Hindawi
Geofluids
Volume 2022, Article ID 6247439, 11 pages
https://doi.org/10.1155/2022/6247439

Research Article

Research on the Safety Thickness of Tunnel Outburst Prevention in Water-Rich Fault Fracture Zone Based on Janssen's Theory

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Received 23 June 2022; Accepted 30 August 2022; Published 23 September 2022

Academic Editor: Jianyong Han

In the construction of tunnel in water-rich fault fracture zone, when the thickness of outburst prevention is insufficient, it is very easy to cause water and mud inrush engineering accident. Therefore, it is very necessary to study the safety thickness of outburst prevention for this type of tunnel. In this paper, the expression of in situ stress in water-rich fault fracture zone is derived based on Janssen's theory. Two mechanical models of outburst prevention rock mass are established, and according to the shear balance theory, the calculation formula for the safe thickness of outburst prevention is determined and the parameter sensitivity analysis is carried out. Finally, it is verified by engineering examples and numerical simulation. The results show that: (1) the calculation formula of outburst prevention thickness proposed in this paper is more perfect and shows good prediction effect for deep- and shallow-buried tunnels; (2) the greater the angle α between tunnel axis and fault zone and the dip θ of fault fracture zone, the smaller the critical safety thickness of outburst prevention and the safer it is for tunnel construction; (3) when the fault fracture zone inclines inward relative to the tunnel face, the gravity of the rock mass in the fault zone will lead to an increase in the safety thickness of outburst prevention, and reinforcement measures should be taken during actual construction.

1. Introduction

When the tunnel crosses the fault zone, the surrounding rock mass is broken, and under the construction disturbance, the groundwater in the original stable state flows along the fault grain gap to the excavation surface. At the same time, the loose medium and mineral components of the fault are dissolved in the water body, and the seepage channel expands. In turn, the seepage rate of the rock mass will be increased, forming a "vicious circle," resulting in the original rock structure damage [1, 2]. Especially for deep-buried tunnels, the surrounding rock is subject to higher ground stress and water pressure, and the hydraulic coupling effect is intensified, which can easily lead to engineering disasters such as water and mud inrush [3–5]. According to the research of Yang et al. [6] and Liu et al. [7], the insufficient safe thickness of tunnel outburst prevention is one of the most important engineering factors causing water and mud inrush. Therefore, it is of great significance for the safe construction of tunnels to study the safety thickness of tunnel outburst prevention in the fault fracture zone.

Since the Hungarian scholar Ribicic [9] first proposed the concept of relative water-resisting rock thickness in 1994, many scholars have carried out a series of theoretical researches on the safety thickness of tunnel outburst prevention, forming some theoretical research methods such as fluid-structure coupling theory, analytic hierarchy process (AHP), fuzzy mathematics, and the limit analysis principle. Liu et al. [10] and Ma et al. [8] established a coupled seepage-erosion water inrush model, and based on the theory of fluid dynamics, they revealed the seepage-erosion mechanism of antioutburst rock mass. Based on the AHP, Xue et al. [11] established the risk assessment model of tunnel water inrush in fault fracture zone, and they found that the surrounding rock grade, permeability coefficient, overburden thickness, tunnel section and construction technology, etc. are the main factors that induce tunnel water inrush. In addition, Wang et al. [12] also drew similar research conclusions through fuzzy mathematics theory. According to the plane failure pattern of rock plug body, Yang et al. [13] derived the expression of tunnel outburst prevention safety thickness by using the limit analysis method and analyzed the influence of various parameters on the safe thickness of the rock plug.

However, when analyzing the safe thickness of tunnel, most of the above theories only consider the effect of groundwater on the outburst prevention rock mass and ignore the influence of in situ stress in the fault fracture zone, resulting in the smaller safe thickness of outburst prevention. Besides, the existing theories do not consider the influence of the distribution range such as the length and width of fault fracture zone, and the calculation process is cumbersome, resulting in a limitation of engineering application. However, the Janssen silo theory applied to the calculation of silo wall pressure can well overcome the above problems. In 1996, Chen and Zhu [14] conducted an extended study on Janssen's theory, expanded the silo lateral pressure calculation theory previously applied to circular or conical sections to rectangular section, and made clear the applicability of the Janssen formula in fault fracture zone with a certain dip angle. Based on this, Zhang [15] applied Janssen's theory to the stability analysis of tunnel face in water-rich fault fracture zone for the first time, and the formula for calculating the safety factor of the tunnel face is derived; subsequently, Meng et al. [16] also applied this theory to study the safety thickness of tunnel outburst prevention in the fault fracture zone, derived the expression of the safety thickness of outburst prevention, and analyzed the influence of the width of the fault fracture zone on the safety thickness. On the basis of Meng et al. [16] and Fu et al. [17] combined with the Sheorey model, determined the stress state of surrounding rock when water and mud inrush occurred, and based on the limit equilibrium method, the expression of the safe thickness of outburst prevention was deduced, and the parameter sensitivity analysis was carried out too.

To sum up, the application of the Janssen silo theory to the study of tunnel outburst prevention thickness in fault fracture zone can better solve some problems existing in other theories and provide a new method for calculating the safety thickness of outburst prevention. However, the existing researches still have the following shortcomings: on the one hand, when solving the stress of the fault fracture zone based on Janssen's theory, the established mechanical model does not take into account the effect of groundwater pressure and friction between fault fracture zone and ordinary surrounding rock (rock mass outside the fault fracture zone), resulting in a large deviation in the final value of in situ stress; on the other hand, when calculating the safety thickness of tunnel outburst prevention in the fault fracture zone, only the special working conditions when the tunnel axis is orthogonal or parallel to the fault zone are discussed, which leads to the limitation of engineering application; in addition, in the process of solving the safety thickness of tunnel outburst prevention, the selected rock mass shear strength calculation method is obviously too large, resulting in the dangerous design of the outburst prevention thickness. Therefore, based on Janssen's theory, this paper improves the mechanical model of fault fracture zone and the calculation formula of outburst prevention thickness and verifies the accuracy of the derived formula through engineering example and numerical simulation.

