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Analysis of Deformation and Failure Mechanism of Broken Schist Tunnel under the Influence of Fault Zone

Bo Yang

Chonfar Engineering and Technology Co., Ltd, Changsha 410007, China

*ango198766@163.com

Abstract

The stability of tunnel surrounding rock in the area with regional fracture zone will be affected by rock mass structure, lithology characteristics and geological structure to a great extent. In order to better realize the tunnel construction process, surrounding rock support control and surrounding rock stability evaluation, we must accurately understand the deformation and failure mechanism of tunnel surrounding rock, geological body and engineering geological characteristics and other important factors. This paper systematically studies the distribution characteristics of unfavorable geological bodies in the fault zone, the deformation and failure mode of tunnel excavation, the analysis of influencing factors of deformation and failure, and the deformation and failure mechanism of schist tunnel under the influence of the fault zone, so as to provide a basis for the construction control of highway tunnel in mountainous area affected by the fault zone and the stability evaluation of tunnel surrounding rock. The results show that the deformation and failure of surrounding rock of mountain tunnel in the fault zone are mainly affected by faults, fault fracture zone, weak weathered rock mass, weak structural plane, topographic and structural bias and other factors. The deformation and failure of surrounding rock are mainly in the forms of bending failure, fracture loosening, plastic extrusion, gravity collapse, tension crack failure, shear slip, expansion and internal bulging. The deformation and failure mechanism of tunnel surrounding rock can be summarized into structural plane control type, strength control type, comprehensive type and special type.

Keywords

Slope; Fault Zone; Schist Tunnel; Deformation and Failure; Stability.

1. Introduction

Highway tunnels in mountainous areas of fault zone need to pass through fault zone, secondary fault zone and various structural planes. Under the intersection or cutting of geological structural plane and rock stratum level, there are often fracture developed structural surrounding rocks. After excavation, such surrounding rocks are prone to large deformation, collapse and other damage due to rebound stress and redistribution stress. In order to better study the tunnel fault zone, we can start from the following aspects: (1) the travel speed of the tunnel face when crossing the fault zone; (2) The tunnel passes through different fault zones; (3) The angle between the fault zone and the tunnel axis. In addition, scholars at home and abroad have conducted in-depth research on the special geological type of fault zone, and finally achieved many research results. Song [1] proposed that when there is no fault zone, the displacement of surrounding rock is small; When the inclination angle is 0 °, the displacement change is the largest. After careful research, Wang [2] pointed out that if the full section excavation method is adopted in the construction of crossing the fault fracture zone, when the buried

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depth of the tunnel is less than 200m, 2m step distance should be adopted; When the buried depth is greater than 200m, 3m step should be adopted. Liu [3] proposed that if the double wall heading method can be combined with other settlement control methods and applied to the condition that the tunnel passes through the shallow buried section of the fault fracture zone, ideal results can be obtained. However, if this method is different in the construction process, we should try our best to avoid affecting each other. After studying the pressure distribution of surrounding rock and the occurrence of fault zone, Zhao [4,5] quantitatively analyzed the internal relationship between them. Huang [6] studied the stress state of surrounding rock of Niuhushan tunnel fault by means of numerical calculation and analysis, and reached the following conclusions: the continuity of rock mass medium at the location of this section is destroyed by the fault, so that the horizontal and vertical stresses no longer have good symmetry, and there are local high stress areas at the side wall and arch foot of the fault area, Finally, the displacement of the side wall and arch foot is significantly increased. Zhang and He [7,8] deeply analyzed the three-dimensional numerical results of Silurian stratum displacement and Wushaoling ridge F7 fault monitored on site, studied the three-dimensional deformation law of slate section and fault section by means of mean comparison method, and compared and analyzed the above research results and in-situ stress field inversion results. Zhao and Wang [9,10] studied the construction mechanical behavior and deformation time-space effect by using three-dimensional nonlinear numerical simulation method for deep soft rock tunnel engineering, and finally analyzed and compared the above calculation results with the actual monitoring data of Wushaoling tunnel construction site. The final research results show that the space range of one time of tunnel diameter in front of the construction operation and two times of tunnel diameter behind the construction operation face is the main area that can be affected by the machine in the fault zone of Wushaoling tunnel. And in this space area, with the increase of the working face distance, the surrounding rock stress is gradually released, and the surrounding rock deformation is also gradually increased, and its rheological characteristic curve is basically consistent with the characteristic curve of Burgers model. Li [11,12] took the lead in building a calculation model for the 300m length of the tunnel in order to better simulate the possible impact of the interruption layer and fault fracture zone on the tunnel during the construction process, At the same time, the actual stress state and actual deformation state of lining and surrounding rock in different construction stages of Xinqidaoliang tunnel are simulated with the help of three-dimensional elastic-plastic finite element method. The final research results show that compared with the non fault area, the plastic zone of surrounding rock and tunnel deformation in the area where the fault fracture zone is located are significantly larger. If you want to better release the denaturation energy in surrounding rock and lining, it can be realized by making deformation joints in the fault fracture zone.

