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A study on truss bolt mechanism in controlling stability of underground excavation and cutter roof failure

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Abstract:	The truss bolt reinforcement system has been used in controlling the stability of underground excavations in severe ground conditions and cutter roof failure in layered rocks especially in coal mines. In spite of good application reports, working mechanism of this system is largely unknown and truss bolts are predominantly designed based on past experience and engineering judgement. In this study, the reinforcing effect of the truss bolt system on an underground excavation in layered rock is studied using non-linear finite element analysis. Different indicators are defined to evaluate the reinforcing effects of the truss bolt system. Using these indicators one can evaluate the effects of a reinforcing system on the deformation, loosened area, failure prevention, horizontal movement of the immediate layer, shear crack propagation and cutter roof failure of underground excavations. Effects of truss bolt on these indicators reveal the working mechanism of the truss bolt system. To illustrate the application of these indicators, a comparative study is conducted between three different truss bolt designs. It is shown that the design parameters of truss bolt systems, including tie-rod span, length, and angle of the bolts can have significant effects on the reinforcing capability of the system.
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A study on truss bolt mechanism in controlling stability of underground excavation and cutter roof failure

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Abstract The truss bolt reinforcement system has been used in controlling the stability of underground excavations in severe ground conditions and cutter roof failure in layered rocks especially in coal mines. In spite of good application reports, working mechanism of this system is largely unknown and truss bolts are predominantly designed based on past experience and engineering judgement. In this study, the reinforcing effect of the truss bolt system on an underground excavation in layered rock is studied using non-linear finite element analysis. Different indicators are defined to evaluate the reinforcing effects of the truss bolt system. Using these indicators one can evaluate the effects of a reinforcing system on the deformation, loosened area, failure prevention, horizontal movement of the immediate layer, shear crack propagation and cutter roof failure of underground excavations. Effects of truss bolt on these indicators reveal the working mechanism of the truss bolt system. To illustrate the application of these indicators, a comparative study is conducted between three different truss bolt designs. It is shown that the design parameters of truss bolt systems, including tie-rod span, length, and angle of the bolts can have significant effects on the reinforcing capability of the system.

Keywords Truss bolt · Reinforcement · FEM · Stability indicators · Underground excavation · Ground control

1 Introduction

Nowadays, rock bolt systems are being extensively used in mining and civil engineering applications. These systems are a dominant part of the New Austrian Tunnelling Method (NATM) and can be used as both temporary and permanent support (Brady and Brown 2005; Karanam and Dasyapu 2005; Osgoui and Oreste 2007; Maghous et al 2012). The common use of rock bolts is because of their flexibility, ease of use and fast installation (Hoek and Brown 1980; Brady and Brown 2005). However, in severe ground conditions and especially in response to cutter roof failure, conventional rock bolt patterns could be inadequate and risky to use. In these circumstances, Peng and Tang (1984) suggest using a special configuration of rock bolts called Truss Bolt systems.

Truss bolt, in its simplest form, consists of two inclined members at two top corners and one horizontal member on the roof. A common truss bolt system, known as the Birmingham truss, consists of two long cable bolts which are connected at the middle of the roof. Horizontal tension is applied by means of a turnbuckle at the connection point of the cables at the roof and transferring a compression to the rock (Gambrell and Crane 1986). A schematic view of the Birmingham truss is shown in Fig. 1.

One of the advantages of truss bolt systems is the ability to control the cutter roof failure. Cutter roof is a

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common type of failure in laminated rock formations in flat roof excavations. In this type of failure, shear cracks propagate from the corners of the roof and as they reach the first bedding plane, a huge block separates from the roof (Su and Peng 1987). Very good responses of truss bolt have been reported in places that systematic rock bolt failed to prevent cutter roof (Stankus et al 1996).

The successful applications of truss bolt have led researchers to develop different truss bolt systems which resulted in several patents (White 1969; Wahab Khair 1984; Seegmiller and Reeves 1990). Alongside with these developments, several researchers initiated studies to understand the mechanism of the truss bolt system and presented a number of practical design schemes. A number of these works has been done by means of photoelastic study during 1970s and 1980s (Gambrell and Haynes 1970; Neall et al 1977, 1978; Gambrell and Crane 1986). In design schemes for truss bolt systems, Sheorey et al (1973) statistically studied the effects of position and thickness of blocking points to find the optimum value of these parameters. Based on several field investigations, Cox and Cox (1978) proposed their design method by considering suspension and reinforcing effect of truss bolt system. Neall et al (1978) proposed a theoretical design approach on the basis of beam building theory of reinforcement systems and tabular overburden load. Wahab Khair (1984) carried out lab experiments to understand the effects of truss bolt on a simulated roof beam. Zhu and Young (1999) proposed analytical based equations to calculate the required minimum horizontal tension and length of tie-rod for single and multiple truss bolt systems. Most recently, Liu et al (2005) published an analytical based design procedure on the basis of a number of simplifying assumptions. Further to these studies, some field investigation and a small number of numerical analyses are available in this field (Seegmiller and Reeves 1990; O'Grady and Fuller 1992; Stankus et al 1996; Li et al 1999; Liu et al 2001; Cox 2003; Ghabraie et al 2012).

Despite these efforts in understanding the truss bolt mechanism, the complicated effects of truss bolts on load distribution around an underground excavation is still largely unknown (Liu et al 2005; Ghabraie et al 2012). This lack of knowledge forces engineers to consider large safety factors while using these schemes.

Understanding the mechanism of truss bolt system on reinforcing the rock around an underground excavation is the most important and the first step in obtaining a practical, reliable and easy to use design scheme. This paper is focused on understanding the mechanism of truss bolt systems on stability of underground excavations and preventing cutter roof failure. For this purpose, numerical modelling techniques are used in order to capture the complicated behaviour of truss bolt systems. Once a comprehensive numerical model is established, one can repeat numerous tests for varying input parameters at relatively little extra cost.

In this paper, the finite element method (FEM) has been used for numerical modelling, using ABAQUS as the software package (ABAQUS 2010). An underground excavation, containing bedding planes, several rock layers and an installed truss bolt system has been modelled. For the purpose of evaluating the effects of truss bolt on stability of an underground excavation, a number of stability indicators have been introduced. Using these indicators, the effects of truss bolt system on reinforcing an underground excavation and preventing the cutter roof failure have been studied. Three regular truss bolt pattern have been modelled to study the effects of different parameters of the system. These patterns have been chosen from several case studies in the literature and adjusted to the dimensions of the model in this study. Using the stability indicators and studying the effects of each truss bolt pattern on the stability of an underground excavation, mechanism and effects of different design parameters have been derived. Results showed that depending on the pattern of truss bolt system, areas of reinforcing effect around an excavation change dramatically. A long span truss bolt with short inclined bolts results in reinforcing the top side areas of the tunnel while a short span truss bolt with long inclined bolts produce an arch shape reinforced area above the roof. In conclusion, truss bolt creates a trapezoid reinforced area above the roof and between inclined bolts in which an arch shape area is the major area of reinforcement.

2 Preliminary Understanding of Truss Bolt Behaviour

Previous studies have pointed out that the effect of reinforcement on the rock material is to apply the confining pressure, suspend unstable blocks and increase the strength properties of rock (Lang 1961; Lang and Bischoff 1984; Huang et al 2002; Li 2006). Among these, applying the confining pressure is the most important effect which is the basis of the systematic rock bolt patterns (Li 2006). The applied compressive force tightens the rock fragments together alongside with increasing the strength characteristics of rock by increasing the mean stress and decreasing the deviatoric stress. Any prestressed rock bolt compresses and reinforces the rock in its vicinity. In a systematic rock bolt pattern, the bolts are placed close enough such that their reinforced area overlaps and a compressed area is produced. This area acts like a beam and carries the load to the sides of the excavation (Lang and Bischoff 1982; Roy and Rajagopalan 1997; Li 2006).