2. Calculation of Safe Thickness for Tunnel Outburst Prevention in Water-Rich Fault Fracture Zone

2.1. Introduction to Janssen's Theory. In the 19th century, scholars researched the stress of silos storing grain, stone, cement, and other granular materials. At first, they simplified the granular materials into a fluid, ignored the friction between the granular materials and the silo wall, and used the theory of fluid mechanics to calculate the lateral pressure of the silo wall at different buried depths, but found that there was a large deviation from the actual situation. In order to improve the calculation method, in 1895, the German scholar Janssen deduced the famous Janssen silo theory, which assumes (1) the vertical stress at the same depth of the silo is uniformly distributed; and (2) the ratio K (lateral pressure coefficient) of the horizontal stress to the vertical stress at different depths of the silo is constant. Although there is a certain deviation between the assumptions of Janssen's theory and the actual situation, the theoretical calculation is simple and the calculation error is relatively small. Therefore, it is widely used in practical projects and has become the silo design code of more than a dozen countries in the world [18–20]. The basic expression of the Janssen formula is

$$P_Z = \frac{\gamma R}{\mu K}\left(1 - e^{-\mu K Z/R}\right), \tag{1}$$

$$P_{xy} = \frac{P_Z}{K}, \tag{2}$$

where γ is granular material weight; R is hydraulic radius of silo section; μ is the friction coefficient between granular material and silo wall; K is the lateral pressure coefficient; and P_Z and P_{xy} are the vertical stress and horizontal stress at the Z depth of the silo, respectively.

2.2. Applicability of Janssen's Theory. The traditional silo theory is suitable for the calculation of granular material lateral pressure in silos with circular or conical section. If the theory is to be extended to the calculation of in situ stress in fault fracture zone, two problems need to be solved. One is whether noncircular section, such as rectangular section silos, is used. Another problem is whether the fault fracture zone can be simplified to granular material in silos. For the first problem, the Janssen formula is derived from the force balance equation of microelements at a certain depth of the silo. Therefore, what we focus on is the force-balanced state of the granular microelement, which is independent of the shape of the silo containing granular materials and the silo with circular, rectangular, and other shapes have good applicability [14]. For the second problem, the basic properties of the silo granular materials are loose particles, low cohesion strength, incompressibility, and there is frictional resistance between the silo walls [21]. It is generally known that the fault fracture zone is due to the relative movement of the two discs of the fault, which breaks the nearby rocks and forms a fracture zone roughly parallel to the fault plane. And the particles of the rock mass are relatively fragmented, especially in the extensional fault zone, where the cohesion between the fault particles is even worse [22]. In addition, when the two discs of the fault move relative to each other, the rock particles and the fault plane will also generate the friction, which has similar properties to the silo granular materials. Therefore, it can be simplified as granular materials, and the lateral pressure can be solved by using the Janssen formula.

Before establishing the mechanical model of fault fracture zone based on silo theory, the following assumptions are made:

(1) The same basic assumptions as Janssen's silo theory

(2) The cohesion strength between the rock mass in the fault zone and the fault plane is not considered, that is, the frictional P_f between the rock mass in the fault zone and the fault plane is the product of the horizontal in situ stress P_{xy} in the fault fractured zone and the friction coefficient μ

(3) The depth of fault fracture zone is infinite

(4) The rock mass and groundwater in the fault fracture zone are incompressible, and the fault plane is a rigid "silo wall"

2.3. In Situ Stress Solution of Fault Fracture Zone. As shown in Figure 1, the mechanical model of fault fracture zone with a certain dip angle and considering groundwater is established.

The angle θ between the fault plane and the horizontal line is the dip angle of the fault fracture zone, and the width of the fault fracture zone is B, the length is L, and the weight is γ, the friction coefficient between the granular particles in the fault fracture zone and the "silo wall" is μ. Take an element with a thickness of d_Z at the buried depth Z for force analysis:

The upper and lower surfaces of the microelement act on the vertical in situ stress P_Z and the groundwater pressure P_W; the buried depth of groundwater is d. Due to the pore development in the fault fracture zone and good connectivity of groundwater, water pressure at depth Z can be calculated by formula: $P_W = \rho g(Z - d)$ (ρ: groundwater density, g: gravitational acceleration); the microelement gravity in the fault fracture zone is γBLd_Z; the lateral surface of the microelement body also have the horizontal in situ stress P_{xy} and the resulting "silo wall" frictional P_f; in addition, the gravity component of the microelement body $\gamma BLd_Z \cos\theta$ also produces a frictional $\mu\gamma BLd_Z \cos\theta$ that is

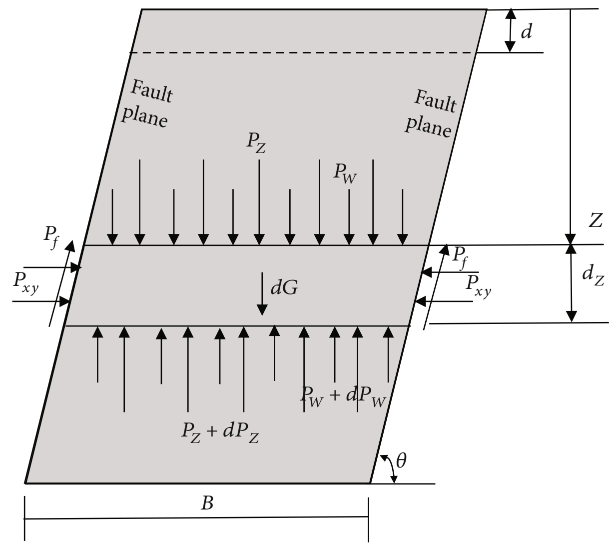


Figure 1: The microelement mechanic model of water-rich fault fracture zone.

