Study on the Influence of different factors on cutterhead shield jamming of gripper TBMs in weak rocks

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Abstract. In the construction of deep-buried and long-mileage tunnels, the use of tunnel boring machines (TBMs) is the preferred excavation method. However, TBMs encounter a variety of problems in adverse geological conditions. When excavating in weak rocks with high in situ stress, the large deformation of the surrounding weak rocks causes TBM jamming, which is very time consuming and expensive to deal with. In practice, the most commonly used method is the advanced geological prediction technology, and support systems are strengthened on the basis of the convergence–confinement method, which is composed of the longitudinal deformation profile (LDP), ground reaction curve, and support characteristic curve. In this work, the LDPs of surrounding weak rocks were obtained using numerical models in FLAC3D. The influence of the elastic modulus (E) of rocks, buried depth of a tunnel (BDt), and tunnel diameter on the cutterhead shield jamming of a gripper TBM was analyzed. In the analysis, the total length of the cutterhead and cutterhead shield of the gripper TBM was 4 m, and the friction between the cutterhead shield and the surrounding rocks was not considered. Results showed that increasing the overcut was the most effective method to prevent TBM jamming. Moreover, E and BDt exerted an obvious effect on the design value of the overcut. Several suggestions to prevent the cutterhead shield jamming of gripper TBMs and countermeasures to resolve such jamming in weak rocks were subsequently derived. The conclusions of this work can facilitate the selection of appropriate overcuts when designing the cutterheads of TBMs and help to prevent and control the cutterhead shield jamming of gripper TBMs in weak rocks.

Key words: TBM (Tunnel Boring Machine), TBM jamming, FLAC3D, Weak rocks, Overcut

1. Introduction

The rapid development of tunnel construction technology has increased the construction of deep-buried and long-mileage tunnels all over the world. By the end of 2020, more than 1,800 tunnels in high-speed railways measuring at least 2,750 km had been under construction in China (Tian et al., 2021). Given their construction period, environmental protection, long ventilation distance, and engineering cost, hard rock tunnel boring machines (TBMs) have become more preferable than the drilling and blasting method in constructing conveyance and traffic tunnels (Liu et al., 2016; Jiang et al., 2020). However, TBMs are not easily adaptable to adverse geological conditions and thus tend to
jam during excavation. Eight TBM jamming cases, including two jamming hazards involving TBM-1 and six jamming hazards involving TBM-2, occurred in Gaoligongshan Tunnel in China (Xu et al., 2021). In the Yintao Conveyance Project in China, a jamming case caused the TBM to be trapped for more than a year (Wang, 2006).

After excavation using a TBM, a small gap forms between the surrounding rocks and the TBM shield because of overcut. When the convergence deformation of the surrounding rocks is larger than the gap, the shield is squeezed, and friction is generated. If the sum of the cutterhead thrust and the friction between the surrounding rocks and TBM shield is greater than the maximum thrust of the TBM, then the risk of TBM jamming increases. In weak rocks with high in situ stress, the time-dependent deformation of the surrounding rocks is obvious, and TBM jamming accidents occur frequently. Therefore, the interaction between surrounding rocks and TBMs, the risk of jamming, and the influence of jamming control measures should be accurately analyzed.

