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Deformation mechanism and collapse treatment of the rock surrounding a shallow tunnel based on on-site monitoring

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Abstract: When tunnels are constructed at shallow depths in areas with poor geological conditions, such as portal sections, valleys and hillsides in regions with granitic bedrock, considerable excavation-induced deformation of the surrounding rock may occur, potentially resulting in tunnel collapses. The main reason for these problems is the lack of understanding of the deformation mechanism and evolution of the soft granitic rock surrounding the tunnel and the adoption of inappropriate construction technology and methods. This article analyzes the deformation mechanism of the rock surrounding a shallow tunnel based on in situ monitoring data as a case study and suggests that certain measures should be taken to effectively control the deformation of the surrounding rock and to minimize the potential for tunnel collapse. The results show that the deformation of the granitic soil surrounding the tunnel can be divided into three stages: the rapid deformation stage, the slow deformation stage and the stabilization stage. Appropriate construction methods should be carefully selected to ensure safety during tunnel excavation in the first stage. To avoid secondary disasters caused by tunnel collapses, three treatment measures may be implemented as part of safety management: enhancing the monitoring of the surrounding rock deformation, adjusting the construction methods and optimizing the support systems. In particular, accurate monitoring data and timely information feedback play a vital role in tunnel construction. Therefore, engineers with considerable engineering experience and professional knowledge are needed to analyze the monitoring data and make accurate

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predictions of tunnel deformation to ensure that reasonable measures are taken in the process of shallow tunnel excavation.

Keywords: Shallow tunnel; Surrounding rock deformation; Field monitoring; Treatment for collapse; Information feedback

Introduction

In shallow tunnels, accidents usually occur during excavation, resulting in a potential safety hazard that can cause construction delays and loss of life and property. (Zhang et al. 2018) counted and analyzed 89 road tunnel construction accidents in China in the past 10 years; among these accidents, collapse accounted for 55%. Some specific information about the soil or rock is normally obtained by drilling test borings; if the engineering properties of the surrounding rock are overestimated and there is a lack of effective measures to restrict the deformation of the surrounding rock in the design of the support structure and construction scheme, a collapse will occur (Wu et al. 2009; Hou et al. 2018).

With the continued development of railway and highway infrastructure, many tunnels have been constructed in areas with challenging geological conditions, such as tunnel entrances, mountainsides and valleys. In particular, because of the complicated geological conditions of shallowly buried tunnels, the deformation mechanism of the surrounding rock during actual construction has been studied in many areas (Huang et al. 2008; Xiao et al. 2016; Cao et al. 2018; Hernández et al. 2019). In shallow or ultrashallow tunnels, due to the associated poor geological conditions, surrounding rock instability and unsymmetrical loading, the bearing arch of the tunnel cannot be formed effectively, and construction may cause a large additional load that results in excessive deformation or partial collapse of the tunnel face during the excavation (Tang et al. 2018; Shi et al. 2019).

Issues related to the deformation mechanism of surrounding rocks have attracted the interest of many researchers, and numerous theoretical models, numerical simulations and experiments have been performed (Zhang et al. 2009; Wang and Zhu (2010); Yang et al. 2013; Liu et al. 2015; Lei et al. 2015; Kaya et al. 2019). Furthermore, accurately determining or predicting the deformation of the surrounding rock is essential to ensuring the safe construction of a shallow mountain tunnel, so numerous methods for predicting surrounding rock deformation have been studied and reported (Peck 1969; O'Reilly et al. 1982; Rankin et al. 1988; Kong et al. 2018; Liu et al. 2020). Several research projects have underscored the importance of on-site monitoring to study the deformation of surrounding rocks and have proposed measures to ensure safe construction during tunnel excavation (Wang et al. 2005; Kontogianni et al. 2005; Zhou et al. 2017). Indeed, on-site monitoring has proven to be a very efficient way to study the deformation of the surrounding rocks during tunnel excavation and the appropriate measures to take to prevent construction accidents; additionally, on-site monitoring can provide data for safety management throughout the tunnel construction process.

Although research on the deformation mechanism of rocks surrounding shallow tunnels has been conducted and some achievements have been made, models applicable to either rock or clay cannot be directly applied to granitic soil (Kim et al. 2019). Because brownish yellow granitic soil contains clay and acts like a cohesive soil, when water seeps into it, its engineering properties are as unfavorable as those of soft clay, which results in the frequent occurrence of tunneling accidents (Fu 2019).

Investigation of the deformation mechanism of granitic soil will provide information to prevent construction accidents during the construction of a shallow tunnel in granitic soil. During shallow tunnel excavation, appropriate decisions and effective measures are made to ensure the safety of construction activities in response to encountering various risks. An improper measure may lead to considerable economic loss, time overrun, and even casualties (Li et al. 2014). Advanced support structure systems and proper construction methods have proven to be effective in a number of cases (Ma 2006; Lai et al. 2018; Xiao et al. 2019; Wang et al. 2019). However, collapse accidents are a common threat during shallow tunnel construction and are not as thoroughly studied as the deformation of the surrounding rock. Consequently, only a small amount of research has been devoted to determining effective treatments for construction accidents in granitic soil tunnels. This research focuses on the deformation mechanism of the surrounding rock and collapse-prevention measures in shallow tunnels. Based on the real-time monitoring of tunnel crown settlement and surface settlement during tunnel construction, an analysis of the deformation characteristics of a shallow tunnel in granitic soil, considering the unique geologic conditions, different excavation methods and support technology, is provided. The aim of the present study is to assess the behavior of the tunnel face during excavation and provide measures to prevent and treat collapse accidents in a granitic soil tunnel. Finally, the importance of field monitoring, measurement and related information feedback during shallow tunnel construction is discussed.

1 Study Area and Methods

1.1 Study area

The Jialongzhang tunnel is located in Dongyuan County, Guangdong Province, South China, approximately 250 km from Guangzhou city, the capital of Guangdong Province. The study area is located at 115.1780°E and 23.7750°N and is in a hilly area. The tunnel entrance is located in Jialongzhang village, and the exit is located at Zhangjiao forest farm (Figure 1 and Figure 2). The surface water system in the area is fairly well developed and is part of the Pearl River water system. There is a nearly east-west gully on the surface of the tunnel entrance and a nearly east-west gully on the surface of the right side of the tunnel exit. Both gullies are nearly parallel to the tunnel line, and the water flow in the gullies is low year round. The surface water is mainly surface flow in response to abundant rainfall. The average annual rainfall is 1717.1 mm, and the maximum annual rainfall is 2563.6 mm. Rainfall is mainly concentrated from April to September; for example, the average rainfall in June is 306.8 mm.