inclined upward along the contact surface on the right "silo wall" fault plane. Project the forces on the microelement to the vertical direction to get the balance equation:

$$\begin{aligned}(P_Z + P_W)\mathrm{BL} + \gamma \mathrm{BL}\mathrm{d}_Z - (P_Z + \mathrm{dP}_Z + P_W + \mathrm{dP}_W)\\ \mathrm{BL} - 2P_{xy}\mathrm{Bd}_Z\mu - 2P_f L\frac{d_Z}{\sin\theta}\\ \sin\theta - \mu\gamma \mathrm{BLd}_Z \cos\theta \sin\theta = 0.\end{aligned} \quad (3)$$

Substitute the horizontal in situ stress $P_{xy} = \mathrm{KP}_Z$ and the frictional $P_f = \mu P_{xy} \sin\theta$ into the equation (3), obtaining the vertical in situ stress formula of the fault fracture zone:

$$P_Z = e^{-((2K\mu(B+L\sin\theta))Z)/\mathrm{BL}} D(1) - \frac{\mathrm{BL}(\rho g - \gamma + \gamma\mu\cos\theta\sin\theta)}{2K\mu(B + L\sin\theta)}, \quad (4)$$

where $D(1)$ is the integral constant, substituted into the initial condition, when $Z = 0$, $P_Z = 0$, we get

$$D(1) = \frac{\mathrm{BL}(\rho g - \gamma + \gamma\mu\cos\theta\sin\theta)}{2K\mu(B + L\sin\theta)}. \quad (5)$$

Substitute expression of $D(1)$ into equation (4), and after sorting out, the expression of in situ stress in the fractured zone of the water-rich fault based on Janssen's theory is as follows:

$$P_Z = \frac{\mathrm{BL}(\gamma - \rho g - \gamma\mu\cos\theta\sin\theta)}{2K\mu(B + L\sin\theta)}\left(1 - e^{-((2K\mu(B+L\sin\theta))Z)/\mathrm{BL}}\right), \quad (6)$$

$$P_{xy} = \frac{\mathrm{BL}(\gamma - \rho g - \gamma\mu \cos\theta \sin\theta)}{2\mu(B + L \sin\theta)} \left(1 - e^{-((2K\mu(B+L\sin\theta))Z)/\mathrm{BL}}\right). \tag{7}$$

2.4. Solution to the Safe Thickness of Tunnel Outburst Prevention. According to the in situ stress expression of water-rich fault fracture zone and the shear instability condition of outburst prevention rock mass, the expression of tunnel outburst prevention safety thickness is derived.

2.4.1. Assumptions. When the tunnel is constructed to the area of the fault fractured zone, a certain amount of unexcavated rock mass should be reserved between the tunnel face and the fault plane to resist the in situ stress and water pressure of the fault zone, and the length of the unexcavated rock mass is the thickness of tunnel outburst prevention. If the thickness is small, it is not enough to resist the pressure of mud and water, resulting in the disaster of water and mud inrush; if the thickness is large, the tunnel advanced support measures are conservative, resulting in project waste.

When the ordinary surrounding rock of the tunnel has higher overall strength than the rock mass in the fault fracture zone, the main failure mode of the antioutburst rock mass is shear instability failure [23]: the stress and seepage field in the fault fracture zone are redistributed due to construction disturbance, which increase the effect on the outburst prevention rock mass, resulting in shear stress concentration, and when the ultimate shear strength is exceeded, shear slip occurs, resulting in water and mud inrush disasters. Therefore, for this kind of surrounding rock, the shear failure of outburst prevention rock mass can be simplified as "plug pulling effect" for analysis, and the following assumptions are made: (1) the strength of the outburst prevention rock mass is relatively high, and the dissolution damage of the groundwater to the outburst prevention rock mass is not considered; (2) the outburst prevention rock mass is a homogeneous, continuous, and isotropic elastic body, which is suitable for the principle of small deformation.

2.4.2. Solution Process. Different inclination directions of the fault fracture zone relative to the tunnel face have different effects on the stability of the outburst prevention rock mass. Figures 2(a) and 2(b), respectively, show the mechanical model of the outburst prevention rock mass when the water-rich fault fracture zone is inclined outward and inward relative to the tunnel face. What needs to be explained is that the outward inclination of the fault fracture zone relative to the tunnel face means that the excavation face is located at the hanging wall of the fault, and the inward inclination of the fault fracture zone relative to the tunnel face means that the excavation face is located at the foot wall of the fault.

The schematic diagram of the intersection between the tunnel axis and the fault zone is shown in Figure 3, and take the distance from the center of the tunnel face to the fault plane as the outburst prevention thickness S. Water and mud inrush in the tunnel is most likely to occur at the position where the thickness of the outburst prevention is relatively weak. When the tunnel axis is orthogonal to the fault zone, that is, when the angle α between the two is 90°, as shown in Figure 3(a), the thickness of outburst prevention along the tunnel axis is the smallest. So, the thickness S in the direction of the tunnel axis is the minimum outburst prevention safety thickness that needs to be solved. When the angle α is less than 90°, as shown in Figure 3(b), the outburst prevention thickness S' in the vertical direction of the tunnel face to the fault plane is smaller than S in the tunnel axis direction. Therefore, the minimum safety thickness of outburst prevention is S', and they have an approximate geometric relationship $S = S'/(\sin\alpha)$.

As shown in Figure 2, the right surface of the outburst prevention rock mass acts on the horizontal in situ stress P_{xy} of the fault fracture zone and the groundwater pressure P_W which is perpendicular to the surface of the outburst prevention rock mass. When the fault fracture zone inclines inward, it is also necessary to consider the self-weight stress component $\gamma B \cos\theta$ of the fault fracture zone; the shear stress τ is uniformly distributed on the potential shear failure surface of the outburst prevention rock mass.

