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Reinforcement mechanisms of rock bolt — a laboratory investigation

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Abstract: The use of rock bolts as rock reinforcement is becoming more popular in Malaysia. However, its effectiveness depends on a number of factors especially with regards to the technique on how the bolt is installed. Its reinforcement mechanism also restricts its application for certain modes of instability and types of rock. This paper highlights a laboratory investigation on the reinforcement mechanisms of rock bolts, specifically on bolt inclination, anchorage type and level of pre-tension. The investigation was conducted using a physical model of a rock bolt intersecting a joint. Results obtained show that a better reinforcement can be obtained if bolt is inclined at an angle so that it elongates upon joint displacement. Full-bonded bolt is more superior in terms of mobilising the anchorage capacity and consequently, this allows for immediate utilisation of the reinforcing element. Pre-tensioning of bolt induces clamping effect on joint surface consequently, helps to reduce joint dilatation and increases the inherent shear strength of the joint.

Abstrak: Penggunaan bolt batuan sebagai kaedah pengukuhan batuan semakin popular di Malaysia. Walaubagaimana pun, keberkesanan kaedah ini amat dipengaruhi oleh beberapa faktor terutama yang berkaitan dengan teknik pemasangan bolt. Mekanisme pengukuhan kaedah ini juga menyebabkan penggunaannya terhad pada jenis batuan dan ragam kegagalan tertentu. Kertas kerja ini membincangkan satu kajian makmal ke atas mekanisme pengukuhan bolt batuan khususnya, mengenai kesan orientasi bolt, jenis ikatan dan tahap pra-tegangan. Kajian dilaksanakan menggunakan satu model fizikal bolt batuan yang bersilang dengan satah kekar. Keputusan kajian menunjukkan tahap keupayaan pengukuhan meningkat apabila bolt dipasang secara condong dan mengalami pemanjangan apabila berlaku anjakan pada kekar. Bolt yang diturap sepenuhnya lebih baik dari segi menggerakkan keupayaan pengukuhan oleh yang demikian, kesan elemen pengukuhan dapat dimenafaatkan serta merta. Pra-tegangan pada bolt dapat mengaruhkan kesan pengapitan pada permukaan kekar dan ini dapat mengurangkan dilatasi dan meningkatkan kekuatan ricih kekar.

INTRODUCTION

Failure in rock mass is implied as the incapability of a rock mass to support its own weight. Installation of stabilising methods ensures the inherent strength of the rock is maintained before excessive failure takes place. The effectiveness of any stabilising method usually depends on the type of instability in rock and the stabilising mechanisms of the selected method. Various methods are currently available for stabilising unstable rock. Usually, more than one method is adopted to achieve the required stability. Methods for rock stabilisation are divided into two types namely, support systems and reinforcement systems (Windsor and Thompson, 1993). The former include shotcrete and wire-mesh where, stabilising elements are installed on the rock surface. The latter comprises reinforcing elements installed in the rock that includes rock bolts and dowels. A rock bolt is a steel bar, which is inserted into a hole drilled in the rock. Despite its many varieties, all rock bolts have in common the following elements: a steel bar (shank), an anchoring device (resin or grout) at one end, and a tensioning device (bearing plate and nut) at the other, as shown in Figure 1 (Brady and Brown, 1985). The reinforcement bar helps to mobilise the inherent strength of the rock mass by modifying its internal strength and deformation characteristics.

LITERATURE REVIEW

Improvement on installation procedures and hard-wares (e.g. fast setting resin and corrosion protection), have made rock bolt as one of the most popular permanent reinforcement for rock engineering structures (Schubert and Schubert, 1993). However, its effectiveness depends on several factors as briefly discussed in the following sections.

Stabilising effect of rock bolt

Rock bolt is most effective for stabilising planes of weakness in rock, as it helps to mobilise the inherent strength of these unstable planes. The reinforcement mechanisms of rock bolt include the creation of radial compression, composition action and mobilising friction resistance (Windsor and Thompson, 1993).

Lets consider instability induces along a joint plane. The shear strength and dilatation versus shear displacement for this joint can be presented as Figure 2. As shown in this figure, it is beneficial to prevent slips between joint blocks before shear strength reaches its residual stage. If joint reaches its residual strength (after certain amount of shear displacement), the rock system then becomes less capable of supporting itself and consequently, will require a proportionally larger amount of reinforcement. This implies the most important rule in rock bolting, i.e. the system should be installed as soon as possible after excavation in order to prevent the loss of an appreciable portion of the inherent strength of the rock mass.

