Research Article

Deformation Characteristics and Influence Factors of a Shallow Tunnel Excavated in Soft Clay with High Plasticity

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A series of problems, including large deformation of supporting structures, shotcrete peeling, and yielding of the steel frame, occurs constantly during tunnel construction in soft clay layers. These problems considerably raise the risk of tunnel construction. Thus, the deformation characteristics of soft clay around the tunnel during construction must be investigated to guarantee safety. In this research, a field test was conducted on 50 sections of a tunnel, which was built in high-plasticity clay layers. Then, the deformation characteristics of surrounding rocks and influencing laws caused by burial depth, invasion thickness of soft clay, and atmospheric precipitation were discussed. Results indicated that surrounding rocks are most likely to undergo large deformation during tunnel construction when the burial depth of tunnel ranges from $1.5D$ to $2.5D$ (D is the tunnel excavation span). Tunnel deformation also increases rapidly when the invasion thickness exceeds 60% of the tunnel height. The ratio between clay thickness and burial depth of the tunnel is another crucial index that could cause a large tunnel deformation as it exceeds 0.25. In addition, a significant correlation was observed between tunnel deformation and rainfall during the construction period. The deformation of surrounding rocks increases rapidly with rainfall and will continually develop for 1-2 weeks when the average daily rainfall is greater than 4 mm.

1. Introduction

High-plasticity soft red clay is a typical soil with high water content and porosity and loose structure, and it easily becomes muddy when absorbing water but shrinks when losing water. A series of problems, including large deformation of supporting structures, shotcrete peeling, and yielding of steel frame, occurs constantly during the tunnel construction in soft red clay with high-plasticity layers. These problems considerably raise the risk of the tunnel construction [1, 2]. With the continuous development of China's infrastructure construction, the number of tunnels constructed in similar soft clay layers also increases [3]. According to incomplete statistics, tunnels constructed in

soft clay layers account for more than a third of all railway tunnels under construction or planned in China [4].

Therefore, the deformation characteristics of tunnels constructed in soft clay layers is a constant research focus in tunnel engineering. Lueprasert et al. proposed a method for predicting the deformation of soft tunnels on the basis of the horizontal and vertical tunnel contraction and elongation [5]. He et al. simulated the deformation and failure process of weak surrounding rocks with an improved discontinuous deformation analysis method and the discontinuous deformation analysis for rock failure (DDARF) joint simulation model, which can simulate the deformation and failure of tunnel surrounding rocks [6]. He et al. established a modified formula for calculating the deformation of

surrounding rocks with time and space effects of tunnel excavation [7]. Feng et al. studied the deformation of surrounding rocks in a cold region tunnel and established an elastic-plastic calculation model of surrounding rocks in cold regions [8]. Zhang et al. fitted the deformation data of tunnel surrounding rocks and developed an empirical formula for estimating final deformation [9]. Sainoki et al. proposed a nonlinear rheological model that can describe the three-stage creep behavior of weak tunnel surrounding rocks [10]. Paraskevopoulou and Diederichs considered the time effect of weak surrounding rock deformation and proposed a simplified method for calculating tunnel deformation [11]. Zhang et al. simulated the time-varying process of soft surrounding rock deformation based on a theoretical model for thermodynamic state variables [12]. Feng et al., based on FLAC-3d numerical simulation, indicated that the large deformation in the contact zone of soft and hard rock and deformation and failure of surrounding rocks of tunnels belong to a type of soft-rock plastic extrusion failure [13].

Numerous research works have been conducted on the influencing factors of surrounding rock deformation during tunnel construction [14]. Zhu and Li studied and analyzed the influences of different properties of surrounding rock, section size, and buried depth of the tunnel on deformation of surrounding rocks and considered that the fundamental reasons for large deformation include the weak surrounding rocks and large ground stress [15]. Vu et al. studied the influencing laws of burial depth, lining thickness, and section size on tunnel deformation in soft soils [16]. Bizjak and Petkovsek observed that when considering 30%–35% relaxation of surrounding rocks, the numerical calculation result is closest to the measured value [17]. Xue et al. considered data mining technology as basis and pointed out that the largest factor affecting surrounding rock deformation of tunnels in loess is the close time of support, followed by burial depth and groundwater [18]. Han et al. studied the influence of water content of surrounding rocks on tunnel deformation through uniaxial and triaxial tests and observed that the strength of surrounding rocks will reduce by 40% under the condition of high water content, which may cause failure of surrounding rocks [19]. Li et al. considered that groundwater seepage will affect the deformation of tunnel surrounding rock. If groundwater seepage is considered in numerical calculations, the results will be closer to the measured values [20]. Liu et al. based on their study on numerical simulation results and engineering data concluded that an increase in grouting pressure in shield construction can reduce the deformation of surrounding rocks [21].