For the outward inclined fault fracture zone, project the forces on the outburst prevention rock mass to the tunnel axis and obtain the equation:

$$\left(P_{xy} + P_W \sin\theta\right) \frac{\pi D^2}{4 \sin\theta} = \pi \mathrm{D} S' \tau. \tag{8}$$

Where $(P_{xy} + P_W \sin\theta)$ is the resultant force projected by P_{xy} and P_W in the axis direction of the outburst prevention rock mass and $(\pi D^2)/(4\sin\theta)$ is the contact area between the outburst prevention rock mass and the fault zone. Substitute equation (7) into equation (8), let $n = (2\mu(B + L\sin\theta))/\mathrm{BL}$, and the expression of the minimum safety thickness is

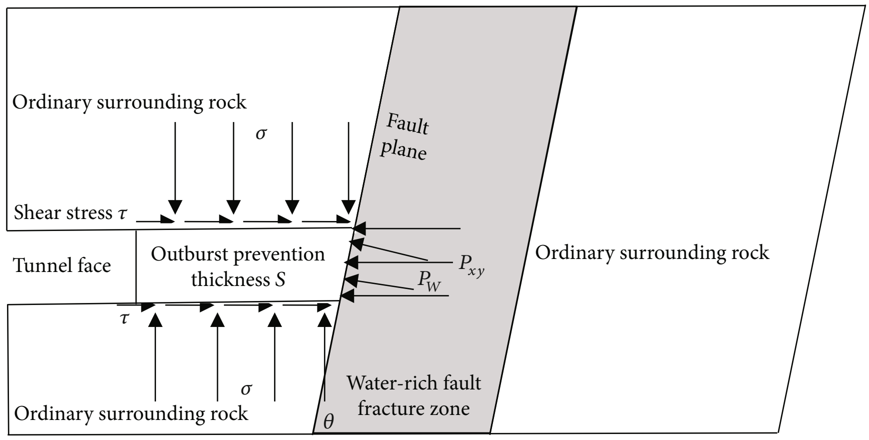
$$S' = \frac{D}{4\tau}\left[\frac{\gamma - \rho g - \gamma\mu\cos\theta\sin\theta}{n\sin\theta}\left(1 - e^{-nKZ}\right) + P_W\right]. \tag{9}$$

Substituted $P_W = \rho g(Z - d)$ and $S = S'/(\sin\alpha)$ into equation (9), obtaining the outburst prevention safety thickness in the direction of tunnel axis:

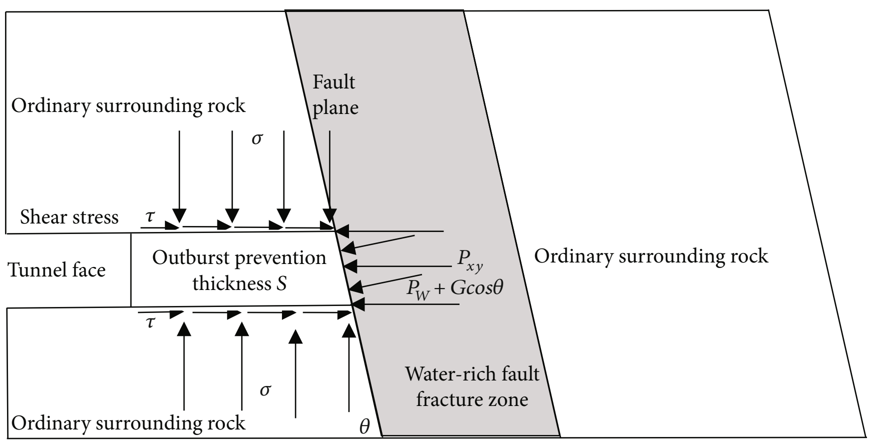
$$S \geq \frac{D}{4\tau\sin\alpha}\left[\frac{\gamma - \rho g - \gamma\mu\cos\theta\sin\theta}{n\sin\theta}\left(1 - e^{-nKZ}\right) + \rho g(Z - d)\right]. \tag{10}$$

The description of the lateral pressure coefficient K and ultimate shear strength τ of rock mass in equation (10) are as follows:

(1) Scholars have carried out a series of related researches on the value of K [24, 25], such as $K = (1 - \sin\phi_1)/(1 + \sin\phi_1)$, $K = 1 - \sin\phi_1$, and $K = \tan^2(45° - (\phi_1/2))$ (ϕ_1: internal friction angle of the fault fracture zone). Liu et al. [26] found through experimental research that when substituting the above