The importance of dilatation effect (δn in Fig. 2) is related to the phenomenon of the build up of the peak shear strength with shear displacement. Dilatation results from the uneven nature of joint surface (Mohd Amin *et al.*, 2001). In order for the joint surface to ride over any asperities/undulations (along its shearing path), work has to be done against the force acting normally to the joint. The higher the force is, the more difficult it is for shearing process to take place. This is due to the law governing the friction acting between sliding joint surfaces:

$$\tau = \sigma_n \tan(\phi + i) + c \qquad (1)$$

where, τ is shear strength of joint; σ_n is normal stress acting on joint; ϕ is angle of friction; i is angle of dilatation, and is c cohesion of joint.

If dilatation is absolutely prevented, it becomes impossible for shearing to occur along a joint plane and the shearing force must be sufficiently high to produce crushing of the surface irregularities. Thus, the prevention of dilatation, which if permitted, removes all constraints on sliding. It can be seen in Figure 2 that the maximum rate of dilatation is associated with the build up to peak strength. This implies that it is better to reinforce the joint before initial displacements and consequent large dilatations have occurred. The shear behaviour of a joint highlighted above can be used to appreciate the mechanisms of reinforcement of a rock bolt as outlined below.

Bolt inclination

The orientation of bolt to the joint plane has a pronounced effect on shear resistance offered by rock bolt. The stabilising action of a tensioned (active) bolt intersecting a joint can be explained using Figure 3. Figure 3(a) shows a bolt installed at right angle to a joint. The pre-tension in the bolt acts like a clamping force on the joint, thus helps to inhibit joint dilatation. Resistance to shearing is contributed by the shear strength of the joint and shear stiffness of the bolt. The latter depends on bolt diameter and material type (Bjurström, 1974). In addition, perpendicular bolt does not experience a considerable amount of tensile stress when joint is displaced thus, additional shear resistance from the bolt is not possible without significant bending and yielding of the bolt (Spang and Egger, 1990). However, if the same joint is reinforced with a similar bolt, but at an angle α to the joint as shown in Figure 3(b), significant improvement can be expected. Haas (1981) has noted that it is most effective if the bolt is inclined in such a way that it elongates as joint starts to shear. In this orientation, the pre-tension in bolt and the additional tensile stress induces into the bolt due to shearing of the joint act in two ways. The component tangential to the joint surface (component t_h) will give a direct contribution to the shear resistance. The component normal to the joint surface (component t_n) will increase the normal stress acting on joint and help to counteract dilatation and thus, increasing the frictional strength of the joint. Generally, the optimum angles of bolt inclination (α) are between 30° and 60°.

Tensioning of bolt

An active bolt is when the bar is tensioned between the fixed end and the plate (see Fig. 1). This essential feature, if properly installed, exerts a positive compression into the rock and maintains the interlocking of rock blocks. Effective bonding between the bolt and surrounding rock is essential

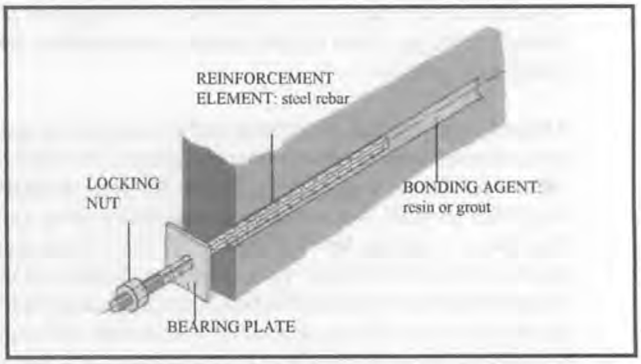

Figure 1. Full-bonded rock bolt (after Brady and Brown, 1985).

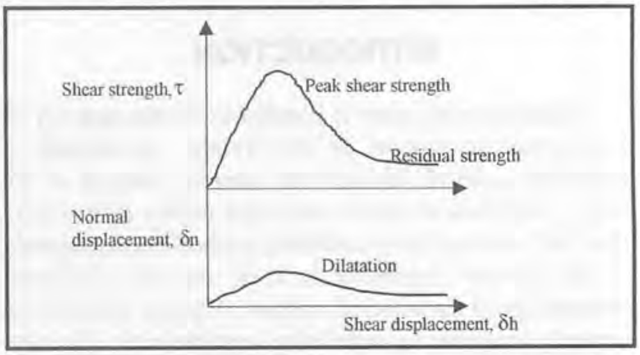

Figure 2. Shear strength and normal displacement versus shear displacement.