To sum up, for mountainous expressway, if it is located in the area with regional fault fracture zone or the area with developed geological structure, the stability of tunnel surrounding rock will be greatly affected by rock mass structure, lithologic characteristics, geological structure and other factors [13,14]. The initial stress field in the fault affected area is very complex, the original rock stress in the tectonic stress field is concentrated, the horizontal stress is often greater than the vertical stress, and the distribution has obvious regionality and anisotropy. The fault zone and its secondary fault zone will produce structural planes of different sizes and levels in the rock mass, making the joints and fissures in the rock mass more developed. At the same time, it will cross or cut with the layers, bedding and schistosity in the rock mass, resulting in poor integrity of the rock mass, increased degree of fragmentation, and reduced macro mechanical strength and engineering performance [15,16]. The quality of surrounding rock has an internal organic relationship with the formation environment, diagenesis and evolution process of geological body. The geological deformation in the fault zone area, such as the compression, folding, mineral particle deformation of rock stratum and the mineral combination formed by metamorphism, directly affects the geological structure type, rock stratum distribution and adverse geological body distribution of tunnel surrounding rock [17].

If we want to better realize the tunnel construction process, surrounding rock support control and surrounding rock stability evaluation, we must accurately understand the deformation and failure

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mechanism of tunnel surrounding rock, engineering geological characteristics of geological body and other important factors [18,19]. This paper systematically studies the distribution characteristics of unfavorable geological bodies in the fault zone, the deformation and failure mode of tunnel excavation, the analysis of influencing factors of deformation and failure, and the deformation and failure mechanism of schist tunnel under the influence of the fault zone. Thus, it provides a solid and powerful basis for the construction control of highway tunnel in mountainous area affected by fault zone and the stability evaluation of tunnel surrounding rock.

2. Influencing Factors of Deformation and Failure of Tunnel Surrounding Rock in Fault Zone

According to the engineering geological characteristics in a large number of fault zone areas, the main adverse geological factors affecting the deformation and failure of tunnel surrounding rock in the fault zone area can be divided into several categories [20-22]: fault and fault fracture zone, weak weathering of rock mass, weak structural plane, groundwater, heterogeneity and anisotropy of rock mass, terrain and structural bias.

3. Deformation Characteristics and Failure Mode of Tunnel Surrounding Rock in Fault Zone

3.1 Deformation Characteristics of Tunnel Surrounding Rock

Surrounding rock deformation is not only an important index for tunnel surrounding rock stability evaluation, but also one of the basic criteria for tunnel design. After tunnel excavation, the deformation of surrounding rock roughly goes through three stages: elastic deformation stage; Coexistence stage of elastic deformation and plastic deformation; Creep deformation is the main stage, plastic and creep deformation coexist, and surrounding rock damage, fracture, extrusion and expansion occur at the same time.

The surrounding rock structure of tunnel in fault zone is mainly divided into four types: massive structure, layered structure, cataclastic structure and bulk structure. According to the hardness of surrounding rock, it is mainly divided into brittle surrounding rock and plastic surrounding rock. The deformation of brittle surrounding rock is mainly elastic deformation and plastic deformation, while the plastic surrounding rock is mainly plastic deformation and creep deformation. The deformation characteristics of tunnel surrounding rock are mainly characterized by large deformation, fast deformation rate, long deformation time, large disturbance range of surrounding rock, fast pressure growth and so on.