In truss bolt systems, the applied tension in the middle of the tie-rod creates areas of compression around the tunnel. The preliminary understanding of the load distribution around truss bolt is shown in Fig. 2. Results of the early photoelastic analysis and physical modelling also confirmed the presence of a compressive force which demolished the shear stress at the middle of the roof (Gambrell and Haynes 1970; Gambrell and Crane 1986). Also, the two inclined members of the truss system are able to create a compressive area above the abutments. Reinforcing this area could be very effective in controlling the horizontal movement of rock layers in the areas prone to the cutter roof failure (Stankus et al 1996).

3 Numerical Model

A typical underground excavation in a coal seam with thickness of 2 m has been modelled. The tunnel is assumed to be long enough to satisfy plain strain assumptions. The model contains four bedding planes, two above and two beneath the tunnel.

Slipping or sticking behaviour of bedding planes are governed by the Coulomb friction model

$$\tau = \mu p \qquad (1)$$

In this equation, τ is shear stress, μ is the coefficient of friction on the plane of weakness ($\mu = \tan\phi$) and p is the contact pressure. In this model, no penetration is allowed and pressure can be mobilized if two surfaces are in contact. The responses of the model and the bedding surfaces have been verified with the analytical solutions proposed by Brady and Brown (2005).

An elastic-perfectly plastic material model has been used to model the intact rock material and the Mohr-Coulomb yield function has been adopted as the failure criterion. The model is capable of capturing separation and slipping along the bedding planes. This material behaviour has been verified by the analytical solution proposed by Hoek et al (1998).

The pretensioned rock bolts (inclined bolts and horizontal tie-rod) have been modelled by using pretensioned one dimensional truss elements. Inclined bolts have been anchored by tightening the end node of the rock bolt element to the rock (no separation is allowed). By increasing deformation in rock around the tunnel, because of the relative displacement of two ends of the bolt elements, the amount of stress in truss elements increases. This extra load on the reinforcement system may exceed the ultimate strength of bolts (Hoek et al 1998). To prevent this, the maximum allowable pretension is chosen at 60% of the ultimate tensile strength of the bolts. Strength parameters of bolts are shown in Table 1.

Truss bolt patterns Three different typical truss bolt patterns have been considered. These patterns are chosen based on the proposed designs by several researchers (Cox and Cox 1978; Liu et al 2005; Ghabraie et al 2012). Design parameters in these models have been adjusted to the dimensions of the tunnel in this study. These parameters are shown in Fig. 1 and Table 2.

4 Stability Indicators

The behaviour of the rock after installing reinforcement needs to be measured via defining some performance indicators. For the scope of this study, these indicators should be able to evaluate the reinforcing effect of the truss bolt system, roof deflection and effects of truss bolt on preventing cutter roof failure.

4.1 Reinforced Arch

After excavating a tunnel, redistribution of the in-situ stress forms a pressurized arch above the tunnel. This arch is stable and can carry the load to the sides of the tunnel. The rock material beneath this arch is considered as loosened material (Fig. 3). This phenomenon can be observed in almost all types of coherent rock formations (Li 2006) and is proved by experience as well as numerical analysis (Bergman and Bjurstrom 1984; Huang et al 2002). Position of this arch changes drastically by changing the in-situ stress distribution. High horizontal in-situ stress is favourable in forming a closer natural arch to the roof, i.e. smaller loosened area. It should be noted, however, that extensive horizontal in-situ stress has negative effects on cutter roof failure and also causes stability problems in pillars.

Usually, the natural arch is positioned far above the tunnel and the loosened area beneath it should be stabilized (Li 2006). This can be achieved by either removing or reinforcing the loosened rock. In coal mines, however, where the shape of the tunnel is normally governed by the shape of the coal layer, removing the loosened rock is not an option and a suitable reinforcement system should be designed (Fig. 3).

Choosing parameters of the reinforcement systems to carry the load of the loosened area, without considering reinforcing effects of the system, normally results in overdesign parameters. The load of the loosened area can be used as only to achieve an upper limit (ultimate capacity) for the parameters of the reinforcement system (Cox and Cox 1978). To have a safe and economic design, the reinforcing effect of truss bolt on the loosened rock area should be taken into account. By applying a new load distribution around the tunnel, truss bolt system reinforces the loosened area and repositions the natural roof arch which results in smaller loosened area (Ghabraie et al 2012).

For specifying the position of the reinforced arch, Huang et al (2002) used the concept of invert stress cone to find the natural arch position around an underground excavation. In their model the thickness of the arch has been governed by the direction of principal stresses. According to Huang et al (2002), reinforced arch is the area in which principal stresses are not in vertical or horizontal direction except on the apex of the arch. Another approach to specify the position of reinforced arch is to use the vertical deformation of the rock above the roof. In this approach, the reinforced arch is defined by the points with the closest amount of vertical deformation to a certain fraction of the maximum vertical displacement of the tunnel roof. This fraction is the amount of displacement which predicts the stable/unstable rock. This condition can be expressed as (Ghabraie et al 2012)

$$|d_i - (n \times d_{max})| = \text{Minimum} \tag{2}$$

where d_i is the vertical displacement at points above the roof in FE mesh, $d - max$ is the maximum vertical displacement on roof and n is a fraction between 0 and 1. In this approach, $n \times d_{max}$ is a threshold (a certain amount of displacement) which predicts the area of the loosened rock. Areas with less deformation than this threshold are considered to be stable and vice versa. The fraction (n) can be chosen with respect to the sensitivity of the tunnel to displacement and can be different from case to case. In this study, $n = 50\%$ has been chosen which implies that areas with less than 50% of the maximum displacement on the roof are loosened area. The output of this method is a line which connects all the points resulting from Eq. 2. It should be noted that this approach does not necessarily predict the actual area of loosened rock and is only used to define a basis for comparing different designs.

Using $n = 50\%$, the position of the reinforced arch and area of the loosened rock for different truss bolt patterns have been derived. These results are shown in Fig. 4. It can be seen that truss bolt system repositions the reinforced arch and reduces the area of loosened rock around a tunnel under hydrostatic in-situ stress. These results highlight the importance of the position and the angle of the inclined bolts. The truss pattern with short span and wide angled inclined bolts (pattern 3) shows the best result. One reason is that the major area of the loosened rock is above the middle of the roof and this pattern has better coverage on this area compared to the other truss bolt patterns. On the other hand, pattern 1, which has a bigger span, has a small effect on the area above the middle of the roof but shows a good response on the areas near the corners. This is because in this pattern the inclined bolts are closer to the corners of the roof.