Abundant research works have been performed on the deformation characteristics of tunnel surrounding rock. However, most of the studies are based on numerical simulation or theoretical deduction with a large degree of simplification and thus lacking the necessary practical verification. The factors influencing the deformation of surrounding rocks of tunnels construed in the soft clay layer are incomprehensible, and most of the research results revolve around the influence law of time and burial

depth on deformation. In addition to the above factors, atmospheric rainfall is a crucial factor for the large deformation of surrounding rocks [22], especially when the tunnel is shallowly buried. However, limited reports are available regarding the influencing law of atmospheric rainfall on deformation of surrounding rock. To this end, based on actual engineering, field tests on surrounding rock deformation during the construction process in 50 tunnel sections were carried out, and the test results were summarized and analyzed. This paper mainly discusses the evolution trend of surrounding rock deformation during tunnel construction in soft red clay with high plasticity and the influencing laws of burial depth, invasion thickness of soft clay, and atmospheric precipitation on deformation.

2. Project Overview

The Qinggangshan tunnel is located in the Chongqing–Guizhou railway line in Western China and measures 2331 m in length. In the tunnel exit section (605 m), the average burial depth is less than 20 m, indicating a shallow or ultrashallow buried tunnel, as illustrated in Figure 1. According to the preliminary geological survey and findings during the construction process, about half of the upper part of the tunnel excavation area occupies the high-plasticity soft red clay layer. Soft red clay with high plasticity is a typical soil with high water content and porosity and loose structure; it easily becomes muddy when absorbing water and shrinks when losing water (Figure 2).

In the 50 tunnel sections used for the field test, we adopted the same construction method, which is the center cross diagram (CRD) method, and supporting structures. Figure 3 demonstrates the construction procedure and supporting structure. To comprehend the deformation of tunnel surrounding rocks in time, the vault crown settlement and horizontal convergence deformation of the whole construction process of the Qinggangshan tunnel were tracked and monitored. Figure 4 exhibits the location of the monitoring site. The longitudinal spacing of the monitoring section is 5–10 m. The data used in this paper were the monitoring findings of 50 sections in the range of DK211 +000 to +400 of the tunnel.

3. Analysis of Deformation Test Results on Surrounding Rocks

During the field test, the duration of tunnel deformation monitoring was determined according to the deformation condition and construction progress of the tunnel section. Generally, the monitoring lasted for 30~50 days since the excavation and then moved to the next tunnel section. Thus, the tunnel deformations presented for Figures 5–12 are the final deformation value measured on the different tunnel sections.

3.1. Typical Deformation Temporal Process. Figure 13 demonstrates the curves for vault crown settlement and

FIGURE 1: Longitudinal profile of shallowly buried section of Qinggangshan tunnel.

FIGURE 2: Soft plastic red clay.

FIGURE 3: Construction procedure and supporting structure.

FIGURE 4: Position of the monitoring site.

FIGURE 5: Continued.

FIGURE 5: Distribution diagram of deformation end value along the longitudinal axis of the tunnel: (a) vault crown settlement; (b) convergence of the left pilot tunnel; (c) convergence of the right pilot tunnel.

horizontal convergence of 50 sections of the Qinggangshan tunnel against time. By comparing the test data between Figures 13(a) and 13(b), the vault crown settlement shares a consistent evolution trend with horizontal convergence. As the curves exhibited various evolution trend, they were classified into three categories on the basis of initial deformation rate: stable, sustainable, and rapid types (as shown in Figures 13(a) and 13(b)).

The deformation rate for the curves of the stable type decreases rapidly with small occasional fluctuation (as shown in Figure 14, curves a and b). The ultimate deformation values of the curves are relatively limited and less than 150 mm. Tunnel deformation is acceptable in such condition as the deformation value remains below the reserve space (as shown in Figure 14, line f). The results indicate that the safety of tunnel construction could be guaranteed with proper

FIGURE 6: Distribution of deformation with burial depth: (a) distribution of the ultimate deformation value with burial depth; (b) distribution of average exceeding deformation with burial depth.

FIGURE 7: Schematic of weak surrounding rock deformation mechanism of the Qinggangshan tunnel section.

supporting structures and construction method designed on the basis of surrounding rocks.

