



Analysis on the Shear Stress Propagation Mechanism in the Rock Reinforcement System

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Rock reinforcement is significant in maintaining the stability of excavated structures, such as tunnels and underground roadways. However, shear failure in the rock reinforcement system, especially the shear failure at the rock reinforcement bolt surface, induces a threat to the rock reinforcement system. To reveal the shear stress (SS) propagation mechanism in the rock reinforcement system, this article conducted a literature review. First, the investigation approaches that were used by previous researchers to study the SS propagation were summarized. The advantages and disadvantages of experimental tests, analytical simulation, and numerical simulation were compared and analyzed. Then, the SS propagation process in the rock reinforcement system was presented. Two typical SS propagation modes were explained. More attention was given to the SS propagation mode in which the maximum SS propagates from the external end of rock reinforcement bolts to the internal end of rock reinforcement bolts. After that, a discussion section was given. In the discussion section, the significance of the SS propagation was further emphasized. Moreover, the limitations in the analytical simulation and numerical simulation were indicated. It is concluded that when studying the SS propagation mechanism of rock reinforcement bolts, combining experimental tests, analytical simulation, and numerical simulation is a better choice. This study is beneficial for revealing the SS propagation mechanism of the rock reinforcement system.

Keywords: rock mechanics, fracture development, rock reinforcement, deformation failure, decoupling behavior

INTRODUCTION

In rock mechanics, failure of rock masses is commonly encountered (Wang et al., 2021a). This is because fractures distribute non-uniformly in rock masses (Nikolenko et al., 2021; Yang et al., 2021). Moreover, experiment work proves that rock masses which are full of fractures are quite low in strength (Gao et al., 2021).

This is more prominent when the rock masses are subjected to manual excavations (Zhang et al., 2021). For example, in civil engineering and mining engineering, excavation activities are performed to create tunnels, chambers, or roadways (Chen et al., 2022). These tunnels and roadways will be later used in serving transportation and ventilation (Yao et al., 2020).

It is ensured that this manual excavation disturbs the initial stability of rock masses (Wu et al., 2018). Moreover, due to manual excavations, stress concentration occurs in rock masses (Chen et al., 2020; Zhang et al., 2022). Consequently, fractures are likely to develop in rock masses (Zhang et al., 2020a; Chen et al., 2021a; Yang et al., 2022). This further weakens the rock mass strength.

To guarantee the safety of the rock mass excavation, rock reinforcement bolts are commonly used (Li et al., 2021a; Wang et al., 2021b; Chang et al., 2021). Experimental work proves that rock reinforcement bolts can combine the jointed rock mass. Moreover, once rock masses converge, shear deformation will occur in the grout column. Consequently, stress can be transferred in the rock reinforcement system (Thompson et al., 2012).

During the loading process, the shear stress (SS) propagation plays a significant role (Wang et al., 2020a). Therefore, proper understanding of the SS propagation mechanism in the rock reinforcement system is quite significant.

This article aims at revealing the SS propagation mechanism in the rock reinforcement system. To realize this purpose, a literature review was conducted. This study is beneficial to propose new reinforcement approaches to prevent rock mass failure.

PREVIOUS STUDY ON THE SS PROPAGATION

Investigation Approaches

To study the SS propagation mechanism in the rock reinforcement system, previous researchers adopted various approaches. Generally, investigation approaches can be classified into three different types: experimental tests (Marian et al., 2021), analytical simulation (Liu et al., 2017; Li et al., 2021b), and numerical simulation (Chen et al., 2021a).

Experimental tests should be the most credible one. Specifically, strain gauges are adhered on the bolt surface (Wang et al., 2019). Then, this instrumented bolt is installed in a rock block. Grout is used to bond the bolt with the rock block (Chen et al., 2021b; Yu et al., 2021). After full curing, the bolt is pulled out. During testing, tensile force distribution along with the bolt can be measured. Then, **Eq. 1** is adopted to simply calculate the SS at the bolt surface (Aoki et al., 2003).

$$\tau = \frac{D_b E (\varepsilon_1 - \varepsilon_2)}{4\Delta L}, \quad (1)$$

where τ is SS at the bolt surface, D_b is the bolt diameter, E is the elastic modulus of the bolt, ε is the tensile strain of the bolt, and ΔL is the spacing between two adjacent strain gauges.

This approach has been used by a number of researchers (Wang et al., 2020b). However, a shortcoming is that the attached strain gauges are likely to be stripped from the bolt surface. To solve this issue, Chekired and Benmokrane (Chekired et al., 1997) developed the tension measuring device. This device can be mounted on the bolt to measure the strain distribution.

