Study on slope stability during tunnel construction in water rich soft soil area

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Abstract. Based on the relationship between soil strength index and water content, the stability of tunnel portal slope during tunnel excavation in water rich soft soil area is analyzed according to the change of soil water content under different working conditions during tunnel construction. The results show that the strength index of soil decreases in inverse proportion with the increase of saturation. Reasonable excavation speed or effective dewatering measures are conducive to the self stability of the open cut slope. When the duration of heavy rainfall does not exceed 2 h, the slope is in a stable state; when the duration reaches 10 h, the slope enters the limit equilibrium state; when the duration reaches 18 h, the slope enters the failure state.

1. Introduction
With the rapid development of China's economy and the improvement of its comprehensive national strength, especially the proposal and gradual implementation of the concept of economic internal circulation, the circulation of resources, energy and personnel in various regions is bound to rise to a new level, which will further promote the development of transportation infrastructure. Tunnel engineering is widely used in highway and railway construction because it can overcome the height difference, shorten the connection distance, and is conducive to environmental protection[1]. However, due to the different geological conditions in different regions, various hazards are often encountered in the process of tunnel construction and use. Among them, the instability of portal slope is one of the common geological hazards in the process of tunnel construction and operation and maintenance[2]. Scholars at home and abroad have done a lot of work on the stability of the portal slope. Jun Wang et al.[3] used the improved viscoelastic plastic model to analyze the joint stability of the mountain slope and the top of the slope by FLAC3D, and determined the potential sliding area and the tunnel influence area. Gang Wei et al.[4] analyzed the disaster of water and sand gushing at the exit of shield tunnel, Xiaojun Zhou and others[5] studied and optimized the slope reinforcement parameters at the entrance of mountain tunnel. In this paper, aiming at the problems of tunnel excavation in soft soil and water rich area, through the soil mechanical strength index under dry and wet state, the slope stability under the effect of tunnel excavation and atmospheric rainfall is analyzed.

2. Characteristics of soil mass under rainfall
Tunnel excavation is a long-term process, during which different intensities of rainfall are often
encountered, and rainfall is often one of the important causes of failure of many geotechnical engineering[6], this is because in the process of rainfall, many physical and mechanical indexes of soil will change. Rainfall can directly cause the change of soil water content. According to the soil water characteristic curve, when the water content changes, the matric suction and permeability coefficient in the soil will change, resulting in the change of soil strength and groundwater permeability rate. At the same time, for fine-grained soil such as cohesive soil, the change of water content changes the thickness of weak cohesive water and free water around clay particles, and also affects the mechanical strength index of soil.

2.1. Relationship between soil water characteristics of unsaturated soil

In stable seepage, the permeability coefficient of saturated soil can be regarded as a constant, but in unsaturated soil, it is no longer a constant, but a function of saturated permeability coefficient and matrix suction between particles[7].

\[ k_w = k_s \cdot \frac{1-a\Psi(t)^{n-1} \cdot (1 + (a\Psi(t))^{-m})^2}{(1 + a\Psi(t)^{n})^{-m}} \]  

(Formula 1)

Where: \( k_w \) is the permeability coefficient of unsaturated soil, \( m/s; k_s \) is the permeability coefficient of saturated soil, \( m/s; \) \( \Psi(t) \) is the matric suction, kPa; \( a, m, n \) are the curve parameters, the unit of \( a \) is kPa\(^{-1}\), and the unit of \( m \) and \( n \) is 1.

In the process of rainfall infiltration, the matric suction is a function of water content, which is affected by rainfall intensity, rainfall duration and rainfall location. Therefore, matric suction and permeability coefficient are both functions of time and space. According to Van Genuchten model[8], the relationship between soil water characteristics can be described as

\[ \Theta_w = \Theta_r + \frac{\Theta_s - \Theta_r}{1 + \left(\frac{\Psi(t)}{a}\right)^m} \]  

(Formula 2)

Where: \( \Theta_w \) is the volume water content of soil at any time, \( \text{cm}^3/\text{cm}^3 \); \( \Theta_r \) is the residual water content, \( \text{cm}^3/\text{cm}^3 \), and its size is equal to the porosity of soil.

Formula 2 reflects the change of unsaturated soil water content in the process of rainfall. The water content at any time is not only related to the maximum water content and residual water content, but also related to the negative pore water pressure inside the soil.

2.2. Mechanical test results of unsaturated soil

The existence of groundwater makes the soil have different properties and sizes of pore water pressure. Below the saturation line, the soil is in a saturated state, and the pore water pressure of each point is positive, while above the saturation line, the soil is in an unsaturated state, and the pore water pressure of each point is negative. According to the principle of effective stress[9]:

\[ \sigma' = \sigma - u_w \]  

(Formula 3)

\[ \sigma' = \sigma - u_a + \chi(u_a - u_w) \]  

(Formula 4)

Where: \( \sigma' \) is the effective stress, kPa; \( \sigma \) is the total stress; \( u_w \) is pore water pressure, kPa; \( u_a \) is the pore gas pressure, kPa; \( \chi \) is the effective stress coefficient, 1;

Formula 3 is the effective stress principle of saturated soil, and formula 4 is the effective stress principle of unsaturated soil proposed by Bishop. In unsaturated soil, the negative pore water pressure makes the effective stress of the soil greater than the total stress, which increases the shear strength of soil and is conducive to the self-stability of soil; In the soil below the saturation line, the pore water pressure makes the effective stress of the soil less than the total stress, weakens the shear strength of the soil, and is not conducive to the self-stability of the soil.