The highest elevation in the tunnel area is 433.46 m, and the lowest elevation is 330.07 m on the left side of the tunnel exit. The direction of the tunnel is nearly perpendicular to the ridgelines and valleys. The hillside has a gentle slope at the entrance of the tunnel (with a gradient of 20° to 30°) but is steeper along the central section of the tunnel (with a gradient of 30° to 40°).

Yanshanian (γ_5^2) granite and Quaternary residual sandy clay (Q^{el}) are exposed at the surface. The residual sandy clay is grayish yellow and yellow-brown and is composed mainly of silty sandy clay mixed with sand and gravel, with a

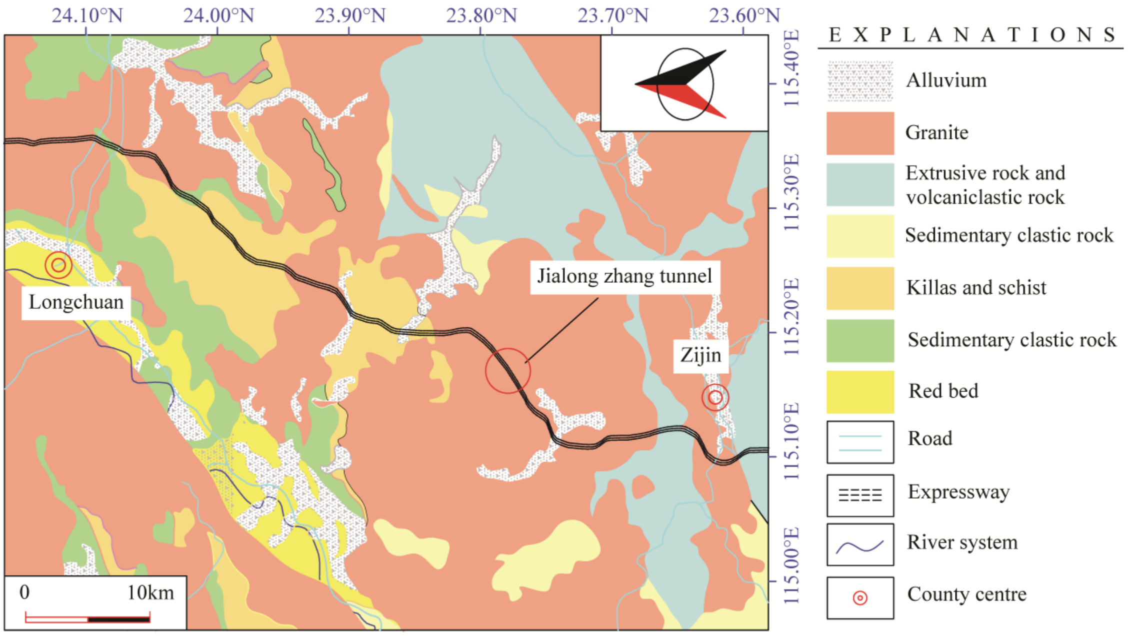

Figure 1 Location and simplified geological map of the study area.

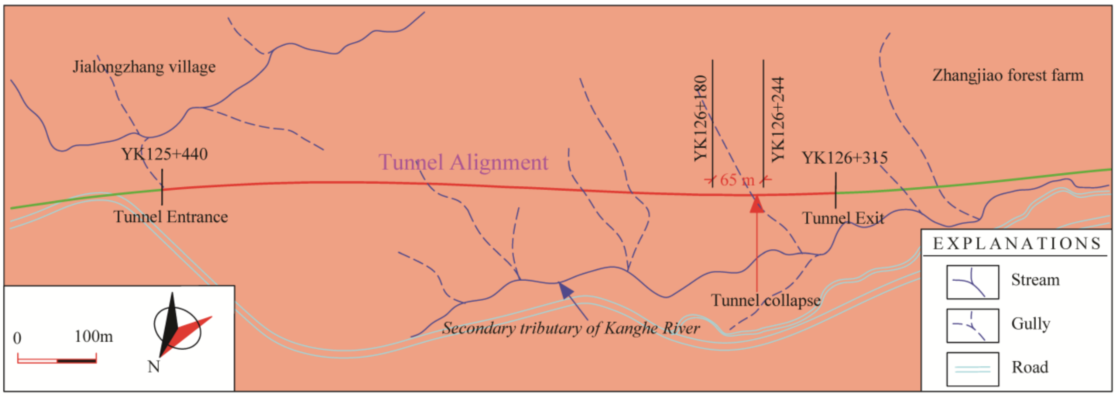

Figure 2 Location of the tunnel and river system.

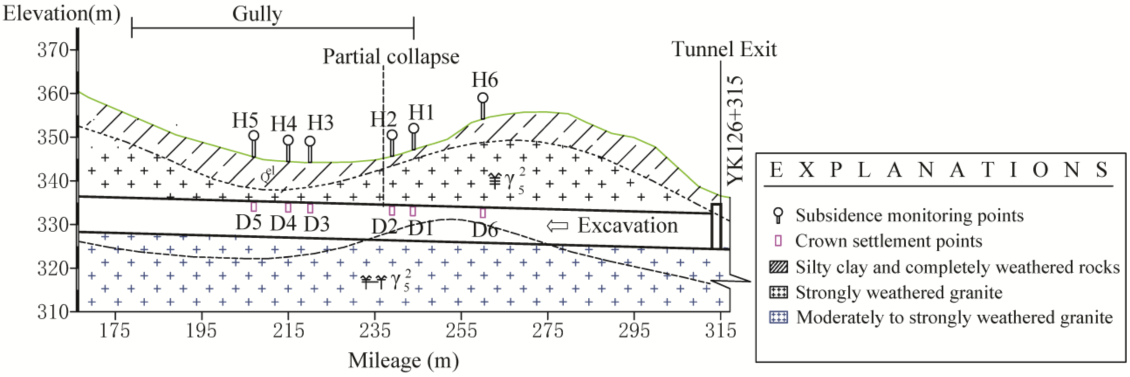

Figure 3 Layout of the monitoring section and strata profile.

nonuniform texture and poor cementation. The granite is gray, light-gray and yellow-brown, with a coarse-grained structure and massive texture. The joints are well developed in the upper layer, which is composed of completely or highly weathered granite, but the rock is intact in the lower layer. The tunnel is located between the Heyuan main fault and the Zijin fault (Qiu et al. 2018). The geological environment of the study area is relatively stable, with no neotectonics or active faults observed.