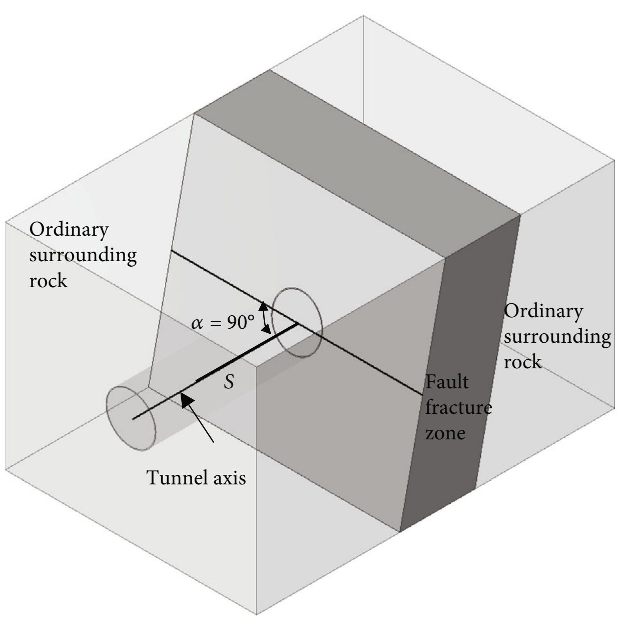


(a) Outward inclination of fault fracture zone

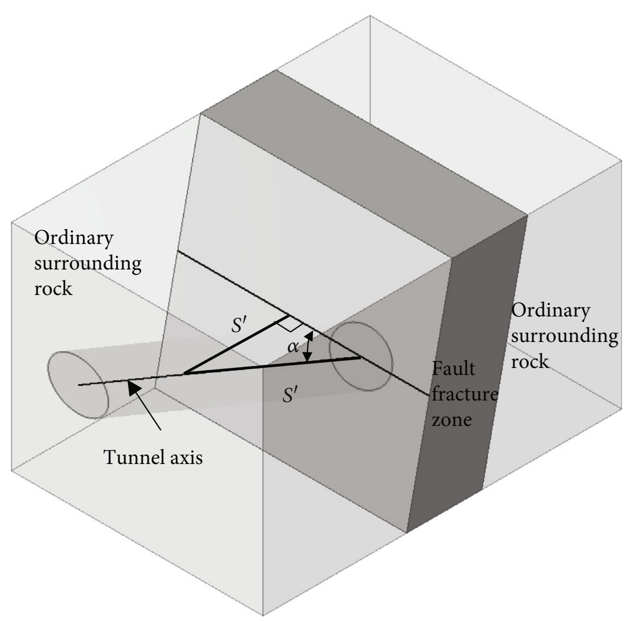


(b) Inward inclination of fault fracture zone

Figure 2: Mechanical model of tunnel outburst prevention rock mass.



(a) The tunnel axis is orthogonal to the fault zone



(b) General angle between the tunnel axis and the fault zone

Figure 3: Schematic diagram of the intersection of the tunnel axis and the fault zone.

lateral pressure coefficient K into the Janssen formula for calculation, the obtained fault zone stress is obviously smaller, while $K = 1.1(1 - \sin\phi_1)$ recommended by the International Organization for Standardization (ISO) is more accurate in the theoretical calculation of silos. Therefore, take$K = 1.1(1 - \sin\phi_1)$

(2) According to the Mohr-Coulomb strength criterion, the shear strength of outburst prevention rock mass is

$$\tau = c + \sigma \tan\phi_2, \tag{11}$$

where c and ϕ_2 are the shear strength indexes of outburst prevention rock mass and σ is the vertical stress acting on the outburst prevention rock mass. Meng et al. [16] used the formula $\sigma = \gamma_i H_i$ of the whole soil column to calculate the vertical stress, which obviously has a large error. Because for deep-buried tunnels, due to the pressure-arch effect after the tunnel is excavated [27], the load acting on the arch is transferred to the arch foot and the surrounding rock, and the vertical stress of the surrounding rock will be much lower than the calculated value of the whole soil column formula. If the vertical stress is still calculated by $\sigma = \gamma_i H_i$, it will inevitably lead to a small safety thickness of outburst prevention, resulting in potential safety hazards. To avoid this, it is suggested to judge whether the tunnel is deep buried or shallow buried according to the "Code for Design of Railway Tunnel" [28]. For deep-buried tunnels, the vertical stress σ is calculated:

$$\sigma = 0.45 \times 2^{s-1}\gamma\omega. \tag{12}$$

Where γ is the surrounding rock weight, s is the surrounding rock grade, ω is the width influence coefficient, and $\omega = 1 + i(B - 5)$, B is the tunnel width, when $B < 5$ m, take $i = 0.2$; when $B > 5$ m, take $i = 0.1$.

In addition, it needs to be explained that the more the rock mass in the fault fracture zone is broken, the closer the rock mass property is to the silo bulk material and the higher the calculation accuracy of the safety thickness using formula (10); the higher the strength of ordinary surrounding rock, the closer the failure form of outburst prevention rock mass is to shear instability failure, and the more consistent with the calculation conditions of formula (10). Therefore, formula (10) has good adaptability to tensile fault fracture zone with high strength of ordinary surrounding rock.

Compared with the outward inclination of the fault fracture zone, the self-weight stress component $\gamma B\cos\theta$ of the fault fracture zone should also be considered in the stress analysis of the right side of the outburst prevention rock mass when the fault fracture zone is inward inclined, and the mechanical equilibrium equation (8) becomes

$$\left[P_{xy} + (P_W + \gamma B\cos\theta)\sin\theta\right]\frac{\pi D^2}{4\sin\theta} = \pi \mathrm{DS}'\tau. \tag{13}$$

Combined with equation (7), and substituting $P_W = \rho g(Z - d)$ and $S = S'/(\sin\alpha)$, the expression of safe thickness of outburst prevention in the tunnel axis direction when the fault fracture zone incline inward to the tunnel face is derived:

$$S \geq \frac{D}{4\tau\sin\alpha}\left[\frac{\gamma - \rho g - \gamma\mu\cos\theta\sin\theta}{n\sin\theta}\left(1 - e^{-nKZ}\right) + \rho g(Z - d) + \gamma B\cos\theta\right]. \tag{14}$$

When the tunnel axis is orthogonal to the fault fracture zone, the fault dip angle θ is 90°; ignore the effect of groundwater, assume the hydraulic radius of rectangular section $R = \mathrm{BL}/(2(B + L))$, the equation (6) is converted into $P_Z = (\gamma R)/(\mu K)(1 - e^{-(\mu KZ/R)})$, which is the same as equation (1). It can be seen that the basic formula of Janssen's theory is a special case of equation (6).

During the blasting construction of the tunnel in the fault fracture zone, the surrounding rock will be disturbed and damaged, resulting in the reduction of the protection capacity of outburst prevention rock mass. Sheorey [29] found that the disturbance distance is less than 1.5 m. Therefore, take the minimum safety thickness of tunnel outburst prevention as $S + 1.5$ m.