4.2 Stress Safety Margin (SSM)

The Mohr-Coulomb failure criterion is frequently used for modelling rock material (Jing 2003). In this criterion, if the Mohr's circle corresponding to the stress condition at a point in rock material touches the Mohr-Coulomb failure envelope, rock yields and the elastic solution is no longer valid. By increasing stress on the surrounding rock around an excavation, more points will undergo failure and the tunnel would collapse. The area beneath the failure envelope represents elastic behaviour of rock with no failure and can be considered as safe. The failure in Mohr-Coulomb failure criterion is a function of two key parameters: a) radius of Mohr's circle $(\sigma_1 - \sigma_3)/2$ and b) position of centre of the circle $(\sigma_1 + \sigma_3)/2$. Failure is happened by increasing radius of the circle or/and decreasing the amount of $\sigma_1 + \sigma_3$. Fig. 5 shows two possible Mohr's circles for these two paths of failure. It can be seen that the possibility of failure by decreasing radius of the circle is always more than failure by decreasing the amount of $\sigma_1 + \sigma_3$ ($x_c > x_r / \sin\phi$). Hence, the shortest distance to failure is x_r where x_r equal to zero represents failure. Now the stress safety margin can be defined based on this parameter. The mathematical expression for x_r can be derived as (Ghabraie et al 2008)

$$x_r = c\cos(\phi) + \left(\frac{\sigma_1 + \sigma_3}{2}\right)\sin(\phi) - \left(\frac{\sigma_1 - \sigma_3}{2}\right) \tag{3}$$

Using a dimensionless expression of this factor makes it easier to compare the results of several models. This will be achieved by the following equation

$$\text{SSM} = \frac{r + x_r}{r} \tag{4}$$

In this equation, SSM equal to one represents failure and plastic behaviour of rock while SSM greater than one means elastic behaviour of rock and safe Mohr's circle. Figs. 6 to 8 show contours of SSM difference before and after installing the three truss bolt patterns around a tunnel under hydrostatic stress distribution ($\text{SSM}_{before} - \text{SSM}_{after}$). By this definition, negative values represent areas in which truss bolt has favourable effect. The green line in these graphs shows the line in which truss bolt does not have any significant effect on the value of SSM around the tunnel. This line demonstrates the border of favourable and unfavourable effects of truss bolt. It can be seen that truss bolt effectively increases the value of SSM around the roof and abutments of tunnel.

Comparing the three truss bolt patterns reveals that short tie-rod, wide angle of inclination and long inclined bolts (pattern 3) results in better effect on the area above the roof but less favourable effect on the rib area. On the other hand, in patterns 1 and 2, the most effective areas around truss bolt are near inclined bolts. This makes truss bolt patterns 1 and 2 capable of reinforcing the area above the walls of the excavation (rib area). The length of inclined bolts, in current design schemes, is a function of the required load carrying capacity of the reinforcement systems. Inclined bolts should be long enough to ensure sufficient length of anchorage in the safe area (behind the rib line) to provide enough capacity to the truss bolt system (Cox 2003; Liu et al 2005). Figs. 6 to 8 show that the length of inclined bolts even changes the load distribution around the truss bolt where long inclined bolts (Fig. 8), in comparison with short inclined bolts (Figs. 6 and 7), are not able to produce a highly reinforced area around inclined members. On the other hand, failure in providing enough length of anchorage results in failure of the truss bolt system. Consequently, the required length of anchorage to carry the applied load on truss bolt system can be always used to find the lower limit for the length of inclined bolts while this length can be adjusted with respect to the required amount of reinforcing effect near corners of the roof.

Fig. 9 shows a different illustration of effects of pattern 3 on SSM around the tunnel. Contour lines in this figure have been chosen to represent three different areas, namely, major reinforced area (less than -0.03), minor reinforced area (between -0.03 and 0) and unfavourable area (greater than 0). It can be seen that the major reinforced area approximately fits in an arch shape above the roof while the minor reinforced area is more like a trapezoid area which is located above the roof and between the inclined bolts. In other patterns the major reinforced area can be seen around the inclined members (Figs. 6 and 7). However, load distribution around these patterns also shows arch shape borders. The applied horizontal tension at tie-rod can be well transferred to the rock at blocking points and by lateral behaviour of inclined bolts. This load produces an arch shape compressive area above the roof. The reinforced areas in Figs. 6 to 9 match the compressive areas of Fig. 2.

On the other hand, the horizontal tension in the tie-rod places the area behind inclined bolts in tension. This unfavourable area is mostly located on sides of the tunnel and can cause stability problems, especially when the side rock is relatively weak. In this case, installing truss bolt can shear the side rock which causes rock sliding in this area. Individual rock bolts can be used to stabilise this area.

4.3 Cutter Roof

Cutter roof failure happens when shear cracks around the corners of the roof propagate towards the immediate roof layer and reach a plane of weakness, resulting in separation of a massive unstable block (Su and Peng 1987). This separation applies a huge load on the reinforcement system that usually exceeds the load carrying ability of regular systems and the whole block drops into the excavated area. In some cases, re-opening and stabilizing a site after cutter roof failure has no efficient solution and the site would be abandoned (Su and Peng 1987). Various researchers had done field investigations and modellings to understand the mechanism of cutter roof failure (Su and Peng 1987; Altounyan and Taljaard 2001; Gadde and Peng 2005; Coggan et al 2012). In these works the main controlling parameters for cutter roof failure are mentioned as entry width, in-situ stress condition, propagation of shear cracks, relative stiffness between immediate roof layer and coal, geological anomalies, separation of bedding, horizontal movement of rock layers and gas pressure. The mechanism of truss bolt on preventing cutter roof failure can be studied by monitoring horizontal movement of the immediate roof layer and shear crack propagation in models under high horizontal or vertical in-situ stresses.

4.3.1 Slip on the First Bedding Plane

In numerical modelling, slip on the first bedding plane can be determined by monitoring the relative displacement of bedding surfaces. This parameter can be interpreted as the relative horizontal movement of the immediate rock layer.

Figs. 10 and 11 show the relative horizontal displacement between surfaces of the first bedding plane before and after installing truss bolt on two different in-situ stress distributions (high vertical $\sigma_v = 2\sigma_h$ and high horizontal $\sigma_v = 1/2\sigma_h$ stresses). These figures show that the truss bolt reduces the amount of horizontal movement in the immediate rock layer in both models.

A closer look at Fig. 10 reveals that, in high vertical in-situ stress the major area of slip before installing truss bolt is approximately located above the roof. This slippage approaches zero near the rib area (radial distance of 2 m). After installing different truss bolt patterns, pattern 3 shows the best response which is due to the location of the inclined bolts that pass through the major area of the slip. By increasing the length of the tie-rod, the effectiveness of truss bolt reduces dramatically and pattern 1 shows small effect on this factor.

In contrast, when the horizontal in-situ stress is high, the slippage on the first bedding plane reaches a peak above the roof and extends to almost 1.5 times of the span of the opening (radial distance of 4 m) and smoothly approaches zero after this distance (Fig. 11). To prevent the cutter roof failure, horizontal displacement, especially above and behind the rib area, need to be controlled. Fig. 11 shows that for the area above the tunnel short span truss bolt has the best effect (similar to results of high vertical in-situ stress, Fig. 10). However, for the area around corners of the roof (radial distance of 2 m) pattern 2 shows the best results. In this area pattern 1 and 2 are more successful than pattern 3 due to having inclined bolts passing through this area. Also, angle of inclined bolts in pattern 2 is another reason for effective application of this pattern where 45° inclined bolts produce a larger horizontal component than 60° for the same amount of pretension. This component is in the opposite direction to the horizontal in-situ stress and reduces the effect of this stress.

4.3.2 Shear Crack Propagation

One of the main limitations of FEM is in modelling fracture growth (Jing 2003). Capturing crack propagation is only possible by employing relatively new methods such as enriched FEM and generalized FEM (Duarte et al 2000; Deb and Das 2011). Using these techniques in a comprehensive model of underground excavation with complex geometry involves significant computational costs. This problem becomes more complicated when the model contains pretensioned elements (rock bolts) and geological features such as bedding planes.

Based on the Mohr-Coulomb failure criterion, shear failure can happen under compressive stresses when the maximum shear stress reaches the critical value defined by the Mohr-Coulomb yield function. After shear failure the rock behaviour could be assumed to be plastic. This failure could thus be captured using an elastic-plastic material model in FEA. Hence the yielded areas resulted from elastic-plastic FEA, provided that the stresses are compressive, could be assumed to represent the shear crack propagation. However, if the failure occurs in tension, due to the separation in material, the post failure behaviour could not be captured appropriately using an elastic-plastic FEA.