1.2 Overview of the collapse

The Jialong Zhang tunnel is a separated expressway tunnel; the left line of the tunnel is 930 m long, and the right line of the tunnel is 875 m long. The distance between the two lines of the tunnel varies from 21.9 m to 30.6 m. The right line of the tunnel crosses a 65 m wide gully 70 m from the exit, and the minimum burial depth of the tunnel in the shallowly buried area is only 8 m. The topsoil in this zone is humus, which is approximately 0.2 m to 0.5 m thick. With increasing depth, the lithology includes sandy clay, intensely weathered granite and moderately intensely weathered granite, and fissure water is stored in these rock formations (Figure 3). The New Austrian Tunneling Method (NATM) was adopted for tunnel construction, and the center diaphragm (CD) excavation method was applied to excavate the shallowly buried tunnel.

An advanced two-layered ductile support system was used in the construction of the shallowly buried section. The materials used in the initial supporting scheme were as follows: I20a steel arches with 0.6 m pitch spacing, twenty-five 3.5 m long hollow grouting anchors per ring with a 1 m × 0.6 m pitch spacing, and a 26 cm thick concrete layer. A 50 cm thick layer of reinforced concrete was used for the secondary lining. A vault collapsed 78 m from the right tunnel exit at 1:00 am on June 27, 2017, and the position of tunnel collapse is shown in Figure 2. Then, the vault continued to collapse intermittently. When the roof partially collapsed, it formed a circle with a diameter of 3 m in the ground at 16:00 on the same day, and the volume of the collapsed rock was approximately 180 m3. The scene is shown in Figure 4.

1.3 Methods

In recent years, geodetic measurements have been effectively adopted to monitor displacement in the field of tunnel construction, especially for a tunnel designed and constructed by empirical methods. Displacement monitoring is the key to verifying the design of the tunnel support and to identifying unpredicted conditions that may require modifications to the excavation scheme or the stabilization and support systems (Xia 2007; Yertutanola 2020).

(1) Layout of monitoring points

Because the depth of the tunnel is shallow from YK126+180 to YK126+244, the stability of the surrounding rock is very poor. According to the requirements of the engineering experience method, the interval of the monitoring section for vault settlement in the tunnel must be 5 m to 10 m (Q/CR 9218-2015; JTG F60-2009), and the monitoring sections of the surface and vault are arranged at the same mileage in the tunnel. One comparison section is set at chainage YK126+260, which is 16 m from the starting point of the shallow area. The corresponding surface settlement and vault settlement are represented by H1 and D1, respectively. Five monitoring sections are set at chainages YK126 + 244, YK 126 + 239, YK 126 + 210, YK 126 + 205 and YK 126 + 197 to monitor the deformation of the surrounding rock in the shallow tunnel. The corresponding surface settlement and vault settlement are represented by H2-H6 and D2-D6, respectively. The point layout is shown in Figure 3, and the point layout of the vault is shown in Figure 5. There are seven observation points in

Figure 4 Collapse field of section YK126+237; (a) Tunnel roof fall. (b) Collapse of tunnel crown.

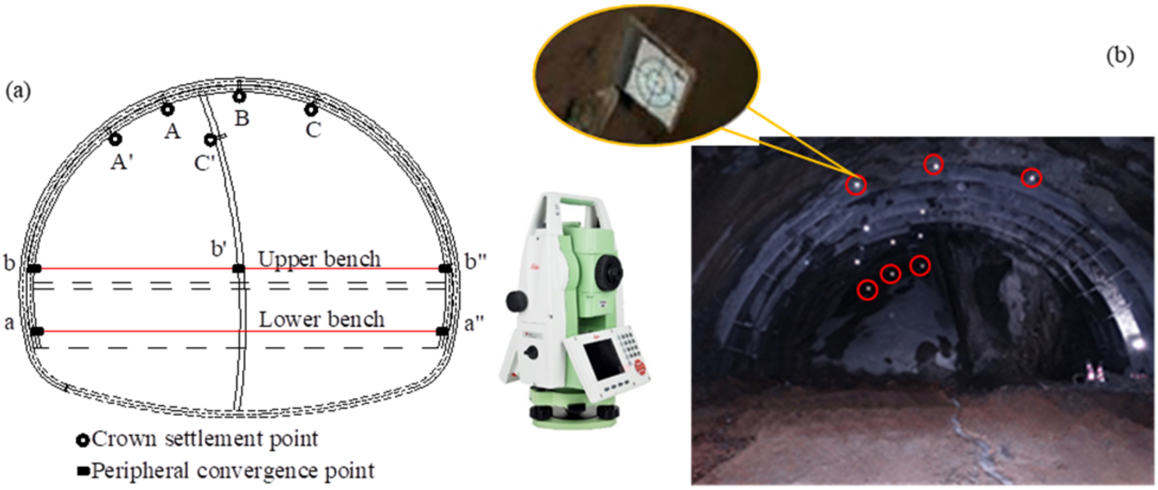

Figure 5 Layout of measuring points of tunnel deformation; (a) Layout of measuring points in transverse section. (b) In-site measuring points.

each monitoring section of surface settlement, and the transverse spacing of each observation point is 2 m to 5 m when the observed range is less than the sum of the tunnel depth and tunnel width (Q/CR 9218-2015; JTG F60-2009). According to this rule, there are 4 observation points on each side with the central axis of the tunnel as the center, and the intervals are 3 m, 5 m and 8 m in turn, as shown in Figure 6.

(2) Data collection

The observation apparatus of vault vertical displacement should be installed after tunnel excavation and primary support installation, and the initial value should be taken 24 hours after installation. For the installation of the surface settlement observation equipment, the distance between the observation point and the excavation surface should not be less than the sum of the tunnel depth and the tunnel height, and all devices should be fixed to stable rock or soil masses to ensure that the data collected are accurate (Lai 2015). To reduce the influence of environmental conditions and human factors on the data collected, the following measurements were taken. The same observation point is monitored by the same measuring instrument, and the same monitoring engineer collects the data from the beginning to the end of the monitoring period. Some environmental conditions, such as the temperature and air pressure, at the first monitoring location were recorded to reset the instrument's parameters for each subsequent measurement.