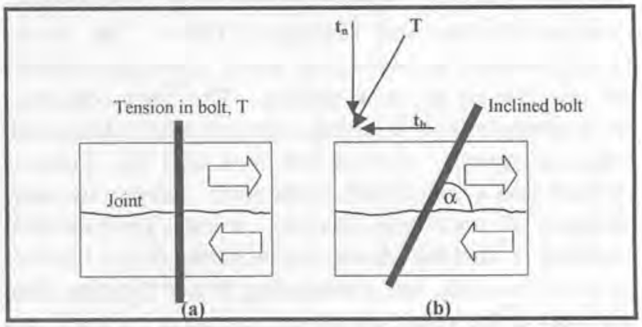

Figure 3. Rock bolt intersecting a joint, (a) perpendicular and (b) at angle α to joint plane.

hence, rock bolt is not suitable for weak rock. The main advantage of tensioned bolt is that it increases shear-stiffness of the bolted joint as soon as it is installed. Fast-setting resin permits tensioning of the bolt a few minutes after installation (Windsor and Thompson, 1993).

The amount of tension applied on the bolt (working load, T_w) depends on the characteristic tensile strength (f_{pu}) of the bolt material. Typically, for high tensile steel, T_w is about 80% f_{pu}. Creep or loss in bolt tension throughout its service life is common hence, bolt is usually tensioned at about 110% T_w or re-tensioned whenever required. It should be noted that when bolt is pre-tensioned, some elastic deformation of the bar is utilised. Additional deformation may be induced into the bolt when there is movement in the reinforced joint. It is due to this reason that T_w is lower than the tensile strength of the bolt particularly, if the reinforced joint is known to dilate.

Bolt anchorage

Point anchored rock bolt (anchored using wedge and expansion shell) is limited to hard rocks and for use as temporary reinforcement (Brady and Brown, 1985). Local crushing of rock at the anchorage point and slippage of anchorage are the main weaknesses of point anchored bolt. When cement/resin fills the annulus around the full length of the bar as means of anchorage, the bolt is called full-bonded bolt. The resin/cement also acts as protection against corrosion. The continuous anchorage ensures the bond between bar and the surrounding rock remains effective although the tensioning end becomes ineffective. Full-bonded bolt requires only a small amount of movement in the rock mass to mobilise its anchorage capacity. This allows for maximum utilisation of the strength of reinforcing element immediately after installation (Windsor and Thompson, 1993). In general, full-bonded bolt displays a better resistance to shearing and more superior in terms of anchorage 'creep' and consequently, it is commonly use for permanent reinforcement. The anchored length (L) of rock bolt to maintain stability is calculated based on the following formula (Douglas and Arthur, 1983):

$$L = (FT_f)/(\pi D\tau_{ult}) \quad (2)$$

where, F is factor of safety ($2 < F < 3$); T_f is ultimate load of rock bolt; D is fixed anchor diameter and t_{ult} is ultimate bond stress.

LABORATORY TESTING

The main objectives of this study are to verify the effect of bolt inclination, type of bonding (full-bonded length and point-anchored) and level of tension on the performance of rock bolt. Laboratory investigation was carried out using physical model of bolted joint blocks. Joint block of dimensions 63 mm↔103 mm↔56 mm was formed by gluing several layers of 4mm thick perspex. Two sets of blocks were prepared and each set representing the upper and lower joint blocks. 5 mm diameter holes were drilled in these blocks at an angle 90°, 70° and 60°. Due to the limited length of the block, hole with inclination angle of less than 60° was not possible. 5 mm diameter bamboo rods, instead of steel rod, were used as bolts. Shear tests on the bolted joints were conducted using portable shear box apparatus model Roctest Phi-10. Description of this equipment is given in Mohd Amin *et al.* (2000). The reasons for using specific materials for the model are mainly due to the following reasons:

- Perspex instead of rock — For ease of drilling of 5 mm diameter holes at various orientations in the blocks. Cutting of cube rock sample was relatively difficult.
- Bamboo instead of steel rod — Shear strength of steel may be too high to be tested on the Phi-10 shear box. Steel rod may induce excessive fracturing of the drill hole walls and bonding material particularly at the vicinity of the joint plane.
- Since this study is to verify the behaviour rather than the ultimate strength of a bolted joint therefore, material characteristics are not essential.

The various types of shear test conducted are listed in Table 1. The shearing rate employed was 1.0 mm/min and the maximum shear displacement is twice the bolt diameter.

Table 1. Various shear tests conducted on bolted joint blocks.