To monitor the effects of truss bolt on cutter roof, progressive failure (shear crack propagation) around the tunnel is modelled using a simplified interactive approach. For this purpose, the model is solved with elastic-plastic material model once and then the most likely area to yield is found with respect to the Mohr-Coulomb yield function and SSM factor (Eq. 4).

As discussed in Section 4.2 changes in radius of Mohr's circle is always smaller than the required change in the amount of pressure to satisfy the failure criterion ($x_r < x_c$). From Eq. 4, SSM equal to one ($x_r = 0$) denotes failure (Fig. 5). Increasing load in rock material results in changing the radius of Mohr's circle and causes an increase in the number of failure points in rock. Modelling this progressive failure in rock is possible by gradually increasing values of x_r and finding the yielded points for the new stress condition corresponding to the new x_r. This approach is essentially a linear extrapolation which helps us estimate shear crack propagation.

The increase in the amount of x_r can be defined through several increments (I_n) where

$$\mathrm{SSM} - 1 = I_n \tag{5}$$

In this equation SSM = 1 represents yielding. By replacing the definition of SSM in Eq. 5, different increments can be derived as

$$I_n = \frac{x_r}{r} \tag{6}$$

This equation identifies the locations where rock will undergo shear failure at increment I_n. I_n equal to zero interprets $x_r = 0$ which shows the area of the failure under current loading condition. Increasing the amount of I_n shows propagation of yielded as loads increase. It should be noted that the resulting yielded areas for different increments do not necessarily mean that these areas are yielded but shows the pattern of potentially yielded area (shear cracked area) in different time spans after excavation.

With respect to the definition of cutter roof by (Su and Peng 1987), when shear cracks reach the plane of weakness, cutter roof happens. Four different increments have been chosen to represent the shear cracks just after excavation ($I_n = 0$) to cutter roof failure (when shear cracks reach the plane of weakness). Two different in-situ stress distributions have been modelled. Results showed that when the horizontal in-situ stress is high ($\sigma_v = 1/2\sigma_h$) shear cracks tend to propagate with a sharp angle to the roof of the opening. Various markers in Fig. 12 show yielded points for different increments. Different increments are shown by different colours. The hypothetical lines in this figure show the areas of yielded rock for different increments. As it can be seen, at the final increment ($I_n = 0.015$) shear cracks reach the plane of weakness and the cutter roof happens. Similarly, using the same method for a tunnel under high vertical in-situ stress ($\sigma_v = 2\sigma_h$), the pattern of shear crack propagation can be obtained as shown in Fig. 13. Comparing these two figures illustrates that the angle of shear crack propagation and shape of the unstable block is deeply related to the condition of the in-situ stress. In high vertical in-situ stress, shear cracks propagate at an approximately right angle to the roof while in high horizontal in-situ stress this angle is less than 90°. Su and Peng (1987) on the basis of numerical analysis, using FEA and safety factor, together with field observations reported the same pattern of cutter roof in high vertical and horizontal in-situ stress conditions.

Figs. 14 to 19 show results of installing three different truss bolt patterns on two identical tunnels under high horizontal and vertical in-situ stresses. Comparing these results with Fig. 12 and 13 (pattern of shear cracks before installing truss bolt), it can be concluded that truss bolt system reduces the possibility of cutter roof by controlling shear crack propagation. It appears that truss bolt system by having inclined bolts near the area of initial shear cracks (around the corners of the roof) prevents continuous cracking and reduces the possibility of cutter roof. It has been shown in Section 4.2 that, because of the pretension force and induced compressive stress around the inclined bolts, a reinforced area will be created near the corners of the roof. In high vertical in-situ stress, where inclined bolts are well located at the area of shear crack propagation, the applied compressive stress by inclined bolts prevents continues shear crack propagation. In addition to this, investigating the results of SSM factor around truss bolt system shows another major reinforced area which is similar to an arch shape between inclined bolts above the roof (Fig. 9). Comparing patterns of shear cracks before (Fig. 12) and after installing truss bolt (Figs. 14 to 16) in high horizontal in-situ stress shows that truss bolt prevents propagation of cracks at areas near blocking points and above the roof. In fact, this area is identical to the produced reinforced arch area by truss bolt.

Results of installing different truss bolt patterns on preventing cutter roof illustrate that, depending on design parameters of truss bolt and in-situ stress distribution, effectiveness of the system on preventing shear crack propagation varies. It can be seen that in high vertical in-situ stress, pattern 2 shows the best application. Inclined bolts in this pattern exactly pass through the initial area of cracking and, by reinforcing this area, this pattern prevents further crack propagation (Fig. 18). Fig. 19 shows that pattern 3 is also able to reduce the possibility of cutter roof in this in-situ stress condition. On the other hand, inclined bolts in pattern 1 are located behind the area of initial cracking and even push the crack propagation pattern slightly towards the middle of the roof instead of controlling it (Fig. 17).

Comparing results of installing different truss bolts on a tunnel under high horizontal in-situ stress shows that patterns 2 and 3 prevent shear crack propagation to reach the plane of weakness. Whilst pattern 1 does not have any significant effect on preventing cutter roof and shear cracks reach the plane of weakness around the middle of the roof. This is probably because of the position of inclined bolts in pattern 1 which, similar to Fig. 17 in high vertical in-situ stress, is located behind the area of initial crack propagation. As discussed in Section 4.2, pattern 3 by having long inclined bolts and short tie-rod length produces a stronger reinforced arch compared to other patterns. This enables it to effectively control the shear crack propagation above the roof and shows the best response.

5 Discussion

The importance of a comprehensive consideration of all the design parameters and site variables can be concluded here. It has been shown that the shorter length of inclined bolts produce better reinforced area around the inclined bolts compared to longer bolts. If a truss bolt system with short inclined bolts is located in the right place to prevent crack propagation in high vertical in-situ stress (by choosing suitable tie-rod length), it can effectively prevent the cutter roof failure. On the other hand, longer inclined bolts have the advantage of adequate length of anchorage in passive zone behind the rib line. The length of anchorage is a key parameter to determine the capacity of the system. If the applied load on truss bolt system exceeds the capacity of truss bolt, the whole block with truss bolt will fail.

The length, position and angle of inclined bolts are also important in controlling horizontal movement and the area of the loosened rock. If inclined bolts pass through the major area of slip (depending on the in-situ stress distribution), the capacity of the truss bolt for preventing horizontal movement increases significantly. The area of slip varies with the in-situ stress conditions. Results showed that medium length tie-rod locates the inclined bolts at the best possible location to prevent slip on the first bedding plane in high horizontal in-situ stress. Further to the importance of length of tie-rod in truss bolt, choosing an angle closer to horizon would result in producing higher resisting force against high horizontal in-situ stresses. It should be mentioned that bolt angles less than 45° will result in significant reduction in the capability of truss bolt to control the area above the roof. Reinforcing this area above the roof is vital to prevent cutter roof failure when horizontal in-situ stress is high. In contrast, the area of slip in high vertical in-situ stress is mainly above the roof where short length tie-rod shows the best response. Same as the latter case, capability of this truss bolt pattern in controlling crack propagation should be taken into account. Truss bolt with medium length of tie-rod and 45° inclined bolts shows the best response in controlling shear crack propagation in high vertical in-situ stress.

Studying the effects of installing truss bolt on the position of natural roof arch also shows that changing the design parameters of truss bolt would result in reinforcing different areas above the roof and corners of the tunnel. These results match perfectly with results of SSM factor where short span truss bolt with wide angle inclined bolts are able to reinforce the area above the roof. By increasing the length of tie-rod and decreasing the length of inclined bolts, the main area of reinforcing effect of truss bolt shifts from an area above the middle of the roof to the area around inclined bolts.