3.2 Deformation and Failure Mode of Tunnel Surrounding Rock

Understanding the deformation and failure mode of tunnel is conducive to the selection of reasonable excavation methods and reinforcement measures, especially the timely reinforcement of weak links in tunnel construction, so as to prevent engineering disasters caused by the further development of surrounding rock deformation. The deformation and failure mode of surrounding rock is obviously affected by structural plane, rock hardness and in-situ stress. Combined with the geological characteristics of tunnel surrounding rock and the deformation and failure problems encountered during tunnel construction, the deformation and failure modes are summarized as follows:

(1) Bending failure. In layered and thin rock mass such as schist and shale, bending failure is the main form of surrounding rock deformation and failure. In the area where the horizontal stress of layered rock mass is relatively high or the buried depth of tunnel is large, when the rock layer is parallel or nearly parallel to the tunnel wall, the thin-layer surrounding rock will bend, crack and break under the action of rebound stress after tunnel excavation, and finally squeeze into the tunnel and collapse. Or at the position with large compressive stress concentration around the cavern, such as the corner of the cavern or the position parallel to or close to the maximum stress of the rock mass, the tangential compressive stress exceeds the flexural strength of the thin-layer surrounding rock, resulting in

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bending and internal bulging failure of the surrounding rock. Typical bending failure is shown in Figure 1. In the jointed massive rock mass, the excessive tangential compressive stress causes the fracture of the surrounding rock surface parallel to the surrounding cavern. Some parallel fractures cut the surrounding rock into thin plates with a thickness of several centimeters to tens of centimeters. They often peel off along the wall and are prone to bending failure.

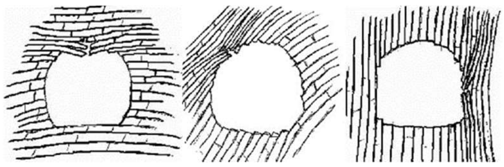

Figure 1. Bending failure mode of layered rock mass

(2) Broken and loose. As the joints and fissures of rock mass in the area affected by the fault zone are relatively developed, fracture loosening is the main form of rock mass deformation and failure. After tunnel excavation, if the stress of surrounding rock exceeds the yield strength of surrounding rock, this kind of surrounding rock will loosen due to shear dislocation along multiple groups of existing fracture structural planes, and form a certain fragmentation loose zone or loose circle around the tunnel. This kind of loose fracture loose dynamic circle itself is unstable, especially when the activity of groundwater is involved, it is very easy to lead to the collapse of the top arch and the instability of the side wall. Because the thickness of the relaxation zone will gradually increase with time.

(3) Plastic extrusion. For soft rock strata such as shale with developed bedding structure, schist with developed schistosity plane, mudstone with poor consolidation and weathered broken interlayer with argillaceous interlayer, after tunnel excavation, when the stress of surrounding rock exceeds the yield strength of surrounding rock, the soft plastic material will be squeezed out to the free space with eliminated resistance along the direction of maximum stress gradient. Especially when these rock masses are rich in water and in plastic or semi plastic state, they are more likely to be squeezed out. This kind of deformation has the characteristics of long duration. If measures are not taken in time, it is easy to cause large deformation of surrounding rock and tunnel collapse.

(4) Gravity collapse. The rock mass is easy to collapse under the action of gravity, which is mainly divided into loose rock mass and local collapse. Local collapse mostly occurs in the arch of the tunnel and sometimes on the side wall, mainly in massive rock mass. Because the rock mass is cut by the structural plane to form unstable structures with different shapes, after the chamber is excavated, the friction between the unstable structures is insufficient, resulting in sliding into the tunnel and collapse. This kind of collapse mainly occurs in class III and class IV surrounding rocks. Arch collapse of tunnel surrounding rock generally occurs in layered rock mass or fragment rock mass, which can be divided into two categories: one is within the tunnel span, only in the arch; The other is the enlarged arch collapse including sidewall collapse. This kind of collapse mostly occurs in soft strata of class IV, class V and below. For shallow tunnels, it often passes through the roof. For deep tunnels, due to the emergence of friction arch, the collapse height is mostly 4 ~ 20m, and the scale is large. The above collapse mode is shown in Figure 2.