The methods for analyzing TBM jamming mainly include engineering experience-based analysis, theoretical analysis, and numerical simulation analysis. The engineering experience-based analysis method mainly focuses on the evaluation of the deformation of surrounding rocks by selecting some indexes that affect TBM jamming. Aydan (1996) used the ratio of rock strength and overlying surrounding rock pressure to evaluate the risk of TBM jamming on the basis of engineering experiences. Ramoni (2011) qualitatively analyzed the influence of the advancing speed and downtime of a TBM on TBM jamming according to the $N^2$ diagram. The theoretical analysis method is mainly based on the theory of elastic–plastic mechanics and is adopted to obtain the stress state and convergence deformation of surrounding rocks. Carranza-Torres (2000) proposed an evaluation method for extrusion deformation that is based on the convergence–confinement method. However, the experience-based and theoretical analysis methods have many limitations because the influencing factors and TBM excavation process are very complex. With the rapid development of computer technology in recent years, the numerical simulation analysis method has been widely used to solve geotechnical engineering problems. On the basis of the FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) software, Hasanpour (2017) established a double-shield TBM model under adverse geological conditions and analyzed the risk of TBM jamming in the process of TBM excavation. Cheng (2016) established a three-dimensional double-shield TBM excavation model in composite strata in FLAC3D and studied the interaction mechanism between the TBM and the surrounding rocks in different strata. Hou (2021) used FLAC3D to simulate the interaction between surrounding rocks and the shield in the process of double-shield TBM tunneling and analyzed the influence of TBM advance rate and overcut on TBM jamming.

Many numerical simulation models of shield TBMs have been established to study the factors that influence TBM shield jamming, but few researchers have paid attention to gripper TBM jamming. In the current work, the jamming mechanisms of different types of TBMs were analyzed, and numerical simulation models considering the TBM excavation process under different situations were proposed in FLAC3D. On the basis of the longitudinal deformation profiles (LDPs) obtained in FLAC3D, the influence of the elastic modulus of rocks and the buried depth and diameter of a tunnel on the cutterhead shield jamming of a gripper TBM in weak rocks was analyzed. Several practical countermeasures to prevent the cutterhead shield jamming of gripper TBMs in weak rocks and methods for ensuring the smooth operation of TBMs were subsequently proposed.

2. Principle of TBM jamming and longitudinal deformation profile (LDP)

2.1. Principle of TBM jamming

TBM jamming is one of the important problems that limit the application of TBMs. In Shanggongshan Tunnel in China, downtime caused by TBM jamming accounted for 53% of the total downtime from January to April 2004 (Song et al., 2004). According to the characteristics of TBM structures (single-shield, double-shield, and gripper TBMs) and the deformation of surrounding rocks, TBM jamming cases can be divided into six categories, including one in which the cutterhead jamming of gripper TBMs is caused by the large deformation of weak rocks. According to the statistics of 121 cases, the
shield jamming of gripper TBMs caused by large deformation accounts for 17% (Xu et al., 2021). The different jamming modes of gripper TBMs are shown in Figure 1.

![Figure 1. Different jamming modes of gripper tunnel boring machines (TBM)](image)

(a) cutterhead jamming  
(b) shield jamming

**Figure 1.** Different jamming modes of gripper tunnel boring machines (TBM)

Generally, the diameter of a tunnel under excavation is larger than the diameter of the shield of the TBM used to prevent TBM jamming; the difference between them is called the overcut. If the convergence deformation of surrounding rocks is larger than the overcut during excavation using a single-shield or double-shield TBM, then the surrounding rocks come into contact with the shield, and friction is generated. When the difference between the maximum thrust of the TBM and the friction generated is not enough for the disc cutters in the cutterhead to break the rocks, TBM jamming occurs, as shown in equation (1).

\[ F_b > F_i - R_f \]  

(1)

where \( F_i \) is the maximum thrust of the TBM, \( R_f \) is the friction between the TBM shield and the surrounding rocks, and \( F_b \) represents the total thrust required for the disc cutters to break the rocks.

