Grant Scheme [grant number RS-59041].

References

[1] Kaiser PK, Cai M. Design of rock support system under rockburst condition. J Rock Mech Geotech Eng 2012;4:215–27.
[2] Cai M. Principles of rock support in burst-prone ground. Tunn Undergr Space Technol 2013;36:46–56.
[3] Sandbak L, Rai A. Ground support strategies at the turquoise ridge joint venture Nevada. Rock Mech Rock Eng 2013;46:437–54.
[4] Kristjánsson G. Rock bolting and pull out test on rebar bolts. Institutt Geologi og Bergteknikk 2014.
[5] Jin FZ, Ming YX. Uplift capacity of shallow anchors based on the generalized nonlinear failure criterion. Math Prob Eng 2016.
[6] Mark C. Science of empirical design in mining ground control. Int J Min Sci Technol 2016;26:461–70.
[7] Li CC, Stjern G, Myrvang A. A review on the performance of conventional and energy-absorbing rockbolts. J Rock Mech Geotech Eng 2014;6:315–27.
[8] Li CC. A new energy-absorbing bolt for rock support in high stress rock masses. Int J Rock Mech Min Sci 2010;47:396–404.
[9] Li CC. Rockbolting: Principles and Applications. Oxfordshire: Butterworth-Heinemann; 2017.
[10] Cai M, Champaigne D. The art of rock support in burst-prone ground. Proc RaSiM. 2009;7:33–46.
[11] Player J, Thompson A, Villasescusa E. Dynamic testing of threadbar used for rock reinforcement. RockEng09, rock engineering in difficult conditions. CIM Montreal 2009;4030:12.

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[12] Stacey T. A philosophical view on the testing of rock support for rockburst conditions. J South Afr Inst Min Metall 2012;112:1–8.

[13] Jan VS, Palape M. Behaviour of steel plates during rockbursts. Perth, Australia: Australian Centre for Geomechanics; 2007.

[14] Farmer I. Stress distribution along a resin grouted rock anchor. Int J Rock Mech Min Sci Geomech Abst: Elsevier 1975;12:347–51.

[15] Li C, Stillborg B. Analytical models for rock bolts. Int J Rock Mech Min Sci 1999;36:1013–29.

[16] Thompson A, Villaescusa E, Windsor C. Ground support terminology and classification: an update. Geotech Geol Eng 2012;30:553–80.

[17] Zou DHS. Analysis of in situ rock bolt loading status. Int J Rock Mech Min Sci 2004;41:509.

[18] Tadolini S. Mine roof bolt load determinations utilizing ultrasonic measurement systems. Can Min Metall Bull. 1990;83:49–54.

[19] Li CC, Kristjansson G, Høien AH. Critical embedment length and bond strength of fully encapsulated rebar rockbolts. Tunn Undergr Space Technol 2016;59:16–23.

[20] Villaescusa E. Geotechnical design for sublevel open stoping. Boca Raton: CRC Press; 2014.

[21] Masoudi R, Sharifzadeh M. Reinforcement selection for deep and high-stress tunnels at preliminary design stages using ground demand and support capacity approach. Int J Min Sci Technol 2018;28:573–81.

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