(3) Analysis of data

Vertical displacement monitoring in both tunnels was performed for a period ranging from 5 to 12 months by utilizing the optical method on the top heading and benches. With the field monitoring data, vertical displacement-time curves and the vertical displacement rate-time curves were drawn for all the observation points in the 6 monitoring sections of the tunnel vaults. Additionally, cumulative settlement-time curves were drawn for all the surface monitoring sections. Through the analysis of all the curves, the deformation of the surrounding rock during tunnel excavation can be obtained, and information feedback can be provided to guide the safe construction of the tunnel. In addition, each of the six monitoring sections studied here has a different burial depth, different surrounding rock conditions and a different geological environment, so the deformation patterns of the surrounding rock and surface deformation around the tunnel will be different.

2 Results and Analysis

2.1 Analysis of monitoring results

2.1.1 Rate of tunnel crown settlement

To investigate the deformation of the surrounding rock following tunnel excavation, six sections for monitoring tunnel crown settlement were selected along the shallowly buried tunnel, and the corresponding monitoring data were collected under different conditions from June 2017 to October 2017. The deformation at chainage YK126+260, which is 16 m from the collapse site, is used for comparative analysis. Data on the vertical

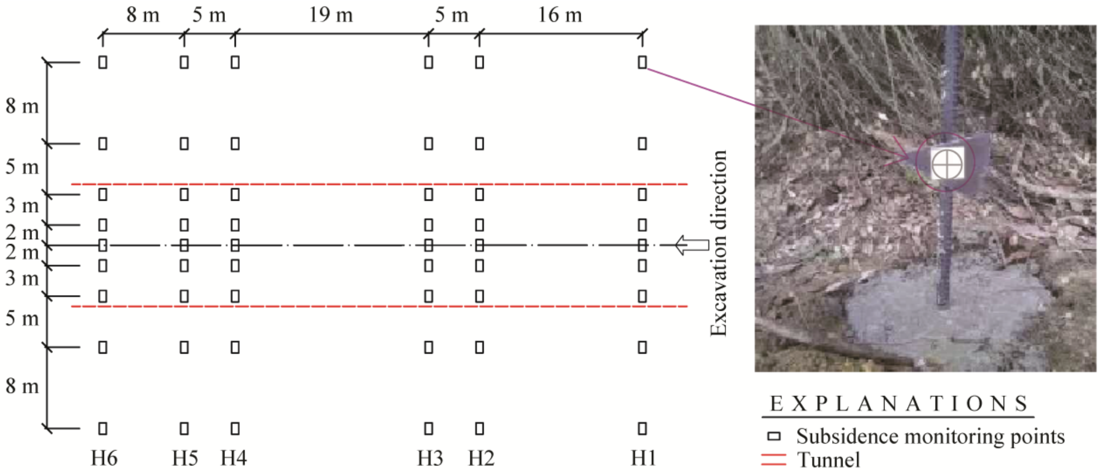

Figure 6 Layout of monitoring points of surface settlement.

displacement and deformation rate of the six sections monitoring tunnel crown settlement are analyzed, and the vertical displacement rate-time curves and the cumulative vertical displacement-time curves from all the sections are shown in Figure 7.

When the tunnel was excavated to chainage YK126+237, the excavation face and nearby vault collapsed. As shown in Figure 7(a), the vertical deformation rate of the tunnel crown in chainage YK126+260 in the first four days was the highest throughout the period, reaching 3.6 mm/d on 14 June, and then remained stable at 0.7 mm/d. Although this section was 23 m from the collapse

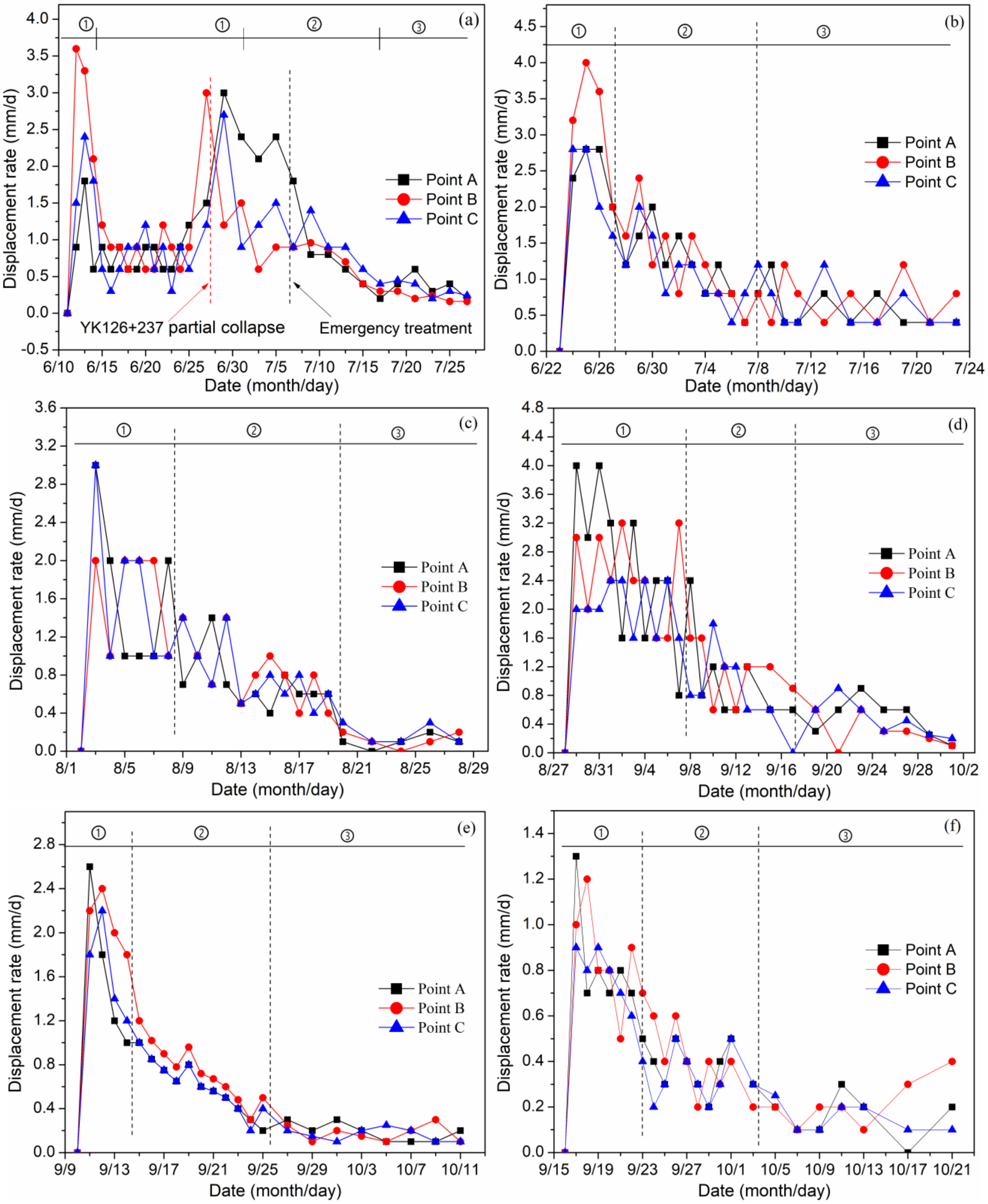

Figure 7 Vertical displacement rate and time curve of tunnel crown settlement; (a) Section YK126+260; (b) Section YK126+244; (c) section YK126+239; (d) section YK126+210; (e) section YK126+205; (f) section YK126+197.