The deformation value for the curves of the rapid type (as shown in Figure 14, curve c) increases substantially in the

early stage. Then, the deformation rates gradually decrease. A large deformation that exceeds the reserve space is usually observed in this condition along with the yielded supporting structures, which could probably cause the tunnel to collapse.

FIGURE 8: Invasion thickness definition schematic.

FIGURE 9: Relation between the surrounding rock deformation and invasion thickness and invasion ratio: (a) invasion thickness; (b) invasion ratio.

The curves of sustainable type feature relatively constant deformation rates, and the deformation value increases linearly with time until failure of the supporting structures (as shown in Figure 14, curve d). The findings indicate the mismatch between supporting structures and construction method and mechanical properties of surrounding rocks in this condition. As a result, the safety of tunnel construction remains unguaranteed. However, the deformation rate of this type is relatively slow. Deformation usually lasts for almost two weeks until the reserve space is exceeded. Therefore, the evolution trend could be transited into the stable type if the reinforced measures for supporting

structures are considered timely based on the monitoring information (shown in Figure 14, curve e). In return, engineering accidents can be avoided.

Based on the above analysis, which considered the bearing capacity of surrounding rocks and construction safety and efficiency, the corresponding suggestions for tunnel construction were given for the different types of curves (Table 1).

3.2. Influencing Characteristics of Tunnel Burial Depth on Deformation of Surrounding Rocks. Figure 5 demonstrates

FIGURE 10: Relationship between λ and surrounding rock deformation.

FIGURE 11: Distribution diagram of surrounding rock deformation and monthly precipitation during construction.

the distribution diagram of vault crown settlement and horizontal convergence (left and right pilots, respectively) of 48 monitoring sections along the longitudinal axis of the tunnel. Figure 6 shows the distribution of deformation with burial depth. Specific data in Figure 6(a) were obtained from literature [23], of which the surrounding rock condition is similar to that of the Qinggangshan tunnel, and the construction method is the same.

As shown in Figure 5, the ultimate deformation of surrounding rocks varies significantly with different burial

depths. Statistics show that tunnel deformation increases to a considerable extent at a burial depth of around 20 m ($2D$), demonstrating a notable pattern of mutation. As shown in Figures 6(a) and 6(b), although the deformation values with different burial depths are discrete to a certain extent, the average exceeding deformation (deformation exceeds the reserve space) of the surrounding rock (with vault crown settlement as an example) is much higher than those of other burial depths when the tunnel burial depth ranges from 15 m to 25 m. From another perspective, the findings indicate the

FIGURE 12: Relationship between surrounding rock and deformation daily precipitation.

FIGURE 13: Continued.

FIGURE 13: Deformation curve of surrounding rocks in the Qinggangshan tunnel exit: (a) settlement of vault crown; (b) horizontal convergence.

FIGURE 14: Deformation curve shape.

high likelihood of large deformation in this period. On the contrary, exceeding of deformation rarely occurs when the burial depth is greater than $2.5D$.

Based on the above analysis, the characteristics of surrounding rock deformation against burial depth of the tunnel can be obtained. The exceeding deformation is centered on the section with a burial depth range of $1.5\text{--}2.5D$. The ultimate deformation value decreases significantly as burial depth exceeds $2.5D$, indicating the low possibility of exceeding deformation. The mechanism behind this phenomenon can be explained by the arch effect, as shown in Figure 7:

- (i) The supporting structures need to bear the whole weight of the overlying soft clay, as the burial depth is less than $1.5D$, which is insufficient to produce the arch effect. However, tunnel deformation can still be controlled with the proper design of supporting structures as the load caused by the overlying clay is limited in this situation.
- (ii) The arch effect can be formed when the burial depth is larger than $2.5D$. The supporting structures only bear the weight of clay within the arch in this condition. Therefore, the final tunnel deformation is relatively small compared with that of other burial depths.
- (iii) The most unfavorable situation for tunnel deformation is at burial depths ranging from 1.5 to $2.5D$. The arch effect has not been formed, and the load of overlying clay is relatively large. Thus, the deformation of the supporting structure increases tremendously, which would cause tunnel collapse.

3.3. Influencing Characteristics of Soft Surrounding Rock Invasion Thickness on Deformation. For convenience of analysis, the thickness of the overlying clay that invades the tunnel section is defined as invasion thickness h and the ratio of invasion thickness to the height of the tunnel vertical span h_0 is defined as the invasion ratio $\eta = h/h_0$, as presented in

TABLE 1: Characteristics of deformation evolution of the Qinggangshan tunnel exit section and suggestions for construction.