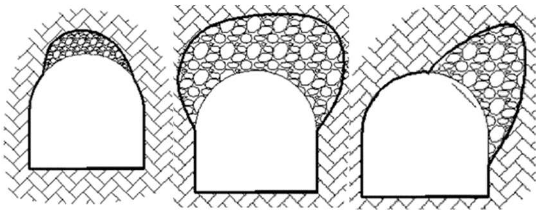

Figure 2. Gravity collapse model of broken loose rock mass

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(5) Tension crack failure. In actual construction, there is a great possibility of tension crack and collapse of the cavern top arch in massive or thick rock mass. When the surrounding rock of the top arch is subjected to relatively concentrated tensile stress, and the tensile stress value is greater than its actual tensile strength, tensile crack failure will occur. In addition, when the tensile stress is small and there is a vertical structural fracture somewhere in the surrounding rock of the top arch, the rock mass will also show a vertical tensile fracture. When there are vertical cracks in rock mass, its center of gravity will shift to a certain extent, resulting in poor stability. At this time, if the tensile strength of the rock mass in the vertical direction is low and the weak structural plane in the horizontal direction is developed, the possibility of roof arch collapse will be greatly increased.

(6) Shear slip. Shear slip failure often occurs in thick layered or massive rock mass. According to the different stress conditions of surrounding rock, it can occur in side wall or top arch. For example, in the stress field where the horizontal stress is greater than the vertical stress, the failure mostly occurs in the parts with high compressive stress concentration and oblique fracture development. In the stress field where the vertical stress is greater than the horizontal stress, the failure mostly occurs in the parts with high compressive stress concentration and steep dip fracture development on the side wall.

(7) Expand the inner drum. For rock layers with strong water sensitivity such as schist, shale and mudstone, after tunnel excavation, the formation of decompression zone on the surface of surrounding rock often leads to the transfer of water from the internal high pressure zone to the surface of surrounding rock, and the bedrock fissure water is concentrated near the tunnel, resulting in strong expansion of expansive minerals in the rock layer and bulging deformation in the tunnel. This kind of expansion deformation is obviously caused by the redistribution of water in the surrounding rock. In addition, this kind of rock mass exposed to the surface after excavation is sometimes more prone to hydration expansion from the air.

4. Deformation and Failure Mechanism of Tunnel Surrounding Rock in Fault Zone

During the excavation of mountain tunnel, some low-strength surrounding rocks may produce plastic deformation and damage to a certain extent because they can not adapt to unloading rebound and other factors. This phenomenon often first appears in the weak parts of the structural plane of the cavern rock mass with low strength but relatively concentrated stress, and then extends to some sub weak parts inside the rock mass. In the actual construction, the above process may occur repeatedly and further trigger a chain reaction, which will eventually lead to loose rings or loose belts near the cavern. The stress released by the loose zone will lead to the redistribution of the surrounding rock stress, reduce the stress in some areas of the surrounding rock surface, but increase the internal stress, which will directly lead to the stress zoning in the surrounding rock. If under the most unfavorable conditions, the stress is less than the rock strength, and the stress will not cause excessive deformation, the surrounding rock of the chamber will remain stable for a long time. When the stress is greater than the strength of rock mass and the rock mass has the trend of instability, the surrounding rock of the chamber must be reinforced and supported [20].

There are two parts of the earliest failure in the process of tunnel excavation: (1) the unstable block formed by the unfavorable combination of structural plane and free face, which leads to the collapse of the block in the surrounding rock. This collapse instability is not caused by local stress concentration, but also has little relationship with the strength of rock blocks, but depends on the combination relationship between joints and tunnel free face. (2) The position where the maximum compressive stress and tensile stress are concentrated. When the control effect of structural plane distribution is weak, such as soft rock tunnel, the rock at the highest compressive stress is easy to enter the stage of plastic deformation and dilatancy deformation, resulting in obvious displacement into the tunnel.