site, there was a marked increase in the vertical deformation rate to 3.0 mm/d in this section on 26 June. The collapse of the tunnel face (YK126+237) had an impact on the tunnel crown settlement in chainage YK126+260.

The deformation patterns of the vertical displacement rate curves of the six sections assessed in this study are consistent and can be divided into three stages based on the deformation rate: the rapid deformation stage, the slow deformation stage and the stabilization stage, corresponding to ①, ② and ③ in Figure 7, respectively. During the first stage, tunnel excavation was a main factor leading to the marked tunnel crown settlement; the maximum deformation rate reached 4.0 mm/d, and the tunnel face partially collapsed at the end of the first stage. In the second stage, the deformation rate decreased over time, but it also fluctuated slightly. Finally, in the third stage, the deformation rate stabilized or decreased by only a small amount, indicating the achievement of a stable state. The deformation rate in the last state is affected by the geological environment, excavation method and support technology. Moreover, it can be concluded that the deformation of the rock surrounding the tunnel changes with time and that the surrounding rock basically reaches stability within 30 days. Notably, the monitoring data plotted on Figure 7 (c) to Figure 7 (f) can be used to determine the vault settlement rate-time curve after adopting the disposal scheme, and the deformation rate in the third stage is less than that before disposal. Clearly, the first stage should be treated as the key monitoring period in the monitoring of shallowly buried tunnels.

2.1.2 Cumulative tunnel crown settlement

The cumulative vertical displacement and time curves of the six monitoring sections of the tunnel vault are shown in Figure 8. In this study, a majority of the monitoring sections exhibit the largest cumulative vertical displacement at point B in the vault center. When the collapse accident occurred, the maximum vertical displacement of monitoring section D1 was 21.3 mm, as shown in Figure 8 (a), and the maximum vertical displacement of monitoring section D2 was 12.8 mm, as shown in Figure 8 (b). In contrast, the reserved vertical displacement of the loess tunnel vault was 700 mm to 800 mm (Lai 2015). The results of the monitoring data show that the maximum vertical displacement of the tunnel vault was 37.55 mm in the stable state of the surrounding rock, which exceeded the relative displacement limit of the primary support (Q/CR 9218-2015); only the vertical displacement of 10.9 mm in monitoring section D6 (Figure 8 (f)) did not exceed that of the surrounding rock.

Figure 8 (a) shows that the gradient of the displacement curve tends to decline after 20 June, indicating that the stability of the surrounding rock and support structure is increasing. However, the gradient of the displacement curve increases to a certain extent before the collapse of the tunnel, and the gradient of the displacement curve tends to decrease again until emergency treatment is taken. Compared with that in Figure 8 (a), the displacement curves of Figure 8 (b) to Figure 8 (f) show that the deformation of the surrounding rock is normal, which indicates that the support system used after disposal is effective.

In addition, the settlement of the vault was effectively controlled after the support measures were taken. The tunnel depths of section D, section E and section F are only 8 m to 10 m. Due to the reinforcement of the surrounding rock, optimization of the construction method and strengthening of the support structure, the minimum cumulative settlement of the tunnel vault was only 10.9 mm, as shown in Figure 8 (f), which was beneficial to the safe construction of the tunnel and the installation of the secondary lining.

2.1.3 Surface settlement

The following graphs illustrate the measured surface settlements of the six monitoring sections from seven observation points in every section. The monitoring instruments in chainage YK126+260 were installed on 26 May 2017, and the monitoring data were collected the next day. The cumulative surface settlement-time curves are shown in Figure 9. When the excavation surface was 3.58 m from the measurement point, the settlement rate of the tunnel surface increased dramatically, and after 2 days, the tunnel surface partially caved in. The surface settlement was effectively prevented by the reinforcement of the surrounding rock and optimization of the construction method after the partial collapse.