From the micro point of view, groundwater has the effect of lubrication between soil particles, which makes the sliding of adjacent soil particles easier; from the macro point of view, the effect of water makes the structure of soil change, which shows the phenomenon of softening. Some scholars[3] have conducted in-depth research on this problem, and obtained the relationship between the strength index
through direct shear test in laboratory, the strength indexes of slope silty clay and completely weathered tuff lava with saturation of 0.3, 0.6 and 1 are obtained, as shown in Table 1.

Table 1. Mechanical index test results

| Geotechnical classification | Saturation | Cohesion (kPa) | Internal friction angle (°) |
|----------------------------|------------|----------------|---------------------------|
| Slope silty clay           | 0.3        | 30.3           | 15.8                      |
|                            | 0.6        | 25.5           | 13.8                      |
|                            | 1          | 22.7           | 13.2                      |
| Completely weathered tuff lava | 0.3 | 24.8           | 24.2                      |
|                            | 0.6        | 20.2           | 19.1                      |
|                            | 1          | 18.2           | 17.8                      |

According to the strength index in Table 1, combined with the curve types in the paper[3], the curves of internal friction angle and cohesion with saturation were obtained by fitting.

Fitting results of slope silty clay:

\[ C = 16.79 + \frac{7.36}{S_r + 0.244} \]

\[ \phi = 12.45 + \frac{0.68}{S_r - 0.097} \]

(Formula 5)

(Formula 6)

Fitting results of completely weathered tuff lava:

\[ C = 15.01 + \frac{3.32}{S_r + 0.039} \]

\[ \phi = 16.28 + \frac{1.31}{S_r - 0.135} \]

(Formula 7)

(Formula 8)

Paper[10] through the direct shear test of unsaturated soil, it is found that the shear strength test results of unsaturated soil are exactly the same as that of soil water characteristic curve, which indicates that the mechanical test results of unsaturated soil are equivalent to that of soil water characteristic. Paper[11] even uses unsaturated strength to invert soil water characteristic curve. Therefore, in the simulation analysis of unsaturated soil, using the unsaturated soil strength curve or soil water characteristic relationship, but considering the relationship between strength parameters and saturation and soil water characteristic curve at the same time is the repeatability consideration of the same problem. Because there is no research on the matric suction of the slope silty clay and the completely weathered tuff lava, based on the saturated and unsaturated regions, this paper uses different strength parameters to assign values to the saturated and unsaturated regions to simulate the change process of the safety of the portal slope in the process of rainfall.

3. Engineering case

Dongfeng Mountain tunnel is located in Changle District of Fuzhou City, which is a 4-hole separated tunnel with an average length of 4059m, belonging to super long tunnel. The tunnel geology is mainly composed of slope silty clay and completely weathered tuff lava. The strength of rock and soil is low, and it softens when it meets with water, and the strength index gradually decreases with the increase of water content, as shown in Table 1. Due to the subtropical monsoon climate and close to the coast, the area has abundant rainfall. At the same time, the tunnel portal is located at the foot of Dongfeng Mountain. Before the tunnel excavation, it belongs to the catchment area at the foot of the mountain. Therefore, the engineering geology and hydrogeology of the site are relatively complex.

According to the regional meteorological data, the maximum rainfall in 24h is 242mm, in order to analyze the most disadvantageous working conditions of tunnel slope, the rainfall is taken as the boundary condition of simulation, and the change of groundwater level in the tunnel at different times is analyzed. The pore pressure and pressure of soil in different time and space are calculated. According to the effective force principle of unsaturated soil, the shear strength of spatial soil at different times is
obtained, and different shear strength of spatial soil is obtained. The stability of tunnel slope at all times.

3.1. Rapid excavation of open cut tunnel section
The site area is mainly composed of slope silty clay and completely weathered tuff lava. Both soil are mainly fine particles. When the excavation speed of open tunnel is fast, the water inside the soil cannot be discharged or the discharge is insufficient to change the distribution of the whole groundwater. Therefore, the change of drainage and groundwater level in the soil during this stage is ignored. The infiltration line in the soil after excavation is the same as before excavation, then the slope stability is as follows.

Figure 1. Pore water pressure diagram of phreatic line after rapid excavation of open cut tunnel
According to the position of water level line, the slope silty clay layer is divided into two layers, the part above the saturation line is treated as dry soil, and its saturation is $S_r = 0$. The soil below the saturation line is considered to be saturated, and its saturation is $S_r = 1$. According to the function relation of formula 5~8, the strength parameters of each soil layer above and below the infiltration line are obtained. The stability of the area above the portal under the condition of rapid excavation is obtained by using the limit equilibrium method, as shown in Fig. 2.