Test no.	Bolt inclination, α°	Type of anchorage	Normal Stress, MPa	Test description
1	N/A	N/A	0.5	Shear test on unbolted joint blocks
2	N/A	N/A	1.0	Shear test on unbolted joint blocks
3	N/A	N/A	2.0	Shear test on unbolted joint blocks
4	90	Full length	0.5	Joint blocks with resin bonded bolt
5	90	Full length	1.0	Joint blocks with resin bonded bolt
6	90	Full length	2.0	Joint blocks with resin bonded bolt
7	70	Un-bonded	0.5	Joint blocks with point-anchored bolt
8	70	Un-bonded	1.0	Joint blocks with point-anchored bolt
9	70	Un-bonded	2.0	Joint blocks with point-anchored bolt
10	70	Full length	0.5	Joint blocks with resin bonded bolt
11	70	Full length	1.0	Joint blocks with resin bonded bolt
12	70	Full length	2.0	Joint blocks with resin bonded bolt
13	60	Full length	0.5	Joint blocks with resin bonded bolt
14	60	Full length	1.0	Joint blocks with resin bonded bolt
15	60	Full length	2.0	Joint blocks with resin bonded bolt

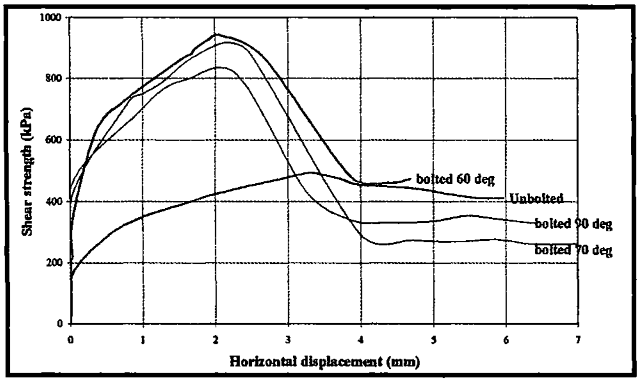

Figure 4. Shear strength of unbolted and bolted joint (90°, 70° and 60° bolt orientation) at normal stress 0.5 MPa.

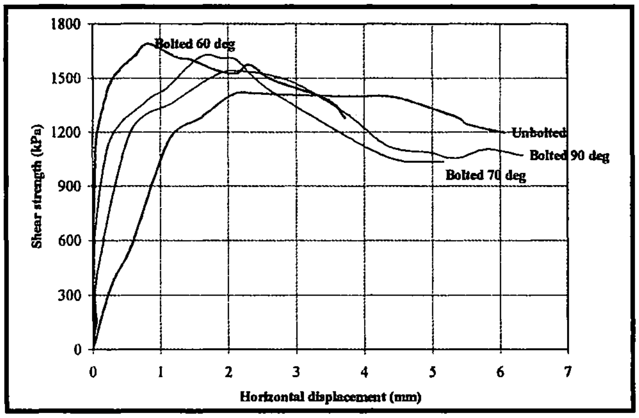

Figure 5. Shear strength of unbolted and bolted joint (90°, 70° and 60° bolt orientation) at normal stress 2.0 MPa.

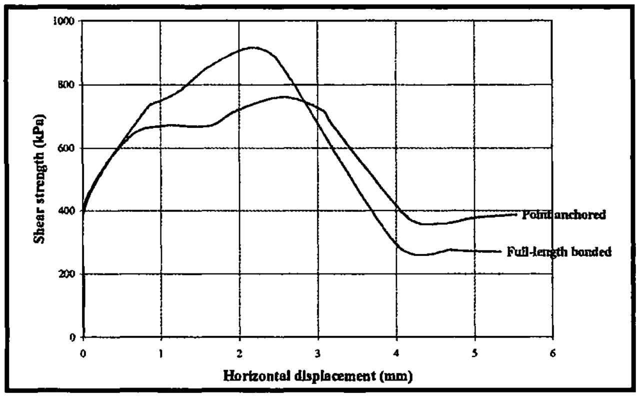

Figure 6. Shear strength of joint bolted with full-length bonded bolt and point-anchored bolt, at normal stress 0.5 MPa.