Additionally, Martin and Pakalnis (Martin et al., 2008) proposed replacing the central wire in the cable bolt with a modified wire. Specifically, along with this modified wire, strain gauges were attached.

In addition, analytical simulation is an efficient approach to study the SS propagation mechanism (Chen et al., 2021c). Specifically, although the bolt may have a long length, the infinitesimal method can be used to analyze the SS at the bolt surface, as shown in **Eq. 2** (Ma et al., 2019):

$$\tau = \frac{D_b}{4} \frac{d\sigma_b(x)}{dx}, \quad (2)$$

where $d\sigma_b(x)$ is the increment of the tensile stress in the bolt.

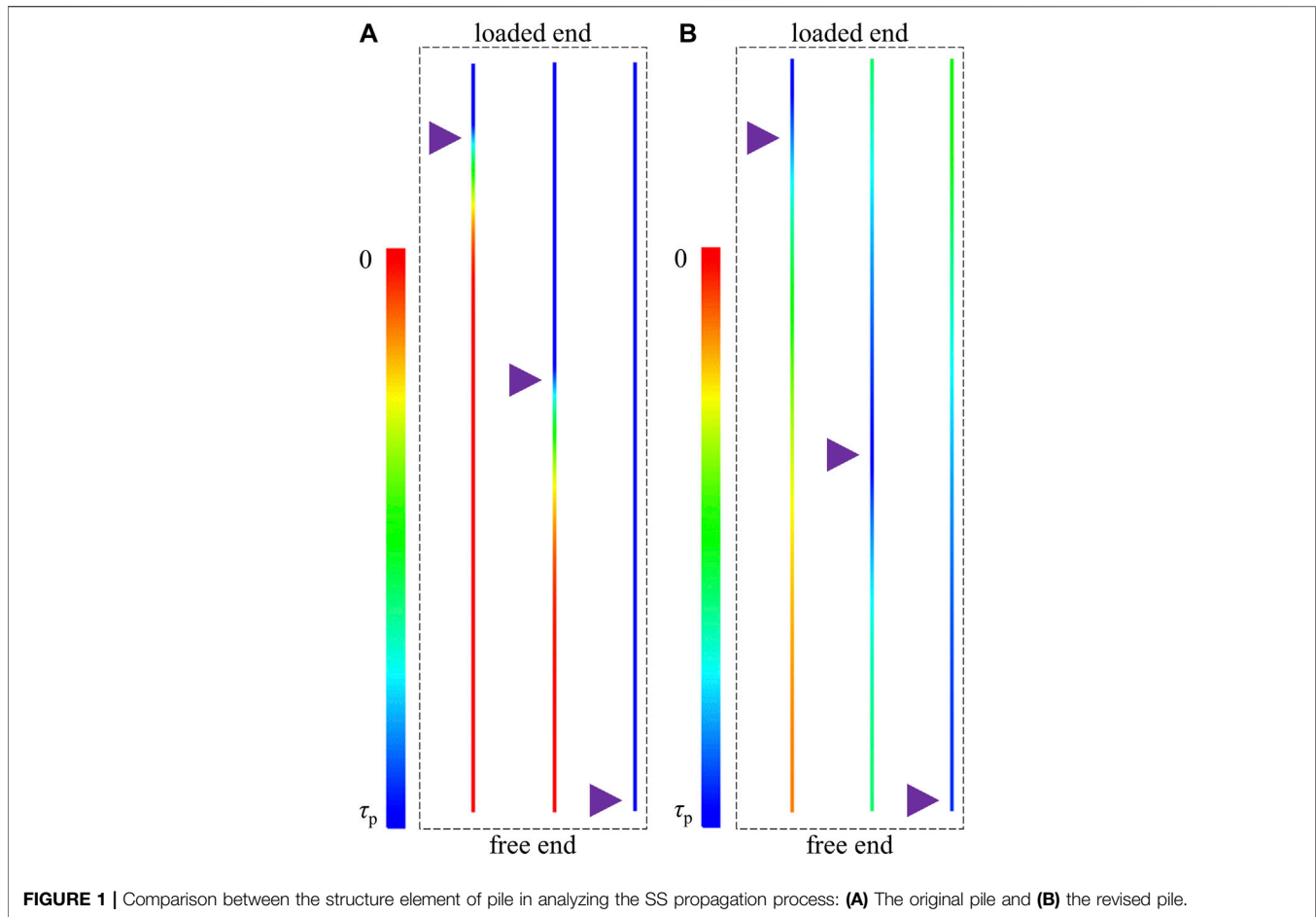
Then, it is assumed that the bolt surface has the same mechanical property (Zou and Zhang, 2019). A bond-slip equation can be used to depict the relationship between the SS at the bolt surface and the slip (Zhang et al., 2020b). By incorporating the bond-slip equation into **Eq. 2**, analytical equations can be developed.