3. Parameter Sensitivity Analysis

According to equations (10) and (14), the factors affecting the safe thickness of tunnel outburst prevention include the parameters of the fault fracture zone: gravity γ, width B, length L, dip angle θ, groundwater depth d, and internal friction angle ϕ_1; tunnel parameters: tunnel diameter D, buried depth Z, cohesion c, internal friction angle ϕ_2, surrounding rock grade s, etc. In addition, it also includes the angle between the tunnel axis and the fault zone α and the inclination direction of the fault fracture zone relative to the tunnel face. The scholars have carried out a lot of research on the variation law of outburst prevention thickness under different tunnel parameters and fault fracture zone parameters [13, 30, 31], which will not be repeated here. This paper focuses on the influence of included angle between tunnel and fault zone α and the inclination direction of the fault fracture zone relative to the tunnel face.

3.1. The Angle between the Tunnel Axis and the Fault Zone. Take the tunnel buried depth 450 m, tunnel diameter 13.2 m, weight 24 kN/m^3, cohesion 1.4 MPa, internal friction angle 30°, and the ordinary surrounding rock grade III. Fault fracture zone has a length of 980 m, a width of 20 m, a dip angle of 48°, weight 21.5 kN/m^3, internal friction angle 48°, groundwater height and tunnel buried depth of the same, and the friction coefficient of the fault fracture zone is 0.25. When tunnel burial depths are 100 m, 200 m, 300 m, 400 m, and 500 m, respectively, the variation law of the critical safety thickness S of outburst prevention with α is shown in Figure 4.

As can be seen from Figure 4, when α is less than 70°, the critical safety thickness S of outburst prevention decreases with the increase of α and at this time, S is sensitive to the

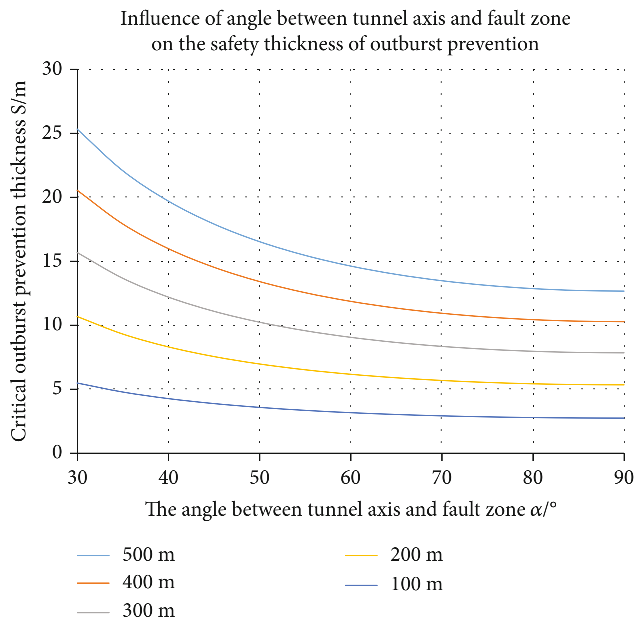


Figure 4: Influence of angle between tunnel axis and fault zone on the safety thickness of outburst prevention.

change of α. When α is greater than 70°, S tends to be stable and basically no longer decreases with the increase of α. According to the above analysis, it can be seen that when the tunnel crosses the fault fracture zone at a small angle, it will have a negative impact on the safety of tunnel outburst prevention and the best angle for the tunnel to cross the fault fracture zone is orthogonal. Figure 4 also shows that when α is the same, the larger the tunnel burial depth is, the larger S is, and the ratio of the increased value of S to the increased value of tunnel burial depth is approximately equal.

3.2. The Inclination Direction of the Fault Fracture Zone. Assuming that the tunnel axis is orthogonal to the fault zone, other parameters are the same as those in "3.1 section." When the fault fracture zone inclines outward and inward relative to the tunnel face, the variation law of S with the dip angle θ of the fault fracture zone is shown in Figure 5.

It can be seen from Figure 5 that in the initial stage, S decreases sharply with the increase of θ and then tends to be stable, which is similar to the effect of α on S. When the fault fracture zone inclines inward, the outburst preventing rock mass needs to bear more gravity action of the fault fracture zone, so that S is greater than the fault fracture zone inclined outward. When θ is equal to 90°, the two have the same effect on the outburst prevention rock mass, and the curve of outburst prevention safety thickness intersects. According to Figure 5, it is also found that the larger the θ, the higher the safety of outburst prevention during tunnel construction.

4. Engineering Project Application

The critical safety thickness is calculated by using the formula proposed in this paper and other commonly used prediction formulas and compared with the numerical simulation result to verify the accuracy of the calculation formula in this paper.

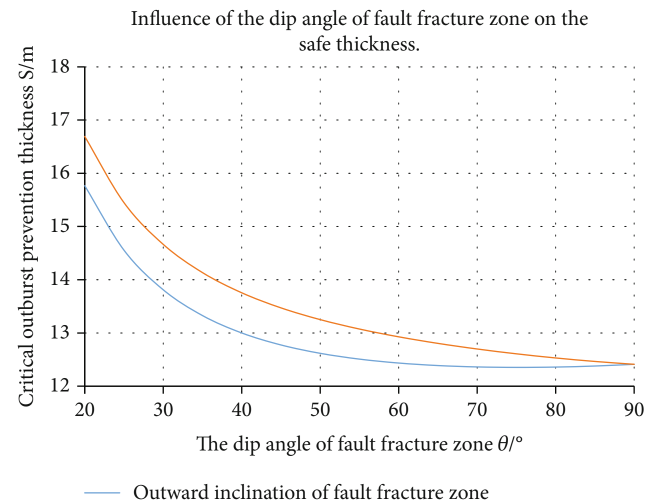


Figure 5: Influence of the dip angle of fault fracture zone on the safe thickness.