According to the theory of rock mechanics and engineering geology, considering the rock mass structure type, stress characteristics, deformation characteristics, deformation and failure mode of

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surrounding rock of mountain tunnel in the fracture area, and combined with the basic type of tunnel surrounding rock instability, the deformation and failure mechanism of tunnel surrounding rock is summarized into several types as shown in Table 1 according to brittle surrounding rock and plastic surrounding rock respectively [23].

Table 1. Failure mode and mechanism of tunnel surrounding rock

Surrounding rock type	Typical rock	Rock mass structure	Failure mode	Controlling factors	Destruction mechanism
brittleness	Albite schist Quartz schist	Cataclastic structure	Fragmentation and loosening	Shear loosening caused by concentrated compressive stress	Structural plane control type
		Medium thin layer structure	Bending inner drum	Bending and tensile cracking caused by concentrated compressive stress and unloading rebound	Mixed type
		Thick layered structure Block structure	Shear slip	Sliding tensile crack and shear fracture caused by concentrated compressive stress	Structural plane control type
			Splitting and spalling	Compression induced tensile cracking caused by concentrated compressive stress	Strength control type
			Tension crack collapse	Tension crack failure caused by concentrated tensile stress	Strength control type
plasticity	Chlorite schist Pinal schist	Bulk structure	Gravity collapse	Collapse due to gravity	Mixed type
			Plastic flow gushing	Suspended plastic flow of water saturated and loose rock mass	Special type
			Plastic extrusion	Plastic flow caused by concentrated compressive stress	Strength control type
		Layered structure	Expansion inner drum	Water absorption and expansion due to water redistribution	Special type
			Plastic extrusion	Plastic flow caused by concentrated compressive stress	Strength control type

(1) Structural plane control type: the maximum stress that the surrounding rock can bear is limited. When the rock strength exceeds this threshold, the rock block will collapse along the weak structural plane due to gravity. At this time, the weak structure plays a decisive role in the deformation and failure of surrounding rock.

(2) Strength control type: when the rock strength is far lower than the stress borne by the surrounding rock, the deformation and failure of the surrounding rock will be mainly affected by the plastic extrusion of the plastic surrounding rock and the bending and internal bulging of the brittle

surrounding rock. At this time, the shear (tensile) or flexural strength of rock plays a decisive role in the deformation and failure of surrounding rock.

(3) Mixed type: when the strength of rock is much lower than the stress of surrounding rock, the strength of rock mass, structural plane and in-situ stress play a decisive role in the stability of surrounding rock. At this time, the surrounding rock will be damaged by relaxation, collapse buckling, collapse, plastic flow, shear and extrusion, while the more common damages inside the tunnel are bulging at the bottom of the inverted arch and extrusion in the side wall.

(4) Special type: Generally speaking, the deformation and failure of surrounding rock controlled by rock mass strength and structural plane are more common. For the fractured rock stratum containing expansive minerals, in addition to the deformation and failure controlled by the above two factors, internal bulging deformation will also occur. This is because when the stress reduction area is formed on the surface of the surrounding rock, the water in the high stress area inside the surrounding rock will gradually transfer and accumulate on the surface. At this time, the rock stratum on the surface of the surrounding rock will undergo significant internal bulging deformation after water absorption and expansion.

5. Conclusion

This paper summarizes the influencing factors, deformation and failure characteristics, deformation and failure mode and deformation and failure mechanism of the fault zone affecting the deformation and failure of the surrounding rock of xiashanling tunnel. The influence of fault zone on the stability of surrounding rock of mountain tunnel is discussed through qualitative analysis and theoretical analysis. The main conclusions are as follows:

(1) The deformation and failure of surrounding rock of mountain tunnel in the fault zone are mainly affected by faults and fault fracture zones, weak weathered rock mass, weak structural plane, topographic and structural bias and other factors.

(2) The deformation and failure of surrounding rock are mainly in the forms of bending failure, fracture loosening, plastic extrusion, gravity collapse, tension crack failure, shear slip, expansion and internal bulging.

(3) The deformation and failure mechanism of tunnel surrounding rock can be summarized into structural plane control type, strength control type, comprehensive type and special type.

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