The cutterhead shield of a gripper TBM is considerably shorter than that of a single- or double-shield TBM. Moreover, the stiffness of the cutterhead shield is low and is thus damaged easily when squeezed by surrounding rocks (Figure 2). Jamming occurs when the deformation of surrounding rocks is larger than the overcut in the gripper TBM as the surrounding rocks come into contact with the shield, as shown in equation (2).

\[ d_R > d_{overcut} \]  

(2)

where \( d_R \) is the deformation of surrounding rocks and \( d_{overcut} \) represents the overcut.
2.2. *Longitudinal deformation profile (LDP)*

The convergence–confinement method (CCM) is a useful and effective analytical method for investigating the mechanical behavior of surrounding rocks during excavation. As comprehensively reported by Carranza-Torres and Fairhurst (2000), the CCM consists of the LDP, ground reaction curve, and support characteristic curve (Figure 3). The interpretation of the interaction between the three components of the CCM allows engineers to determine the deformation of surrounding rocks and the internal pressure that the ground transmits to the support as the tunnel face advances.

As a result of the force redistribution after excavation, the decrease of fictitious internal pressure induces the accumulation of tunnel convergence. When the deformation of surrounding rocks reaches the ultimate value, the internal pressure decreases to the minimum value. Simultaneously, a support system should be supplied to prevent the surrounding rocks from collapsing. However, the cutterhead shield of a gripper TBM lacks enough zone to apply support that would prevent the increase of the deformation of surrounding rocks. If deformation increases rapidly, especially under high ground cover or in weak rocks, the TBM is bound to become trapped. The LDP shows the deformation of surrounding rocks at different distances from the face, and it can thus be used to analyze the shield jamming problem.
3. Numerical modeling and result analysis

In this work, FLAC3D based on the finite difference method was used to simulate the excavation process. FLAC3D software adopts an explicit Lagrangian algorithm and hybrid partition technology and is capable of simulating the plastic deformation of rocks accurately. It can also simulate a wide range of 3D problems while consuming minimal computer memory space.

3.1. Numerical modeling

The numerical simulation model considering the TBM excavation process was established herein (Figure 4). To reduce the boundary effect on the simulation result, this study adopted the following measures: (1) the transverse simulation range of the model was not less than 10 times the tunnel diameter, (2) the longitudinal simulation range of the model was 40 m, and (3) 10 m-long rocks were assumed to have been excavated before calculation. Several models with different parameters were established in this study with consideration of the influence of the elastic modulus of rocks (E), tunnel diameter, and buried depth of a tunnel (BDT), on the deformation of surrounding rocks. The rock mass parameters are given in Table 1. In each model, 31 excavation steps, including 1 initialization step and 30 excavation steps, were simulated. Each excavation step was modeled by advancing the face by 0.5 m.

| Table 1. Rock mass parameters |
|-----------------------------|
| Elastic modulus, (GPa) | 1.4 |
| Poisson’s ratio | 0.25 |
| Cohesion, (MPa) | 0.60 |
Friction angle, (°) 28
Dilatancy angle, (°) 8

3.2. Influence of elastic modulus of rock (E) on TBM jamming
To analyze the influence of E on the cutterhead shield jamming of a gripper TBM, this study set E in the models to 1.4, 3, 5, 8, 10, and 12 GPa. Meanwhile, the tunnel diameter was 10 m, and the buried depth of the tunnel was 1,000 m. Figure 5 illustrates the simulation results in terms of the deformation of the surrounding rocks at the crown, which was proportional to the LDP. Given a constant E, the farther the surrounding rocks are from the tunnel face, the greater their displacement will be. If the distance to the face is constant, then the displacement of surrounding rocks becomes increasingly small with the increase of E. Assuming that the total length of a cutterhead and the cutterhead shield of a gripper TBM is 4 m, the overcut should be designed such that it is larger than the displacement of surrounding rocks 4 m away from the face. The fitting relationship between E and overcut, which is an inverse proportion, is given in Figure 6 and equation (3). The design of the overcut is obviously influenced by E.

\[
d_{\text{overcut}} = \frac{57.53}{E}
\]

Figure 5. LDPs for tunnel with different E, 10 m diameter, and 1,000 m buried depth