This analytical approach was initially proposed by Farmer (Farmer, 1975). However, at that period, the decoupling behavior was not considered. Later, this analytical method was adopted by others (Zhu et al., 2021). Aydan and Ichikawa (Aydan et al., 1985) made a significant improvement on analytical simulation. Their innovation is that the classic trilinear equation was proposed to describe the slip behavior of the bolt surface. Based on the trilinear equation, the bolt surface encountered the elastic, softening, and decoupling behavior. Therefore, the coupling and decoupling behavior of the bolt surface can be simulated.

Moreover, the trilinear equation may be simplified into the bilinear equation to evaluate the SS propagation of the bolt surface (Cai et al., 2004). The main difference between the bilinear equation and the trilinear equation is that there is no linear softening behavior in the bilinear equation.

In recent years, numerical simulation has become more popular in rock reinforcement analysis. It is because numerical simulation is powerful in establishing and calculating complicated structures (Mohamed et al., 2020). As for the rock reinforcement analysis, more research was focused on using the structure element, such as the cable or pile. There is a significant difference between the cable and pile. Specifically, the cable only considers the longitudinal performance of rock reinforcement bolts. In contrast, the pile can analyze both the longitudinal performance and the lateral performance of rock reinforcement bolts.

The advantage is that numerical elements have already been created by commercial companies. Therefore, users can conveniently adopt the structure element to simulate different rock reinforcement cases. In contrast, the shortcoming is that the original constitutive equation may not truly reflect the proper behavior of the rock reinforcement system. For example, in the structure element of the cable, the bolt surface is assumed to deform following an elastic perfectly plastic equation, as shown in **Eq. 3** (Nemcik et al., 2014).



$$\begin{cases} \tau = k_g \delta (\delta \leq \delta_p) \\ \tau = \tau_p (\delta > \delta_p) \end{cases}, \quad (3)$$

where k_g is the shear stiffness of the grout column, δ is the slip of the bolt surface, δ_p is the slip of the bolt surface when the peak strength reaches, and τ_p is the peak strength of the bolt surface.

It neglects the post-failure behavior of the bolt surface. Therefore, it cannot truly simulate the loading performance of bolts without modification.

Nevertheless, the commercial software usually reserves the secondary development interface. For example, for the structure element of the cable, the Itasca Company prepared a number of FISH functions (Chen et al., 2021d). For the structure element of the pile, the Itasca Company created the TABLE function (Chen and Li, 2022). Therefore, users can use these FISH functions or TABLE function to modify the original rock reinforcement elements. For example, **Figure 1** shows the comparison between the original pile and the revised pile. Apparently, with the original pile, at the end of the SS propagation process, the SS at the full bolt surface equaled the peak strength. This overestimated the loading capacity of bolts. In contrast, with the modified pile, there was always a non-uniform SS distribution at the bolt surface. This was more consistent with the experimental test results. Consequently, it

saw a wide application of the commercial numerical tools in the rock reinforcement analysis (Shang et al., 2018).

SS Propagation Mechanism

Based on the previous research, it is accepted that the SS at the bolt surface may have a uniform distribution if the anchor length was short enough (Blanco Martín et al., 2010). Benmokrane and Chennouf (Benmokrane et al., 1995) indicated that when the anchor length is less than four times the bolt diameter, the SS can be treated equal. Based on this concept, **Eq. 4** was used to calculate the SS at the bolt surface (Ma et al., 2013):

$$\tau = \frac{F}{\pi D_b L}, \quad (4)$$

where F is the pulling force and L is the anchor length.

It should be noted that **Eq. 4** is valid when the anchor length is constant during the pulling process. Nevertheless, it is more common to encounter the scenario where the anchor length decreases gradually. Then, **Eq. 5** can be used to calculate the SS (Ma et al., 2013).

$$\tau = \frac{F}{\pi D_b (L - u_b)}, \quad (5)$$

where u_b is the pulling displacement.

More importantly, rock reinforcement bolts usually have a long length (Cao et al., 2013). In this case, after the bolt is subjected to tensile loading, a non-uniform SS distribution occurs. For the laboratory monotonous loading condition, the bolt usually has two ends. One is embedded in the rock block, and it is called the internal end. By contrast, the other one is left outside and it is called the external end. Since there is a non-uniform SS distribution, SS propagation between the two ends of the bolts generates.