4.1. General Engineering Situation. Dechang Tunnel is a long railway tunnel, with a total length of 14280 m, a maximum buried depth of 1030 m, a section excavation width of 12.3 m, and a height of 11.1 m. According to the engineering geological survey, the surface covering layer of the tunnel site is Quaternary Holocene slope residual layer (Q_4^{d1-e1}) silty clay, and the lower layer is Quaternary middle and upper Pleistocene (Q_{2+3}) silty clay and pebble soil, and the underlying bedrock is granite (γ_2^{1}), and surrounding rock grade II-III. The geological section is shown in Figure 6. The tunnel intersects with Gaojiawan fault fracture zone near D2K504+250, and the tunnel is buried at a depth of about 450 m. Gaojiawan fault fracture zone has a strike of N12°E, a dip angle of 48° and an extension length of 980 m. The rock mass of the fault is extremely fractured, mainly composed of fault breccia, and surrounding rock is grade IV. It has a weight of 21.5 kN/m^3, a friction angle of 30°, and the friction coefficient of the fault zone is taken as 0.25. The ordinary surrounding rock of the tunnel is mainly granite, with a grade III, a weight of 24 kN/m^3, a cohesion of 1.4 MPa, a friction angle of 48°, and the equivalent diameter D of the tunnel is 13.2 m. The mechanical parameters of surrounding rock and supporting structure are shown in Table 1.

4.2. Calculation of Safety Thickness. As shown in Figure 7, FLAC 3D numerical simulation is used to study the outburst prevention thickness of Dechang Tunnel, and the tunnel is excavated according to the actual construction method. However, since the width of the Gaojiawan fault fracture zone is more than 100 m, the nodes of FLAC 3D model will be as high as hundreds of thousands, which makes the numerical calculation very difficult. Therefore, to improve the computing efficiency, it is assumed that the fault fracture

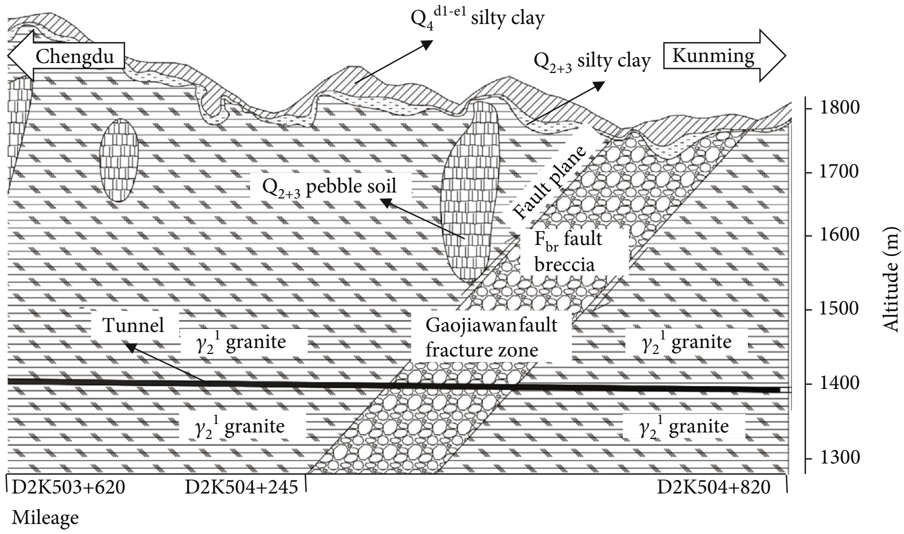


Figure 6: The geological section of Gaojiawan fault fracture zone.

Table 1: Mechanical parameters of surrounding rock and support structure.

Parameter	Ordinary surrounding rock	Fault zone surrounding rock	Initial support	Secondary lining
Weight γ (kN/m^3)	24	21.5	25	26
Elastic modulus E (GPa)	20	5	26	28
Poisson's ratio μ	0.28	0.32	0.2	0.2
Cohesion c (MPa)	1.5	0.6	—	—
Internal friction angle φ (°)	48	30	—	—
Permeability coefficient (m/s)	8×10^{-8}	5×10^{-6}	1×10^{-8}	5×10^{-8}

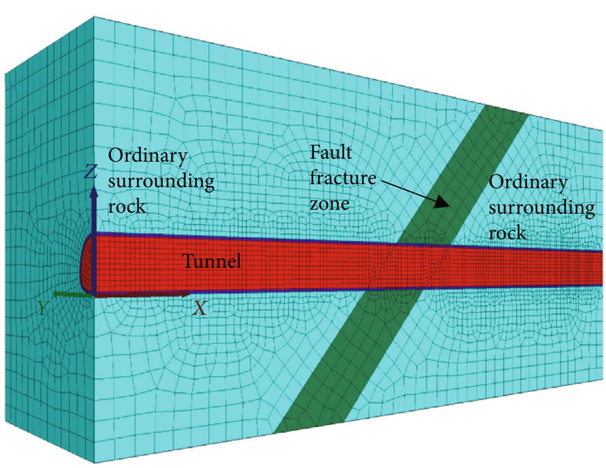


Figure 7: Longitudinal section of 3D numerical model.

zone width is 20 m and the rest of the calculation parameters are the same as those of the Dechang tunnel. With the increase of excavation footage, the plastic zone of tunnel face will gradually increase, and finally connect with the plastic zone of fault fracture zone, indicating that water and mud inrush is about to occur. Therefore, the thickness of the anti-outburst rock disk when the plastic zone of the tunnel face is connected with the plastic zone of the fault fracture zone is taken as the critical safety thickness of outburst prevention.

In addition, the relevant parameters of Dechang Tunnel are, respectively, substituted into the formula (10) in this paper, Meng et al. [16] formula, Fu et al. [17] formula, and the formula for calculating the safe thickness of karst cave outburst prevention proposed by Xu et al. [32] for specific formula expressions). And the relative errors of different calculation formulas are calculated based on the numerical simulation results. The results are shown in Table 2.