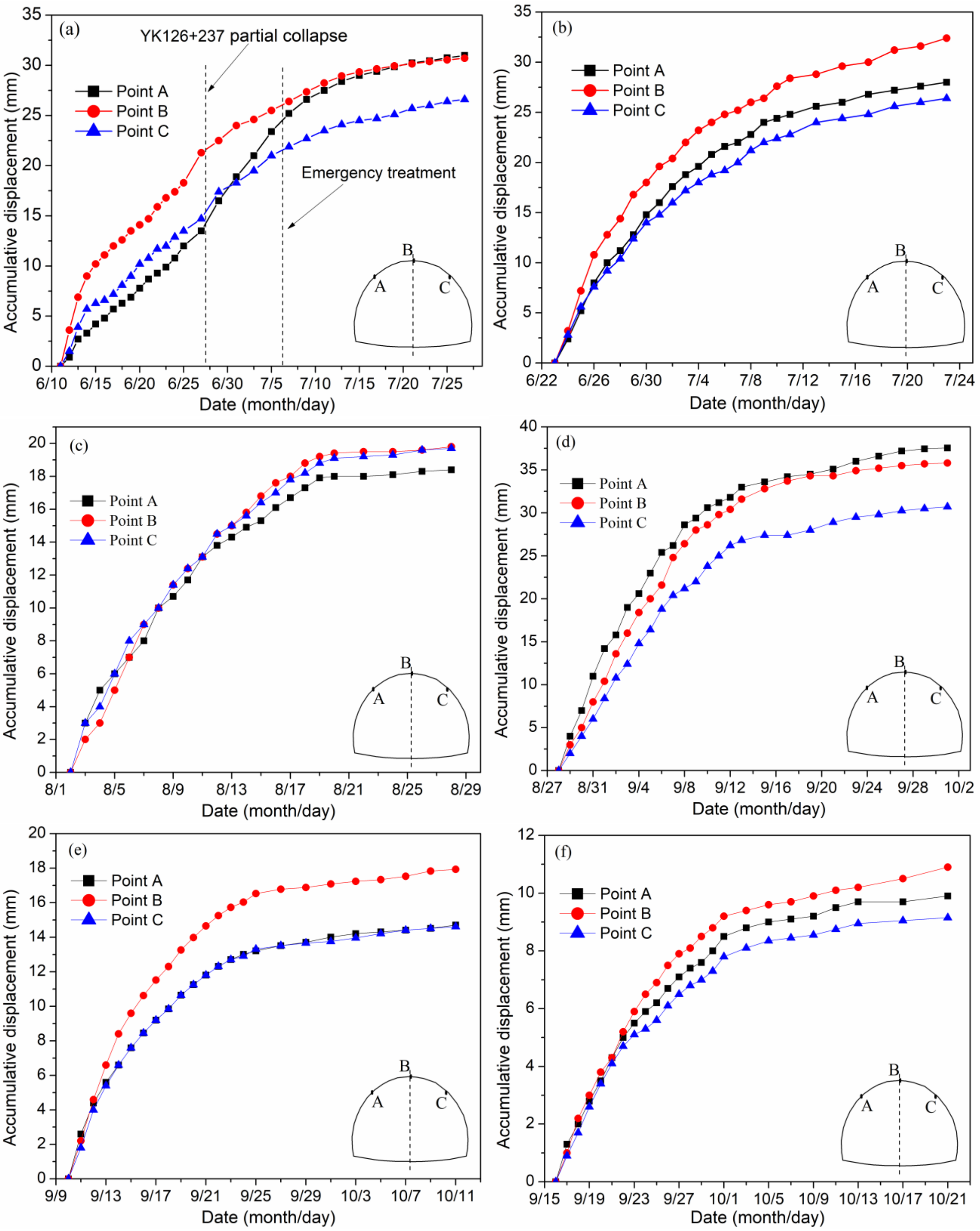

Figure 8 Accumulative vertical displacement and time curve of tunnel crown settlement; (a) Section YK126+260; (b) Section YK126+244; (c) section YK126+239; (d) section YK126+210; (e) section YK126+205; (f) section YK126+197.

The monitoring instrument at H2, located at chainage YK126+244, was installed on 9 June 2017, and the curve shows that the surface settlement changed greatly with time until emergency treatment was taken. After that, the ground settlement increased uniformly until the invert construction was completed. The monitoring data from H3 were collected after emergency treatment, and the previous data were lost, mainly because of the collapse of the ground above the tunnel. The cumulative settlement curve appears to be relatively smooth until the end of the construction of the secondary lining structure, and then the deformation of the surface decreases and gradually

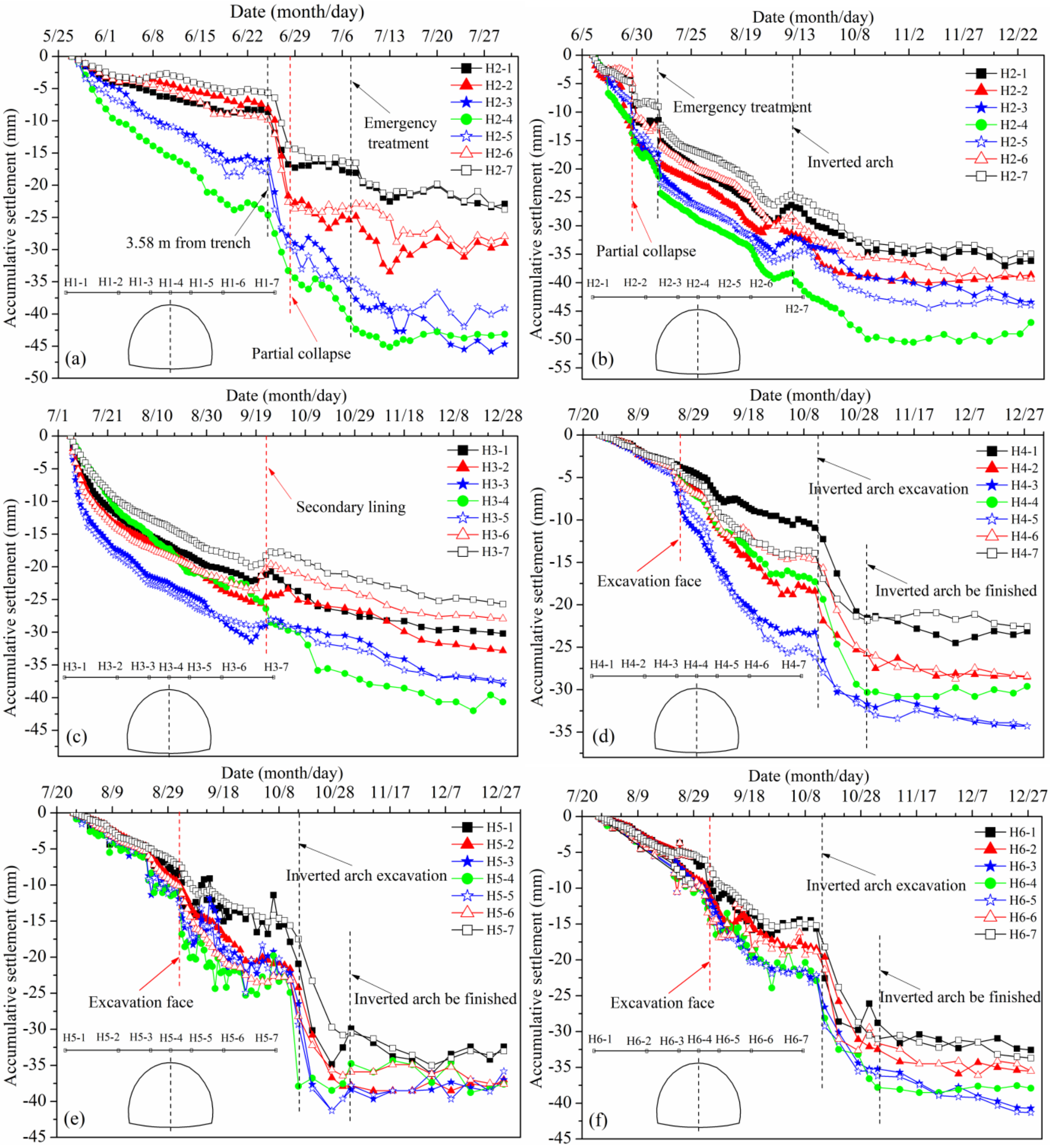

Figure 9 Surface settlements at seven observation points in section H1. (a) Section YK126+260; (b) Section YK126+244; (c) section YK126+239; (d) section YK126+210; (e) section YK126+205; (f) section YK126+197.

becomes relatively stable. In addition, the surface settlement-time curves show that the monitoring data of other sections were collected after reinforcement of the surrounding rock, optimization of the excavation method and strengthening of the support structure. The figures show that the surface settlement fluctuated slightly after the tunnel excavation, and the largest deformation occurred during the period of excavation from the inverted arch to the closed ring. When the inverted arch was completed, the surface settlement deformation gradually stabilized.