Figure 2. Stability of tunnel top slope after excavation (FS = 0.993)
The analysis results in Fig. 2 show that the stability of the tunnel top slope is 0.993, less than 1.0, which belongs to sliding state and is easy to cause slope instability during rapid excavation in the slope silty clay and completely weathered tuff lava. Therefore, when excavation of slope silty clay is carried out quickly, some engineering measures should be taken in time; or the construction speed should be controlled to discharge the underground water of slope in time. The analysis results show that when the construction speed is slow and the water inside the slope is discharged or led out in time, the maximum slope stability coefficient can be increased to 1.366, reaching the safety standard. The specific construction speed should be combined with the permeability characteristics of the soil for in-depth analysis.

3.2. The change of groundwater in the slope of tunnel excavation
The construction process of tunnel in the dark tunnel section is complex and the construction speed is slow. It is considered that during the tunnel excavation, the internal water of soil mass can be discharged through the side of tunnel and the diameter guide water hole, so the surrounding soil can be drained and consolidated effectively. The infiltration line after excavation is shown in Fig. 3.
The simulation results show that (as shown in Fig. 3), with the advance of the tunnel face, the radial and axial water diversion holes reserved between the tunnel secondary lining and the surrounding rock become the groundwater discharge channels. At this time, the safety factor of the tunnel is 1.366 because the tunnel is in the dry and shallow state.

3.3. Analysis of rainfall infiltration and underground seepage field

But in the actual process, the roof slope is not completely dry. In the long-term construction process, atmospheric rainfall is the main source of water supply for the roof slope. According to the meteorological data of Fuzhou, the maximum daily rainfall in this area is 242mm / D, which is $2.8 \times 10^{-6}$ m / s when loaded on the model boundary.

In the process of rainfall, the slope surface changes from dry state to unsaturated state and saturated state. In the whole process, the volume water content, permeability coefficient and matrix suction are related. According to the permeability characteristics of unsaturated soil and Van Genuchten model[6]. The change of groundwater in the process of rainfall is obtained, as shown in Fig. 5 and Fig. 6.
Figure 5 shows the infiltration of groundwater at each point in the slope after 20 hours of continuous rainfall. The figure shows that at a certain distance from the surface and slope surface, a large amount of precipitation infiltrates into the ground and becomes groundwater. Due to the shallow buried depth of groundwater in situ, the groundwater far away from the tunnel area has formed a hydraulic connection with the surface rainfall, but only a certain thickness of saturated layer is formed on the top slope of the tunnel. With the continuous rainfall, the thickness of the saturated layer increases, and the negative pore water pressure in the saturated layer decreases gradually (as shown in Fig. 6).

3.4. Analysis results of slope dynamic stability
According to formula 3 and 4, when the negative pore water pressure decreases gradually, the effective stress also decreases gradually, and the shear strength of soil decreases gradually. At the same time, with the continuous expansion and extension of the saturated area, the softening area near the slope gradually increases, which is not conducive to the self-stability of the slope. According to the analysis results of groundwater in Section 3.3, combined with the variation law of rock mass strength parameters in softening area, the minimum safety factor of tunnel top slope under continuous rainfall of 2h, 4h, 6h, 8h, 10h, 12h, 14h, 16h, 18h and 20h is calculated as shown in Fig. 7.
Figure 7. Safety factor of different rainfall time

When the rainfall duration is 2 hours, the minimum safety factor of the tunnel top slope is 1.254, which still meets the requirements of the specification; when the rainfall duration is 8 hours, the minimum safety factor of the slope is 1.11, which is still in the stable state; when the rainfall duration is 10 hours, the minimum safety factor of the slope is 1.049, which is in the limit equilibrium state; when the rainfall duration is 18 hours, the slope is in the limit equilibrium state. The minimum safety factor is 0.994, and the slope is unstable.

4. Conclusions

The stability of portal slope is a common geological problem in tunnel excavation in soft soil area. In this paper, according to the variation characteristics of groundwater and the relationship between soil mechanical properties during tunnel excavation in water rich soft soil area, considering the influence of construction and atmospheric rainfall, the stability of portal slope in different states is obtained.

- The strength parameters of soft clay decrease approximately in inverse proportion with the increase of saturation (water content). Through laboratory tests, the relationship between strength index and saturation of slope silty clay and completely weathered tuff lava is established. The relationship curve shows that with the increase of saturation (water content), the strength parameter of soil decreases gradually.
- Rapid excavation of open cut tunnel section in soft clay area is not conducive to the self-stability of tunnel portal slope. The permeability coefficient of soft clay in Dongfeng Mountain tunnel is very small. When the excavation speed of open cut tunnel is too fast, the seepage field inside the soil cannot be adjusted. At this time, the minimum safety factor of the portal slope is 0.993, which is in sliding state.
- The excavation of the tunnel in the dark tunnel section is beneficial to the drainage of the soil layer at the top of the tunnel and the stability of the slope. In the vicinity of the tunnel entrance, the water content of the soil layer at the top of the tunnel and the stability of the slope can be significantly reduced by setting radial and axial drainage holes.

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