It has been shown that, impact of truss bolt system changes with respect to the condition of the in-situ stress distribution. There are many other geological features that might have significant influence on the practice of truss bolt systems, such as thickness of the rock layers, strength parameters of rock, condition of discontinuities, time factor, etc. (Neall et al 1978). Consequently, it can be concluded that obtaining an optimum design for truss bolt systems entails consideration of effects of each individual design parameter alongside with comprehensive study of all of the external geological and ground controlling parameters.

6 Conclusion

Truss bolt systems have proved effective in controlling the stability of underground excavations in severe ground conditions particularly in coal mines and layered strata. Despite this, knowing the mechanism of truss bolt systems on reinforcing underground excavations is vital. The objective of this study was to understand the mechanism of truss bolt by means of numerical modelling. To evaluate and monitor the effects of truss bolt on load distribution around the tunnel and understand the mechanism of reinforcement, several stability indicators have been introduced. These indicators cover several features of a reinforcement system and are, namely, area of the loosened rock above the roof, stress safety margin, slip on the first bedding plane and shear crack propagation. None of these indicators alone is able to determine the stability of an underground excavation, but together, they help to understand the effects and mechanism of truss bolt system.

Results of employing these stability indicators reveal that truss bolt systems stabilize underground excavations in several ways such as repositioning the natural reinforced arch and reducing the area of loosened rock above the roof, creating a trapezoid reinforced area in which an arch shape structure is the major reinforced area, reducing horizontal movement of rock layers, preventing shear crack propagation, and decreasing the chance of cutter roof failure. Results of studying several truss bolt patterns also showed that changing the design parameters of the truss bolt will change the effectiveness of the system in facing different stability problems. Parameters such as angle and length of the inclined bolts and the span of the system or length of the tie-rod have been changed and results have been studied. It has shown that to reinforce the loosened area beneath the natural arch a short span truss bolt with wide angle inclined bolts is more appropriate while in high horizontal in-situ stress, to prevent horizontal movement of the immediate layer, a wider span and sharper angle of inclination response better. In case of cutter roof failure, to prevent shear crack propagation in high vertical in-situ stress, a pattern with medium length of tie-rod and inclined bolts and 45° inclined bolts results in the best application whilst other patterns do not show considerable improvement.

Results have showed that obtaining an optimum, safe and efficient design of a truss bolt system is only possible by considering all the design parameters, site variables and the interacting effects of each parameter on the other. This study has provided the necessary understanding of the mechanism of truss bolt which is an important step towards achieving a comprehensive guideline to design a truss bolt pattern.