To summarize, it is necessary for work safety to effectively monitor and measure the deformation in a timely manner. Monitoring data collection and analysis from this project example indicate that the deformation rate of the tunnel surface and crown increased significantly before serious deformation or the collapse of the surrounding rock occurred in the tunnel. Therefore, ensuring the analytical accuracy of monitoring data and the reliability of tunnel deformation prediction can guarantee construction safety and minimize losses due to geographical disadvantages.

2.2 Deformation mechanisms of surrounding rock

2.2.1 Analysis of factors

Deformation of the rock surrounding highway tunnels is a phenomenon in which the surrounding rock deforms and fails due to unfavorable environmental factors, such as ground stress, disturbed soil and groundwater activity. In essence, partial or total loss of the self-bearing capacity and constraint forces of the surrounding rock causes plastic deformation and failure because the redistributed ground stress exceeds the yield stress as a result of excavation, eventually leading to varying degrees of destruction of the surrounding rock support. Several factors have crucial impacts on the serviceability of underground openings, including the quality of the rock mass, the presence and geometrical properties of rock joints, the presence of groundwater, the depth below the surface, the opening geometry, and the excavation techniques applied (Fang 2016; Abdellah et al. 2018).

(1) Lithology characterization

The deformation of soft rock surrounding a tunnel is governed by factors such as its strength, structure, cementation degree, cement properties and expansive mineral content. The geological conditions of the very shallowly buried tunnel studied here are poor. In fact, the tunnel is located in soft clay and highly weathered granite, which exhibit poor mechanical properties, such as a high proportion of weathered material and a low integrity and solubility. Furthermore, in terms of deformation, the local terrain conditions have a negative impact on the surrounding rock and have resulted in the formation of a set of joints in the surrounding rock oblique to the orientation of the tunnel.

(2) Effect of groundwater

Groundwater from infiltration of rainfall or river water has a negative influence on expansive clays, highly weathered soil and fractured rock. In fact, groundwater not only increases the weight of the rock mass but also reduces the strength of the rock mass. Landslide accidents are triggered during the rainy season, when heavy rainfall occurs on a regular basis. When rainwater infiltrates the rock and soil, the effective shear strength of the surrounding rock decreases, and the hydrostatic pressure increases at the crown of the tunnel. Additionally, the load of the surrounding rock and support increases, which reduces their stability.

(3) Effect of construction

The tunnel was excavated to chainage YK126+244 on 17 June 2017, and the lithology of the tunnel face was highly weathered granite, which was fractured and soft. A small part of the surrounding rock of the arch and sidewall collapsed, and the amount of water infiltration was considerable, so the remaining surrounding rock was also prone to collapse. In chainages YK126+244—YK126+234, the support system was reinforced, and the surrounding rock was grouted to fill rock crevices and fracture zones. Nevertheless, construction activities such as machine operation, presupport installation and excavation impacted the stability of the surrounding rock, which eventually led to the tunnel collapse.

2.2.2 Mechanism of deformation

The granitic soil in this study area has a uniform particle size and high permeability, which causes a reduction in the strength of the rock surrounding the shallow tunnel under heavy rainfall (Hu et al. 2009). The softening of fractured rock due to water infiltration is the main reason for the rock instability because highly weathered rocks contain materials whose strength decreases in the presence of water, such as clay particles and cementing materials. Because of the permeability of granitic soil, the rainwater that collects in the gully will slowly seep to the excavation face and arch crown, and this seepage will affect the strength of the surrounding rock. In addition, as the weight of the granitic soil increases during infiltration, large deformation or small-scale collapses of the tunnel vault and excavation face will easily occur after excavation.

For this kind of tunnel with poor engineering properties, the excavation method and drifting footage have a certain influence on the deformation of the surrounding rock. The CD excavation method was used before the tunnel collapse, and the optimized cross diaphragm (CRD) excavation method has been proven to be effective. It can be concluded that the deformation rate of the former is slightly higher than that of the latter, as shown in Figure 7 (b) and Figure 7 (e). After the loose, fractured surrounding rock was excavated, the release of ground stress led to a reduction in the surrounding rock instability.

After the excavation, partial stress redistribution led to deformation of the surrounding rock. Under such conditions, weak rock is prone to partial crushing, and the initial support can efficiently prevent deformation caused by excavation. However, in this case, the water content of the upper soil reached saturation because of heavy rainfall infiltration; the infiltration of fissure water into the underlying rock mass, which was strongly weathered, formed rock crevices, so the initial support was insufficient to prevent deformation of the surrounding rock. Considering this mechanism of deformation and collapse of surrounding rocks in shallow tunnels, the basic approach of the treatment is to avoid the harmful influence of rainfall infiltration and improve the stability of surrounding rock.

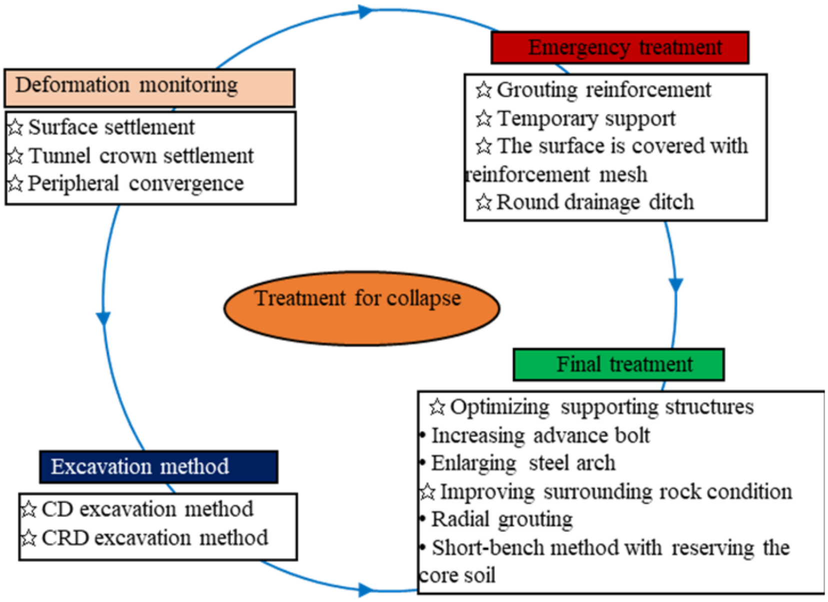

Figure 10 The scheme for treatment of collapse.