As can be seen from Table 2, the Meng formula does not consider the influence of the seepage field in the fault fracture zone and uses the whole soil column formula $\sigma = \gamma_i H_i$ to calculate the vertical stress acting on the outburst prevention rock mass, resulting in a large deviation in the calculation of the shear strength τ of the outburst prevention rock mass, and the predicted safety thickness of outburst prevention is much lower than that of numerical simulation. The S calculated by Fu formula is 10.39 m, which is close to the numerical simulation result of 11.5 m. The calculation result of Xu formula is 8.88 m, which is 2.62 m less than the numerical simulation value, and will lead to the construction of the site on the dangerous side. The formula in this paper takes into account groundwater, the friction between fault fracture zone and ordinary surrounding rock and the

Table 2: Calculation results of the tunnel critical safety thickness S in fault fracture zone.

Calculation method	Numerical simulation	Formula in this paper	Meng formula	Fu formula	Xu formula
S (m)	11.5	11.98	1.93	10.39	8.88
Relative error (%)	—	4.2	83.2	9.7	22.8

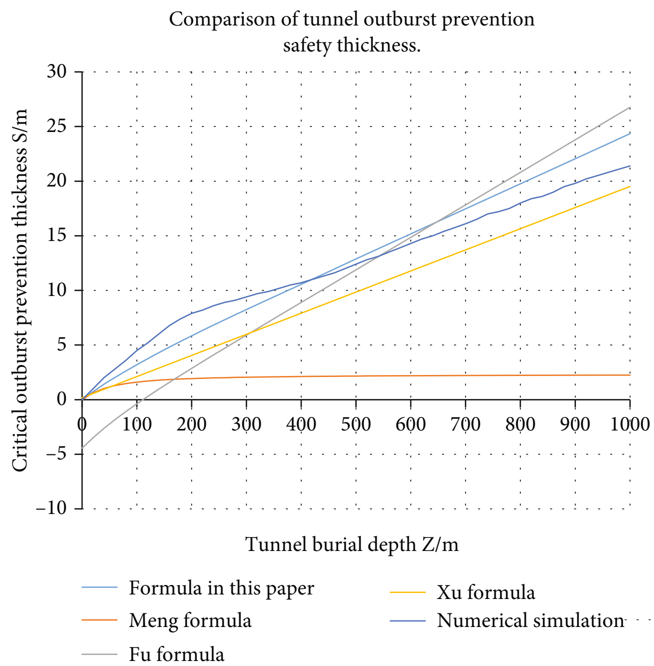


Figure 8: Comparison of tunnel outburst prevention safety thickness.

formula for calculating the shear strength of outburst prevention rock mass is corrected too, which gives the smallest relative error of S and safe calculation result.

Further, the above calculation methods are used to calculate the critical safety thickness of tunnel outburst prevention under different buried depths, and the numerical simulation is used as the benchmark to compare and analyze the different calculation results. The results are shown in Figure 8.

As can be seen from Figure 8, the calculation results of the Fu formula are close to the numerical simulation results when the tunnel burial depth is large, especially in the 400 m-600 m buried depth. However, the formula has a negative value when the buried depth of the tunnel is less than 100 m, which is obviously unreasonable, indicating that this formula is only suitable for the calculation of the safety thickness of the deep-buried tunnel; Xu formula does not consider the influence of the fault fracture zone stress on outburst prevention thickness, so calculation results is about 2 m lower than that of the numerical simulation, resulting in dangerous outburst prevention construction. The predicted value of Meng formula increases with the increase of tunnel burial depth, but soon tend to flatten. When the tunnel depth is less than 50 m, the calculation results of Meng formula are close to the numerical simulation, but the prediction results are much lower than the numerical simulation when the tunnel depth is large. Therefore, this formula is only suitable for the shallow tunnel. The formula in this paper is the closest to the numerical simulation results, and the curves of the two increase approximately linearly with the tunnel burial depth and have good consistency. When the depth is greater than 400 m, the formula in this paper is slightly greater than the numerical simulation, which is conducive to the safety of tunnel outburst prevention.

5. Conclusions

By introducing the traditional silo theory into the fault fracture zone, the in situ stress expression of the water-rich fault fracture zone with a certain dip angle is derived. Then, according to the established mechanical model, the prediction formula of the outburst prevention safety thickness is obtained. The sensitivity of some parameters is analyzed and compared with the numerical simulation and other calculation formulas. The main conclusions are as follows:

(1) The rock mass in the extensional fault fracture zone is fragmented, with low cementation strength, and similar mechanical properties to the silo granular materials. Therefore, Janssen's theory is applied to solve the ground pressure of the water-rich fault fracture zone, providing a new method for calculating the safety thickness of tunnel outburst prevention in the water-rich fault fracture zone

(2) According to the different inclination directions of the fault fracture zone relative to the tunnel face, two mechanical models for calculating the safety thickness of tunnel outburst prevention are proposed. On the basis of Janssen's theory, the formula for calculating the thickness of outburst prevention when the fault fracture zone is inclined outward takes into account the influence factors such as groundwater, "silo wall" friction, the angle between tunnel axis and the fault zone, etc.; when the fault fracture zone inclines inward, the calculation formula also needs to consider the gravity effect of the rock mass in the fault fracture zone, which leads to an increase in the safety thickness of outburst prevention

(3) The parameter sensitivity analysis shows that the sensitivity of the tunnel safety thickness gradually decreases with the increase of the angle α between the tunnel axis and the fault zone and the dip angle θ of the fault fracture zone, and the larger α and θ are, the smaller critical safety thickness is, and the more conducive to safe construction of tunnel

(4) The formula in this paper is applied to calculate the safety thickness of Dechang Tunnel outburst prevention, and compared with other prediction formulas, it is found that the calculation results of the formula in this paper are the closest to the numerical simulation results, and it shows better prediction effect for both deep- and shallow-buried tunnels, indicating that the formula has wider application and higher accuracy

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was financially supported by the National Natural Science Foundation of China (Grant No. 52074042).

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