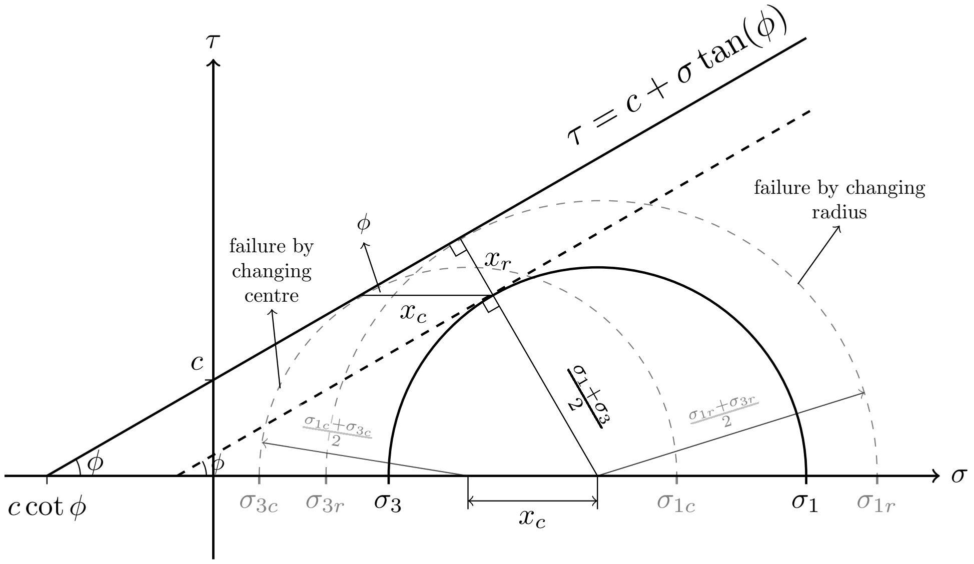

Fig. 5 Two possible paths of failure in Mohr-Coulomb failure model

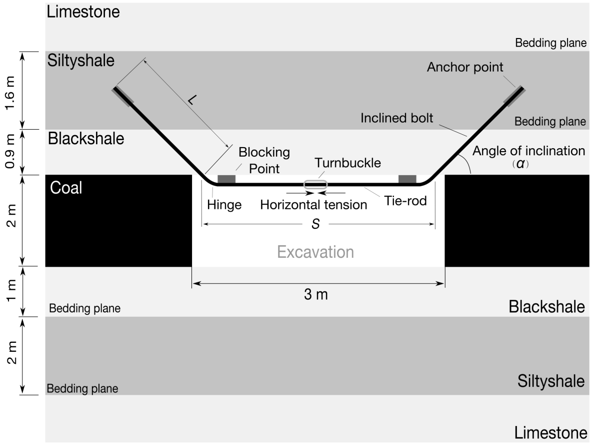

Fig. 1 Schematic view of truss bolt, tunnel and model dimensions

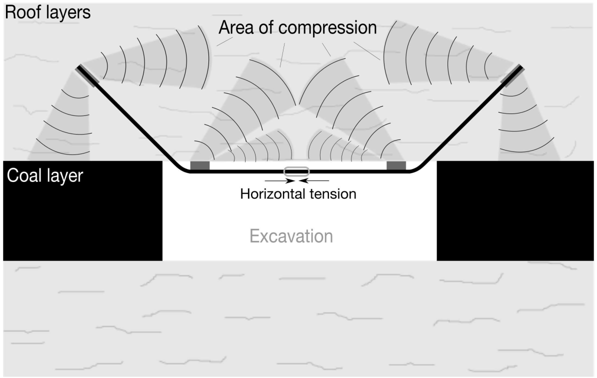

Fig. 2 Compressive areas around truss bolt

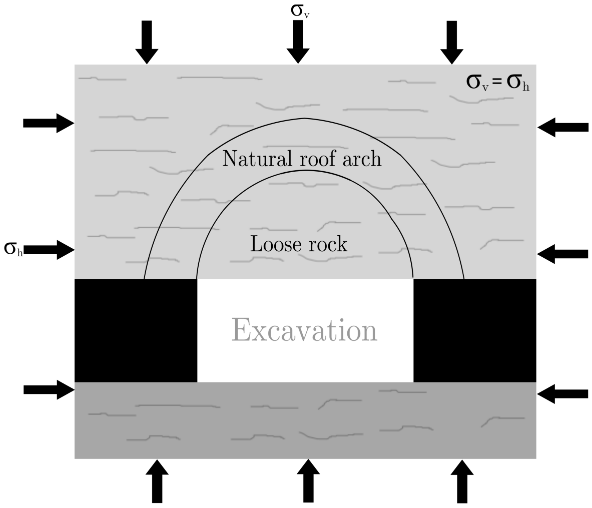

Fig. 3 Natural arch and loosened area

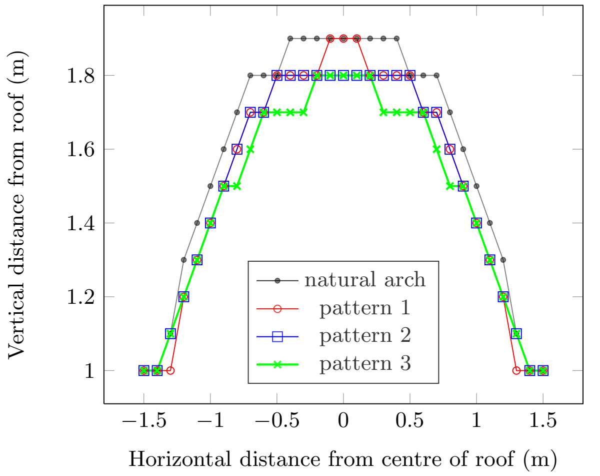

Fig. 4 Reinforced arch after installing truss bolt patterns

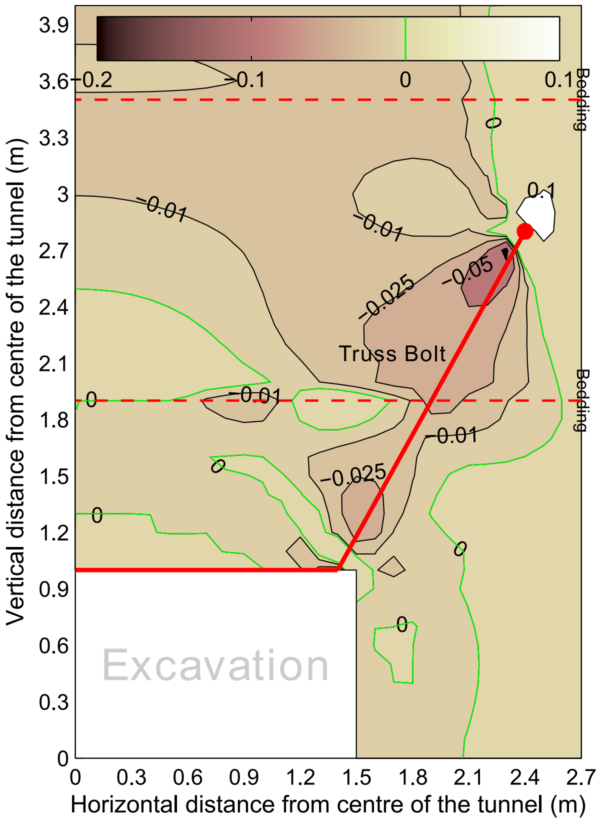

Fig. 6 Effect of pattern 1 on SSM

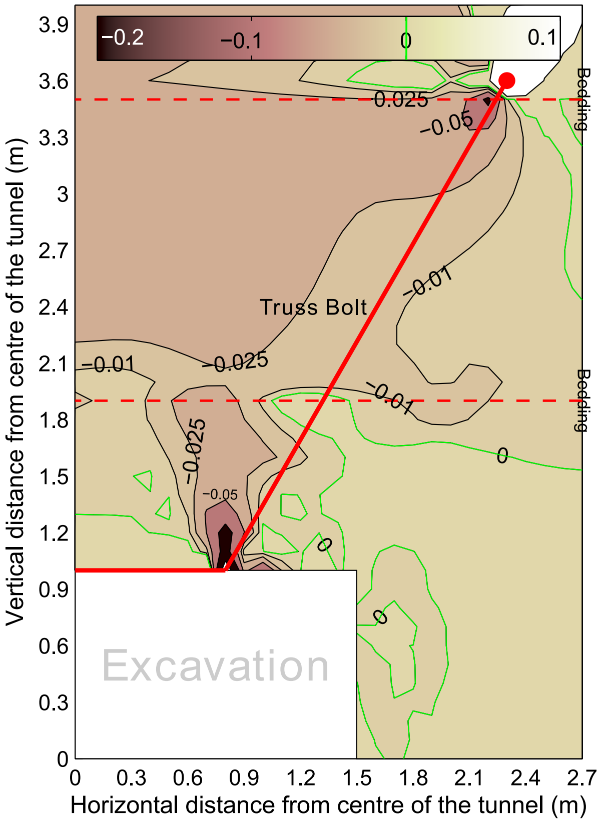

Fig. 8 Effect of pattern 3 on SSM

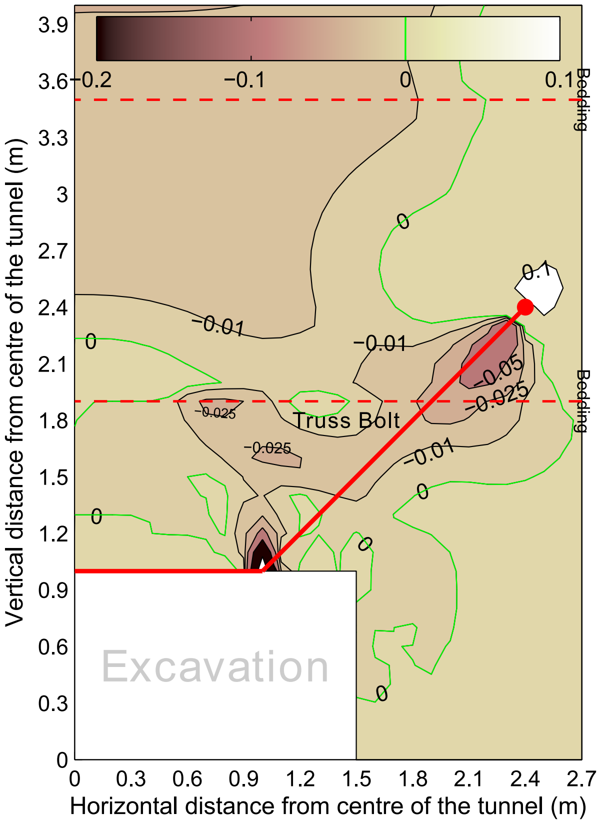

Fig. 7 Effect of pattern 2 on SSM

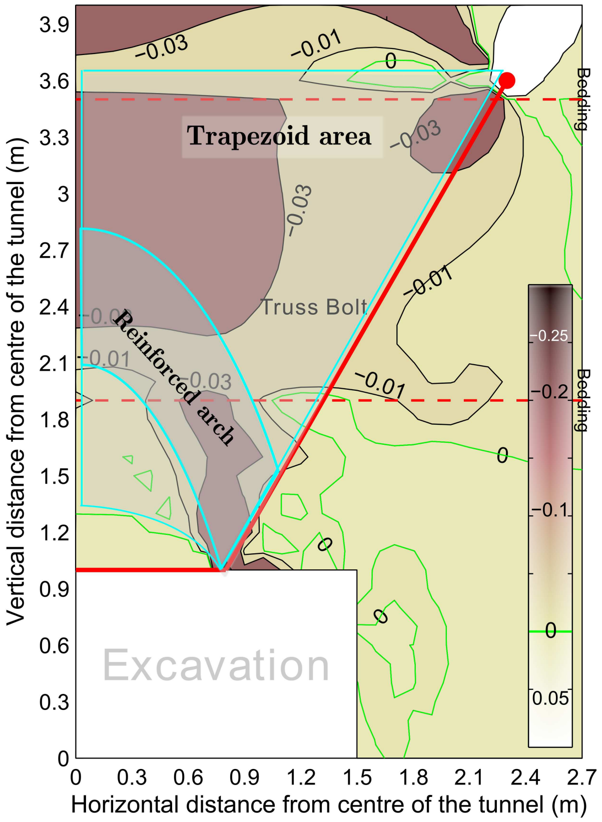

Fig. 9 Different reinforced areas around pattern 3

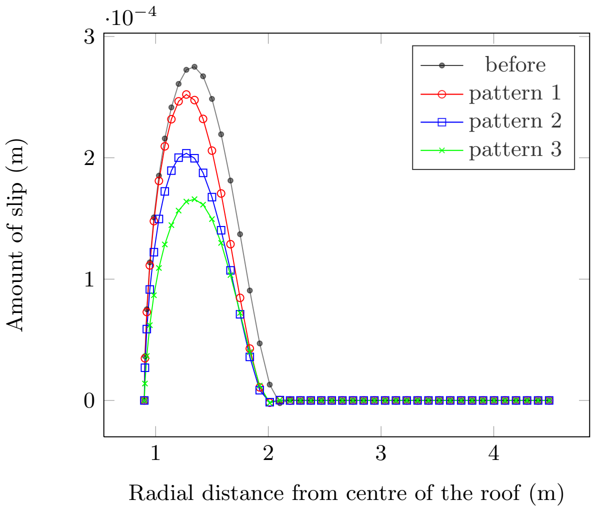

Fig. 10 Amount of slip on the first bedding plane ($\sigma_v = 2\sigma_h$)