Deformation type		Deformation characteristics		Suggestions for construction
Type	Form	Initial rate	Development trend	
Stable development type	“a” line	Slower	The rate decreases and stabilizes rapidly	Increase the construction footage or weaken the strength of support
	“b” line	Slow	The rate increases slowly and then decreases quickly and tends to be stable	Maintain the support strength and construction method in the current state and ensure that support is carried out in time
Rapid development type	“c” line	Faster	The rate decreases slowly or unchanged, develops rapidly, and breaks through critical value in 1-2 days	Unable to do monitoring and early warning, stop construction, and use high strength temporary support
Sustained development type	“d(e)” line	Fast	The rate is relatively stable and lasts for a long time (about 2 weeks); the deformation value increases continually	Strengthen the monitoring and early warning, close the support structure in time, or take some strengthening measures

Figure 8. Figure 9 illustrates the relation between the surrounding rock deformation and invasion thickness and invasion ratio.

Tunnel deformations, including vault crown settlement and horizontal convergence, increase consistently with increasing invasion thickness and invasion ratio. The deformations are relatively limited when the invasion thickness is lower than 6 m, or the invasion ratio is lower than 0.6. However, as invasion thickness exceeds 6 m, the deformations are highly likely to increase rapidly, which could probably cause the failure of supporting structures. Thus, necessary reinforcement measures should be adopted promptly to guarantee the bearing capacity of the support system on the basis of monitoring information if the invasion thickness exceeds 6 m, or invasion ratio exceeds 0.6.

Based on the above analysis, the deformation of the shallow tunnel built in soft clay is simultaneously affected by burial depth and invasion thickness. A combined parameter was defined as the ratio of invasion thickness to burial depth ($\lambda = h/H$) to further investigate the characteristics of tunnel deformation. Figure 10 demonstrates the correlation between tunnel deformation and parameter λ . As observed, tunnel deformation is acceptable when the value of λ is less than 0.25. In this period, λ shows negligible influence on tunnel deformation which is within the reserve space. Then, the tunnel deformation presents a steep increase and exceeds the allowable deformation when λ is larger than 0.25. An exponential-type relation was observed between deformation and parameter λ . The equation of the fitting line is expressed in the following equation:

$$\log_{10} U = 0.003 \exp\left(\frac{\lambda}{0.065}\right) + 1.323. \quad (1)$$

3.4. Analysis of the Influence of Atmospheric Rainfall on Surrounding Rock Deformation. Figure 11 exhibits the distribution of tunnel deformation and rainfall during construction. Figure 12 illustrates the relationship between daily rainfall and tunnel deformation. The rainfall data, which is the average value from 1951 to 2008, were obtained through the website of “Sina weather.” The red line in Figure 12

indicates the evolution trend of tunnel deformation against daily precipitation.

As shown in Figure 11, a significant positive correlation was observed between tunnel deformation and the corresponding monthly rainfall during the construction process. The maximum deformation appeared in the tunnel section that was built in the month with the maximum rainfall, which could easily induce tunnel collapse. On the contrary, tunnel deformation was relatively small if the tunnel section was built in the month with limited rainfall.

The maximum rainfall appeared in mid-June. However, the tunnel section with maximum deformation was built in early July. A time difference of around two weeks was noted between the maximum rainfall and tunnel deformation, and this result was caused by the seepage process of rain.

On the basis of the statistics presented in Figure 12, the rain causes limited influence on tunnel deformation when the daily rainfall is lower than 4 mm. Then, the deformation increases markedly when the rainfall ranges from 4 mm to 8 mm. In this period, the rainfall not only increases the bulk weight of clay but also weakens the mechanical properties of the overlying clay; both results are unfavorable to tunnel stability. However, deformation is insensitive to rainfall when it is larger than 8 mm as clay is fully saturated in this condition. Thus, based on the above analysis, the corresponding suggestions for tunnel construction are given according to the different values of rainfall in Table 2.

4. Discussion

As for the development characteristics of surrounding rock deformation, numerous relevant studies have drawn the same conclusion as this paper. Meng et al. [24] and Wang et al. [25] conducted a field test and pointed out tunnel deformation will gradually converge and stabilize in 20~35 days, on the premise that the supporting structure is strong enough to bear the load of surrounding rocks. This deformation characteristic is consistent with that of “stable development type” in Section 3.1. However, tunnel deformation is influenced by various factors, including the burial depth, invasion ratio, and rainfall. Thus, a different evolution trend of deformation, such as rapid

TABLE 2: Suggestion for construction of shallowly buried soft surrounding rock tunnel during atmospheric rainfall.