Some research indicated that the maximum SS under each loading level was likely to occur around the same position (Teymen and Kılıç, 2018). Moreover, that position was close to the borehole collar.

In contrast, it is more common to see that during the initial load process, the SS at the borehole collar increased gradually. With the loading increasing, the SS at the borehole collar increased to the peak strength. Then, it started dropping. More interestingly, the maximum SS moved toward the internal end direction. This SS propagation ended when the SS at the internal end of the bolt reached the peak strength.

As a validation of this SS propagation concept, Rong and Zhu (Rong et al., 2004) conducted laboratory pull-out tests on bolts. Strain gauges were attached on the bolt surface to record the tensile force distribution. Later, Ma and Nemicik (Ma et al., 2013) analyzed these experimental data. Eq. 1 was used to calculate the SS at the bolt surface. The analysis results showed that at the initial loading grade, the SS at the borehole collar increased gradually. However, after a certain loading level, the SS at the borehole collar reached the peak strength. With the loading level further increasing, the maximum SS propagated gradually toward the external end. This analysis result was consistent with the above SS propagation concept. Therefore, the experimental work and the corresponding data analysis proved the reliability of the SS propagation concept.

Additionally, the analytical simulation and numerical simulation can better reflect the SS propagation process. Ren and Yang (Ren et al., 2010) used the classic trilinear equation to depict the slip behavior of the bolt surface. They analyzed the SS propagation process at the bolt surface. The results showed that the maximum SS at the bolt surface propagated from the external end to the internal end. Moreover, although each point at the bolt surface experienced the elastic, softening, and decoupling behavior, the full bolt surface underwent five different grades. They were the elasticity, elasticity-weakening, elasticity-weakening-decoupling, weakening-decoupling, and decoupling grades. Later, Blanco Martín and Tijani (Blanco Martín et al., 2013) indicated that when the trilinear equation was used to depict the slip behavior of the bolt surface, the full bolt surface may undergo a pure softening grade.

It should be mentioned that when different bond-slip equations are used, the full bolt surface may undergo different grades. For example, Chen and Liu (Chen et al., 2021e) indicated that when a bilinear equation was used to depict the slip behavior of the bolt surface, the full bolt surface only experienced three grades: the elastic grade, elastic-decoupling grade, and decoupling grade.

Although different bond-slip equations can be used, the SS propagation mechanism was consistent. Specifically, the maximum SS at the bolt surface consistently propagated from the external end to the internal end, as shown in Figure 2.

This finding was also confirmed with the numerical simulation. Nemicik and Ma (Nemicik et al., 2014) modified the original structure element in FLAC2D and simulated the SS propagation process at the bolt surface. A non-linear bond-slip equation was used. The results showed that each point at the bolt surface obeyed the same non-linear bond-slip equation. With the loading level increasing, the maximum SS at the bolt surface propagated toward the internal end. This finding was consistent with the others (Nie et al., 2018).

DISCUSSION

The SS at the bolt surface plays a significant role in determining the loading capacity of bolts (Wu et al., 2019). Under the static loading condition, the loading capacity of the bolts equals the sum of the shear force at the bolt surface (Ho et al., 2019). Since the SS at the bolt surface can be calculated directly with the shear force at the bolt surface, as shown in Eq. 6, there is a close relationship between the SS at the bolt surface and the loading capacity of the bolts (Zuo et al., 2019).

$$\tau = \frac{F_s}{A_s}, \quad (6)$$

where F_s is the shear force at the bolt surface and A_s is the contact area between the bolt and the grout column.

Therefore, it is valuable to understand the SS propagation mechanism of bolts. To realize this purpose, previous researchers used various approaches. It is believed that the experimental approach is more credible. This is because compared with the experimental approach, the analytical simulation and numerical simulation usually relied on a number of assumptions (Yokota et al., 2019). Whether those assumptions are reasonable is doubted. In the analytical simulation, it is usually assumed that the bolt, grout column, and surrounding rock masses deform elastically. In fact, in experimental tests, failure of the rock masses may occur because of the radial dilation at the bolt surface. Therefore, under this scenario, the analytical simulation which assumes that only slip failure occurs at the bolt surface may not be trustable.