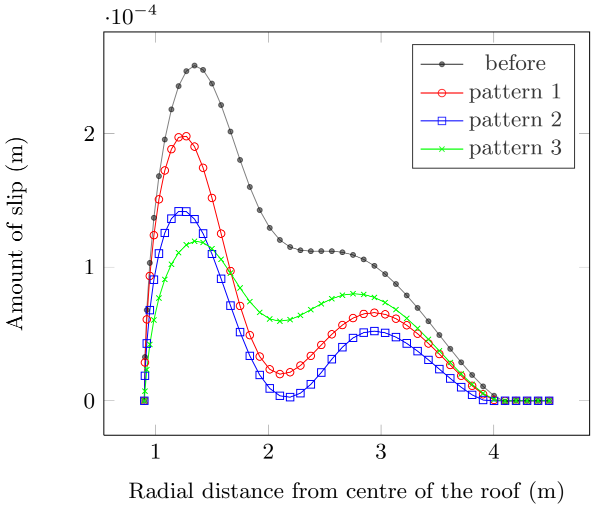

Fig. 11 Amount of slip on the first bedding plane ($\sigma_v = 1/2\sigma_h$)

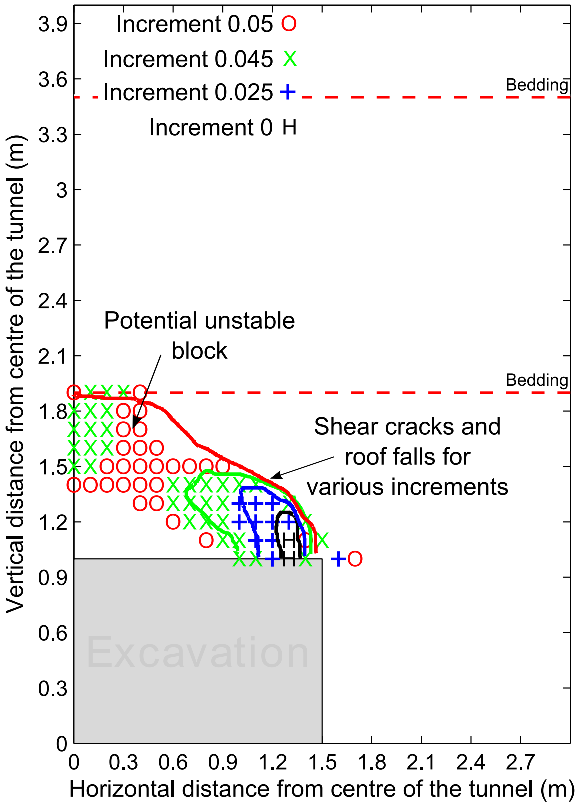

Fig. 12 Pattern of shear crack propagation ($\sigma_v = 1/2\sigma_h$)

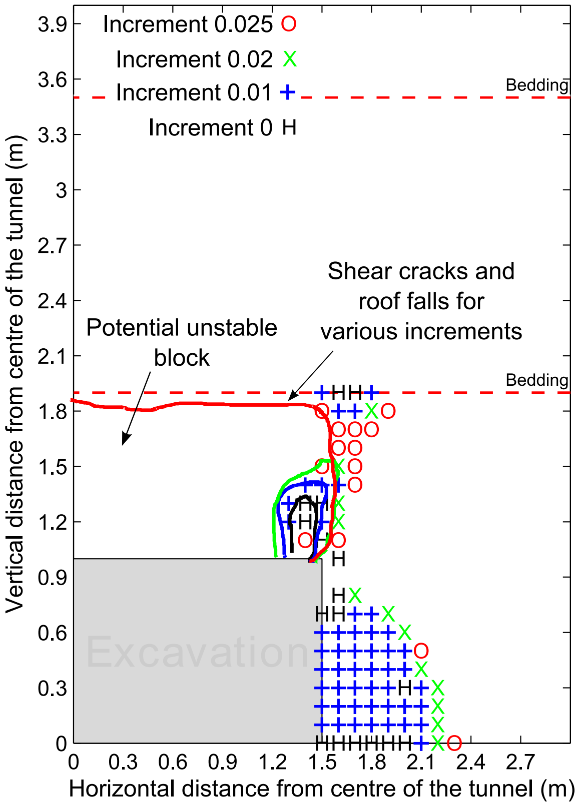

Fig. 13 Pattern of shear crack propagation ($\sigma_v = 2\sigma_h$)

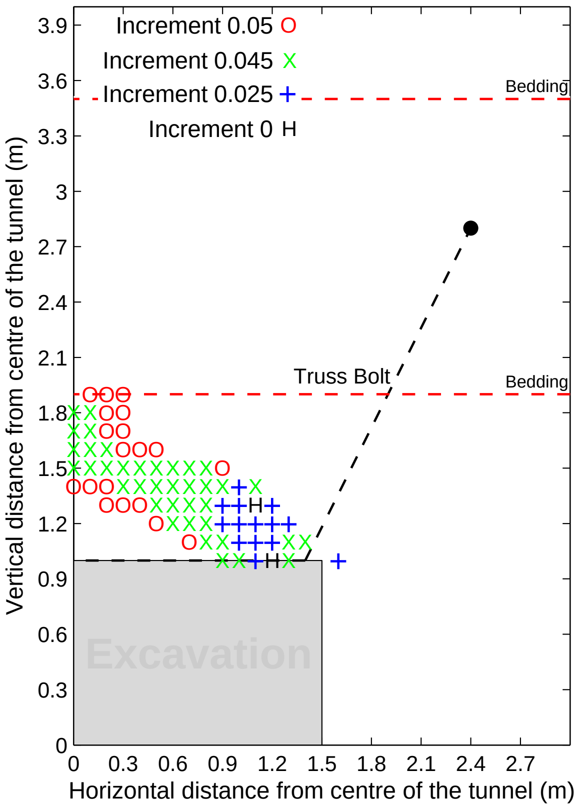

Fig. 14 Pattern of shear crack around pattern 1 ($\sigma_v = 1/2\sigma_h$)

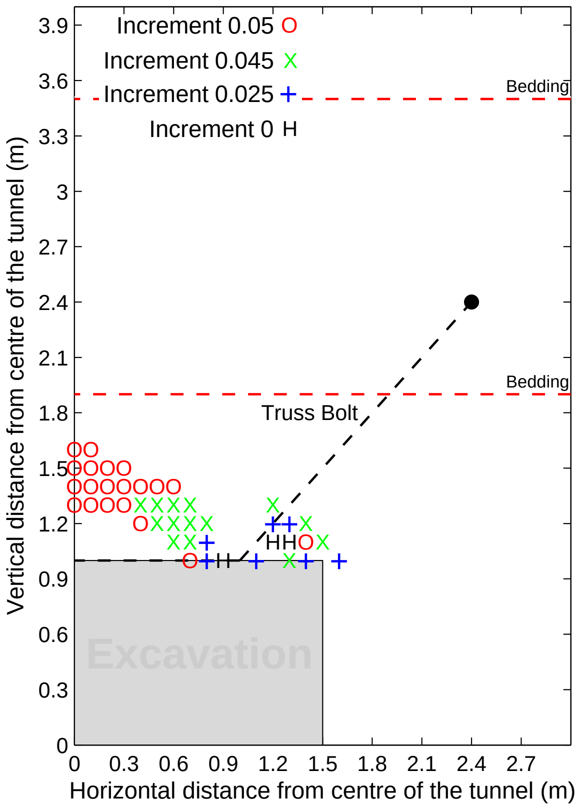

Fig. 15 Pattern of shear crack around pattern 2 ($\sigma_v = 1/2\sigma_h$)