Daily precipitation (mm)	Influence degree	Suggestions for construction
≤ 4	Small impact	Can maintain the previous state
> 4	Significant impact and 1-2 weeks of lag time	Shorten the excavation footage, reinforce the support structure, and strengthen deformation monitoring in the next 2 weeks

type or sustainable type, would appear even with the same supporting structures and surrounding rocks conditions. Then, corresponding measures should be considered to strengthen the supporting structures to control the tunnel deformation and guarantee safety.

Most previous studies adopted numerical analysis to investigate the influence of burial depth on the surrounding rock deformation and thus cannot consider the arching effect. The conclusions based on field test data in this paper present a more realistic relationship between the surrounding rock deformation and buried depth of the tunnel. In addition, Wei collected data from 27 field measurement points, as shown in Figure 15 [23, 26]. Results showed that the maximum ground settlement occurred when burial depth ranged from $1.25D$ to $2D$. Notably, ground settlement decreases as burial depth continually increases. This phenomenon is consistent with the conclusion presented in Section 3.2, further verifying the reliability of the test results in this paper.

As stated by Wei, rainfall would increase the bulk density of clay and weaken its mechanical strength, which could result in rapid load increase on the supporting structures and large tunnel deformation [23, 26]. The statistics presented in Section 3.4 show a consistent trend for tunnel deformation against rainfall. Thus, rainfall significantly influences the deformation of soft surrounding rocks during tunnel excavation. However, this topic is rarely discussed in existing research. This paper presented a detailed analysis of the influence of rainfall on tunnel deformation, and the findings could provide reference to relevant studies.

5. Conclusion

- (1) According to the deformation characteristics of surrounding rock against time, the deformation of the tunnel constructed in the soft layer can be classified into three categories: stable, sustainable, and rapid types. In tunnel construction, the rapid type should be prevented. The sustainable type can be transited to the stable type with carefully designed reinforcement measures, which is the most ideal state for tunnel construction as the bearing capacity of surrounding rocks is fully used. The supporting system and construction method of tunnel for the stable type, which is unfavorable to take advantage of the bearing capacity of surrounding rocks, are highly conservative and expensive.

FIGURE 15: Distribution of ground settlement with ratio of burial depth to tunnel span [26].

- (2) Tunnel deformation can be well controlled with the proper design of supporting structures when the burial depth is less than $1.5D$. Although the arch effect cannot be formed in this condition, the load caused by the overlying clay is relatively limited. The arch effect will be formed when the burial depth is larger than $2.5D$. The supporting structures only need to bear the weight of clay within the arch in this condition. Therefore, the final tunnel deformation is relatively small compared with other burial depths. The largest deformations usually exceed the reserve space concentrated on the section at burial depth range of $1.5-2.5D$. The arch effect has not been formed in this condition, and the load of overlying clay is relatively large, with both increasing tunnel deformation. Thus, proper reinforcement measures should be implemented to improve the strength of the support system, and more attention should be paid to monitor tunnel deformation in this situation.
- (3) Deformations are relatively limited when the invasion thickness is lower than 6 m. As the invasion thickness exceeds 6 m, deformations are highly likely to increase rapidly. Combined parameter λ shows minimal influence on tunnel deformation when the value is lower than 0.25. However, tunnel deformation presents a steep increase and exceeds the allowable deformation as λ becomes larger than 0.25. Therefore, deformation monitoring must be strengthened, and timely reinforcement measures must be applied if invasion thickness exceeds 6 m or when λ reaches more than 0.25.
- (4) A significant positive correlation exists between the deformation of surrounding rock and rainfall during construction. The rain shows limited influence on tunnel deformation when the daily rainfall is lower than 4 mm. Then, deformation increases markedly when rainfall ranges from 4 mm to 8 mm. A time difference of around two weeks exists between the maximum rainfall and tunnel deformation, and this finding is caused by the seepage process of rain. However, deformation shows no sensitivity to the

rain when it is larger than 8 mm as the clay is fully saturated in this condition. The tunnel can be constructed normally when the daily rainfall measures less than 4 mm. However, if the daily rainfall amounts to more than 4 mm, the excavation length of the step should be shortened in the next two weeks, and support and monitoring should be strengthened.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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