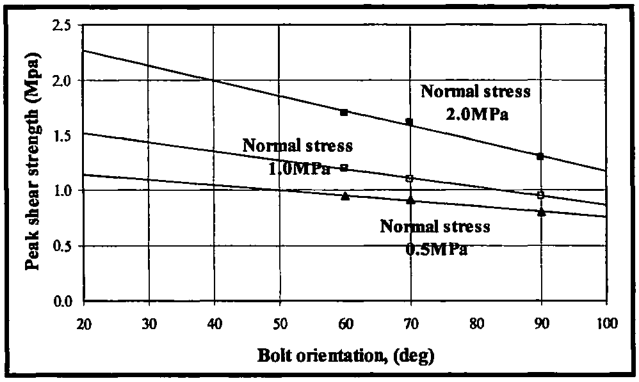

Figure 7. Peak shear strength versus bolt orientation at normal stress 0.5, 1.0 and 1.0 MPa.

Table 2. Peak shear strength and horizontal displacement for full-bonded bolt installed at different orientations.

Bolt orientation, α	Peak shear strength, MPa	Horizontal displc. at peak strength, mm
90°	0.81	2.30
70°	0.92	2.11
60°	0.98	2.03

Normal stresses applied during shear were 0.5, 1.0 and 2.0 MPa. For the full-length bonded bolt, epoxy resin was used to bond the full length of the bamboo rod into the drill hole. As for point-anchored bolt, the 5 mm rod was just inserted into the drill hole without any bonding. Since the rod and the hole were of similar diameter therefore, the rod was in rigid position once inserted into the hole. Effect of joint dilatation on bolt was not verified. This is mainly due to the difficulty in preparing the typical surface roughness on the perspex model. Detailed samples preparation and testing procedures are discussed in Khoo (2002) and Chai (2002).

DISCUSSION OF TEST RESULTS

Only selected plots are discussed in this section. Series of tests conducted on the unbolted joint blocks are mainly to verify the shear strength of the model joint surface. The strength represents the 'inherent strength' of an unbolted joint and this is used as a basis to substantiate any improvement in strength due to bolting.

Figure 4 shows the behaviour of same joint reinforced with full-bonded bolt, at different inclination angle and at normal stress of 0.5 MPa. An increase of about 50% in strength can be observed after bolting. The highest and the lowest shear strength of the reinforced joint are observed at bolt inclination of 60° and 90°, respectively. Similar improvement in joint strength can be observed in shear test at higher normal stress (Fig. 5) however, the increment in strength is less significant. This is probably due to the strength increase induced by a higher normal stress over shadows the effect of bolting. Table 2 summarises the effect of bolt inclination on peak shear strength and shear displacement to reach the peak strength. Joint with bolt inclined at 60° exhibits the highest peak strength and the lowest shear displacement to reach this strength compared to other bolt orientations.

The effect of bolt anchorage on joint strength can be seen in Figure 6, at normal stress 0.5 MPa. Joint reinforced with full-length bonded bolt exhibits a higher strength compared to joint reinforced with un-bonded bolt. Similar behaviour is observed in tests at higher normal stresses. Table 3 highlights several advantages of full-bonded bolt. In addition to a higher joint strength, this bolt offers less shear displacement to mobilise the peak strength hence, immediate utilisation of the reinforcing effect. The joint also exhibits less dilatation, as indicated by the smaller normal displacement at peak strength.

Table 3. Peak strength, horizontal and vertical displacement for different type of anchorage (bolt inclination 70° and normal stress 0.5 MPa).

Bolt anchorage	Peak shear strength, MPa	Horiz. displc. at peak strength, mm	Vert. displc. at peak strength, mm
Un-bonded/point anchored	0.76	2.56	0.12
Full-length resin bonded	0.92	2.10	0.09

Finally, Figure 7 exhibits the effect of bolt orientation and tension level on joint strength. As pointed out earlier, bolt tension induces a clamping effect on the joint. Consequently, tests conducted at various levels of normal stress may be taken to characterise this effect, i.e. component t_n in Figure 3(b). For a given bolt orientation, Figure 7 illustrates that bolted joints tested at higher normal stress (i.e. higher bolt tension) consistently exhibit a higher strength. At a given normal stress, joints with bolt installed at a smaller angle of inclination (< 90°) exhibit higher shear strength. If the trend-lines in Figure 7 are extended beyond 60°, a higher joint strength can be expected, say inclination angle of 30°.

CONCLUSIONS

Laboratory test results show that the reinforcement mechanisms of rock bolt are affected by bolt inclination, anchorage type and level of pre-tension on the bolt. Optimum reinforcement can be obtained if bolt is inclined at an angle so that it elongates upon joint displacement. Full-bonded bolt is superior to point-anchored bolt in terms of mobilising the anchorage capacity and this allows for immediate utilisation of the reinforcing element. Pre-tensioning of an inclined bolt induces clamping effect on joint surface consequently, helps to reduce joint dilatation and increases the inherent shear strength of the joint.

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