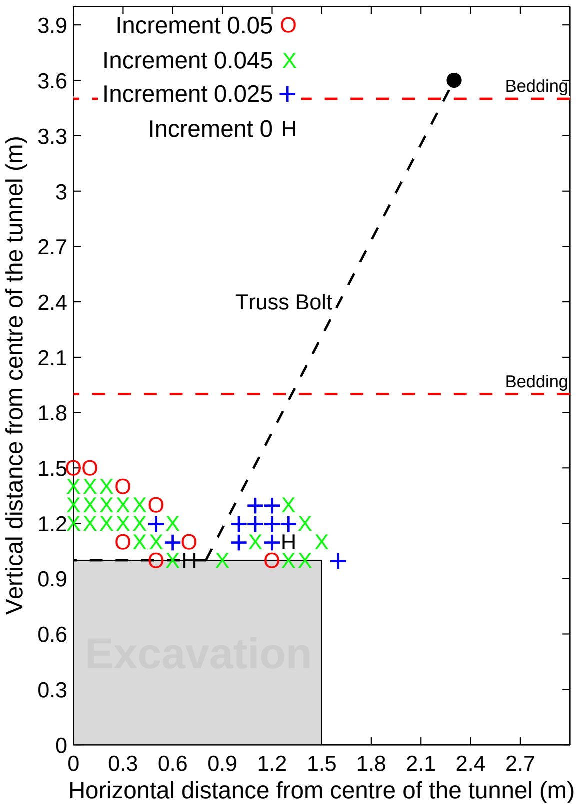

Fig. 16 Pattern of shear crack around pattern 3 ($\sigma_v = 1/2\sigma_h$)

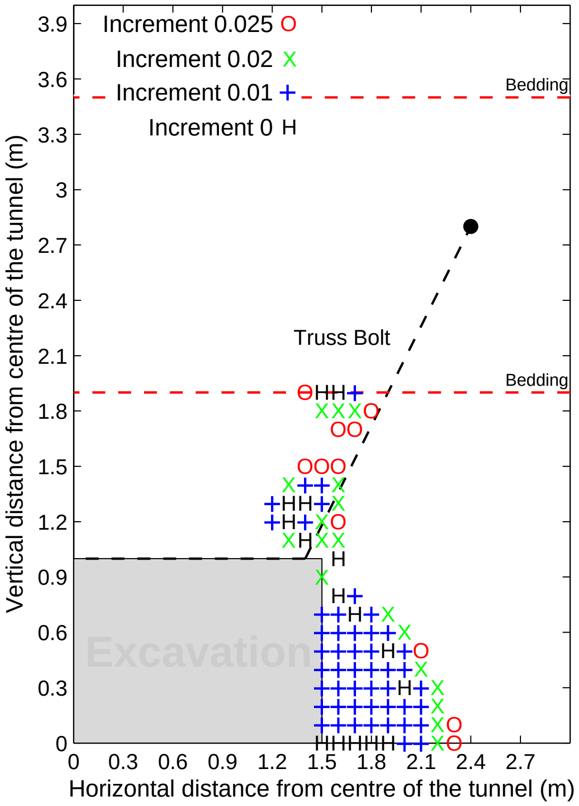

Fig. 17 Pattern of shear crack around pattern 1 ($\sigma_v = 2\sigma_h$)

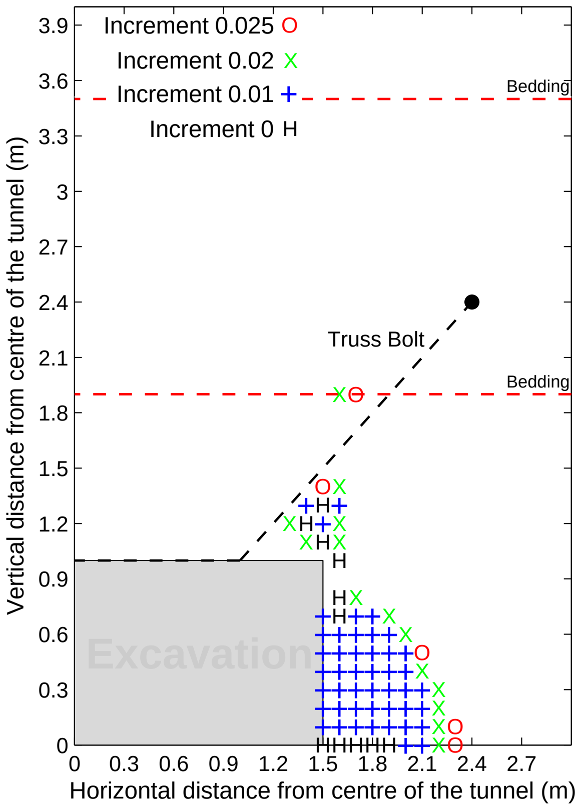

Fig. 18 Pattern of shear crack around pattern 2 ($\sigma_v = 2\sigma_h$)

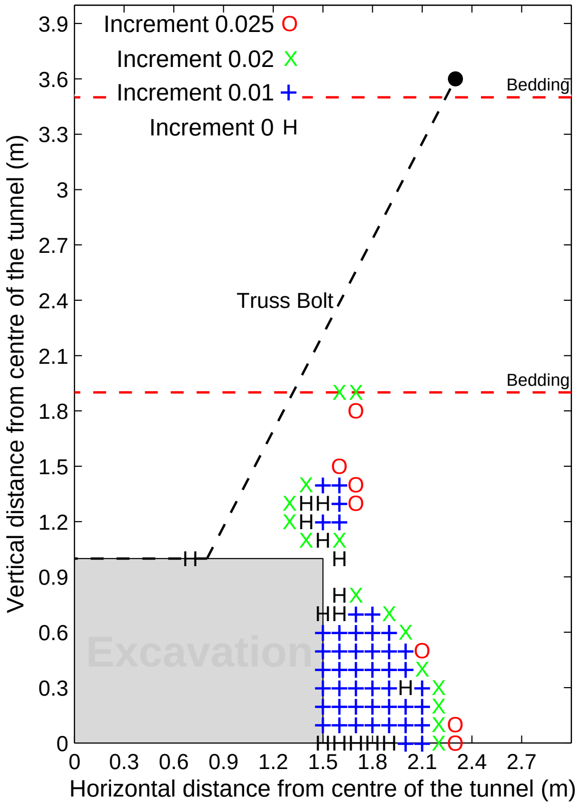

Fig. 19 Pattern of shear crack around pattern 3 ($\sigma_v = 2\sigma_h$)

Table 1 Bolt strength properties

Bolt properties	
Cross-sectional area	313 mm^2
Module of elasticity	200 Gpa
Ultimate tensile strength	1670 Mpa
Mass per meter-cable	2.482 kg/m

Table 2 Three different truss bolt patterns (see Fig. 1)

Truss bolt pattenrs	L(m)	S(m)	$\alpha(^\circ)$
Pattern 1 (Liu et al 2005)	2	2.8	60
Pattern 2 (Cox and Cox 1978)	2	2	45
Pattern 3 (Ghabraie et al 2012)	3	1.6	60

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