3.3. Influence of buried depth of tunnel (BDₜ)
The models under different BDₜ were established to study the influence of BDₜ on the cutterhead shield jamming of the gripper TBM. BDₜ was set from 250 m to 1,500 m with an interval of 250 m. The E value of the rocks was 1.4 GPa, and the diameter of the tunnel was 10 m. As shown in Figure 7, with the increase of BDₜ, the displacement of the surrounding rocks increased obviously. Specifically, the in situ stress inside the surrounding rocks increased with the change of BDₜ, resulting in the increase of rock displacement. Similarly, the displacement of the surrounding rocks at 4 m away from the face was taken as the design of the overcut. The fitting relationship between BDₜ and the overcut is illustrated in Figure 8. BDₜ exerted a serious influence on the design of the overcut.

Figure 6. Fitting relationship between E (GPa) and overcut (cm)

Figure 7. Displacement of surrounding rocks at 4 m away from the face

Figure 8. Fitting relationship between BDₜ and overcut (cm)
3.4. Influence of tunnel diameter

The influence of tunnel diameter on the cutterhead shield jamming of a gripper TBM was also studied herein. As shown in Figure 9, when the buried depth was 1,000 m and $E = 1.4$ GPa, the change of displacement of the surrounding rocks was not obvious as the tunnel diameter increased from 6 m to 12 m with an interval of 2 m. The displacement of the surrounding rocks at 4 m away from the face was stable at 40 cm. Thus, the tunnel diameter exerted little influence on the design of the overcut.

4. Countermeasures for controlling cutterhead shield jamming of gripper TBMs

When a large deformation of weak rocks occurs in front of the tunnel face, some countermeasures should be taken to prevent the cutterhead shield jamming of gripper TBMs. On the basis of the principle of TBM jamming and project experiences, this study summarizes the measures that should be taken in practical engineering to prevent the cutterhead shield jamming of gripper TBMs caused by weak rocks:

1. Increasing the overcut at the crown and sidewalls by refitting the equipment;
2. Making the gripper TBM pass through the section quickly and setting the support structures as soon as possible;
3. Excavating small pilot tunnels quickly on both sidewalls to release pressure;
4. Excavating the upper half of the face manually and excavating the lower half of the face by TBM;
5. Performing large pipe shed grouting in advance to reinforce weak rocks;
6. Passing through the section using the drilling and blasting method.

The following countermeasures are suggested when the cutterhead shield jamming of a gripper TBM occurs:

1. Using the maximum thrust or torque to pass through the jamming section as soon as possible;
2. Excavating small pilot tunnels quickly around the cutterhead shield of the TBM to keep the TBM out of trouble;
3. Shrinking the cutterhead shield in the radial direction and then passing through the jamming section when other measures fail.

5. Conclusion
This study focused on the cutterhead shield jamming of gripper TBM. Numerical simulation models considering TBM excavation under different situations were established in FLAC3D. In each model, 31 excavation steps, including 1 initialization step and 30 excavation steps were simulated. Each excavation step was modeled by advancing the face by 0.5 m. The LDPs obtained after the result analysis showed that the E value of the rocks and the buried depth of the tunnel exerted an obvious effect on the deformation of the surrounding rocks. Such effect was not observed for the tunnel diameter. The deformation at the crown decreased with the increase of the E value of the rocks and increased as the buried depth of the tunnel changed from 250 m to 1,500 m.

Increasing the overcut was found to be the most effective method to prevent the cutterhead shield jamming of gripper TBM. In the analysis conducted herein, the total length of the cutterhead and the cutterhead shield of a gripper TBM was assumed to be 4 m, and the friction between the cutterhead shield and the surrounding rocks was not considered. The design of the overcut of the gripper TBM was proposed with consideration of the buried depth of the tunnel and the E value of the rocks.

Some countermeasures to prevent the cutterhead shield jamming of gripper TBM and some methods to ensure the smooth operation of machines during excavation in weak rocks with high in situ stress were proposed and summarized on the basis of the principle of TBM jamming and actual project experiences.

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