Similarly, in the numerical simulation, rock masses are simulated with different elastoplastic equations. Among kinds of equations, the Mohr–Coulomb equation is more commonly used. This equation is relatively simpler and its input parameters can be acquired directly from experimental tests. However, it cannot properly simulate the post-failure behavior of rock masses. Specifically, after the peak, the strain softening behavior and residual behavior of rock masses cannot be properly simulated. In this case, the interaction between the numerical rock mass and bolts cannot be the same as in the reality. This is also the reason why the numerical simulation work should be calibrated and compared with experimental results.

Nevertheless, this is not to deny the significance of analytical simulation and numerical simulation. In fact, these two approaches are more effective for researchers to understand the SS propagation mechanism of bolts. Therefore, it is suggested that combining the experimental tests, analytical simulation, and numerical simulation is a better choice for studying the SS propagation mechanism of bolts.

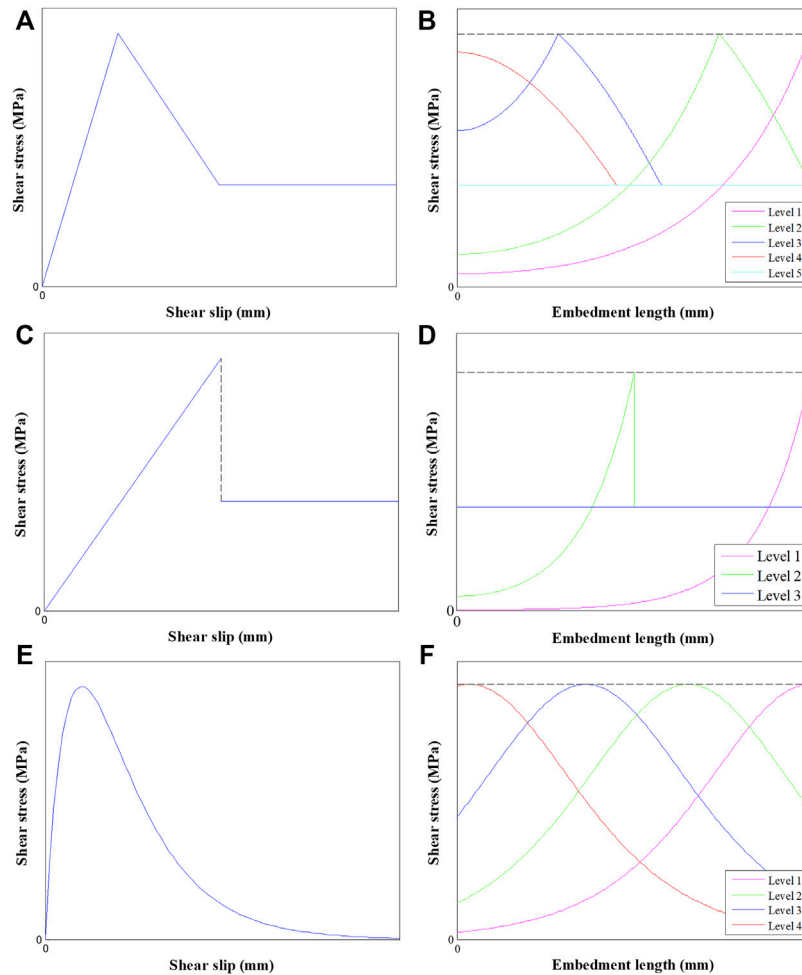


FIGURE 2 | SS propagation process: **(A)** Trilinear equation, **(B)** the corresponding SS propagation process, **(C)** bilinear equation, **(D)** the corresponding SS propagation process, **(E)** non-linear equation, and **(F)** the corresponding SS propagation process.

CONCLUSION

This article conducted a literature review on the SS propagation mechanism of rock reinforcement bolts. The previous investigation approaches were summarized. It is concluded that previous researchers usually used experimental tests, analytical simulation, and numerical simulation. Among those approaches, the experimental approach is more widely used. The experimental test results are also more likely to be accepted by others. By contrast, the analytical approach had more degree of freedom. With this approach, researchers can use different bond-slip equations to depict the slip behavior of the bolt surface. As for the numerical simulation, it is convenient for users since the original constitutive equation has already been created by the developer. Moreover, developers usually reserve the secondary development interface for users to modify the original constitutive equations.

As for the SS propagation mechanism, it is more commonly agreed that during the pulling process of bolts, the SS at the borehole collar firstly increased. With the loading level increasing, the SS at the borehole collar gradually reaches the

peak strength. Then, with the further increasing of the loading level, the maximum SS starts propagating toward the internal end. This phenomenon was consistently observed in experimental tests, analytical simulation, and numerical simulation.

AUTHOR CONTRIBUTIONS

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Conflict of Interest: HL is employed by the company China National Coal Group Corporation.

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