3 Treatment and Discussions

3.1 Scheme of treatment

Based on the deformation mechanism of the rock surrounding the tunnel, a treatment scheme should be developed as soon as possible after a construction accident. A tunnel collapse accident during construction not only threatens worker safety but also may negatively impact the investment and the construction period. As a part of safety management, the selected construction techniques play an important role in a project's timely completion (Lai et al. 2011; Ding et al. 2014). Therefore, it is vital and crucial for tunnel construction to undertake reasonable measures to minimize the impact of a tunnel collapse.

During excavation, once a collapse event occurs, measures should be urgently taken to avoid serious secondary disasters. The selection of the excavation method should be beneficial to the control of the surrounding rock deformation. In general, the CD excavation method and CRD excavation method have been shown to be effective in tunnel excavation in poor geological conditions. After excavation, the final treatment for collapse can be performed through two measures: increasing the bearing capacity of the support structures and improving the stability of the surrounding rock. Deformation monitoring of the rock surrounding a tunnel is important in the treatment of tunnel collapse. In the process of tunnel excavation, the monitoring data can show the deformation of the surrounding rock; by considering these data, engineers can implement effective emergency measures to prevent the tunnel from collapsing further and can then choose appropriate methods for further excavation and optimization of the support structure scheme. The treatment measures are shown in Figure 10.

3.2 Support measure of tunnel

Installing support structures in a tunnel is an effective method for controlling the deformation of the surrounding rock and preventing tunnel collapse. In weak rock, this reinforcement is accomplished by bolts, sprayed concrete and ribs of reinforced concrete (RRS). Details of a combined excavation and support process based on RRS are described in Wang 2010 and Høiena et al. (2019). In fact, presupporting techniques have been found to improve the stability of the surrounding rock during tunneling while minimizing the environmental consequences due to the tunneling process (Zarei et al. 2019).

(1) Emergency treatment

This process started with the clearing of the loose soil around the roof collapse and the wall cavity. Steel mesh with an 8 mm diameter was hung in the cavity, and then a 20 cm layer of C25 concrete was sprayed to reinforce the surface. In the next stage, injection pipes were used to grout the rock around the cavity 5 m above the vault. In addition, efficient measures were required to reduce the impact of rainfall and groundwater on fractured rocks. In this case, some drains with dimensions of 60 cm×60 cm were dug, and a 26 cm thick layer of M7.5 mortar rubble was added around the cavity, as shown in Figure 11 and Figure 12. Next, residual material was backfilled on the tunnel face, and pipes with a 42 mm radius and 6 m length were inserted into the tunnel face with a 120 cm pitch spacing. A layer of C20 concrete 15 cm thick was applied to the backfilled surface in

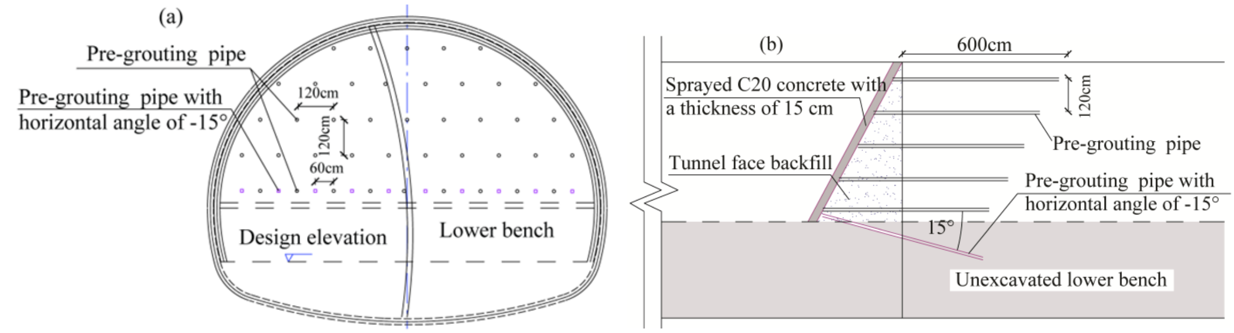

Figure 11 Excavating face treatment (a) Grouting on excavation surface; (b) Reinforcement of tunnel face backfill.

Figure 12 In situ photographs showing implementation of the countermeasures. (a) Grouting reinforcement; (b) Temporary support; (c) The surface is covered with reinforcement mesh; (d) Round drainage ditch.

the next step. Then, I20a steel arches were used for temporary support to control the deformation of the surrounding rock to a distance of 10 m from the tunnel face. The cavity 5 m above the vault was filled with C20 concrete, and the remaining part of the cavity was backfilled with the residual material and packed down.

(2) Final treatment

After reinforcing the surrounding rocks and the tunnel surface, monitoring data on tunnel crown settlement and surface settlement were collected twice daily, and analysis of the data showed that the deformation of the surrounding rock stabilized, so the excavation and rock support continued. In this case, the original support systems were optimized, including the use of presupport before excavation and adjustment of the primary lining. Two rows of grouting pipes with a diameter of 50 mm were used for presupport; the pipes had a length of 5 m, and radial distances from the tunnel axis to the first row and the second row were 30 cm and 20 cm, respectively. The surrounding rock condition was improved by the grouting pipes after excavation, and the lateral and radial distances from the tunnel axis to the grouting pipes were 50 cm and 100 cm, respectively. In the original plan, I20a steel arches with a 60 cm pitch spacing were considered, but after optimization, the pitch spacing of the I22b steel arches decreased to 50 cm. In addition, the thickness of the primary lining C25 shotcrete was increased by 2 cm. Before-and-after photographs are shown in Figure 13.

3.3 Tunnel construction methods

The deformation of the surrounding rock is directly related to the size and shape of the excavation section. The smaller and rounder the cross-sectional area is, the more effective the support. Tunnel blasting excavation and support cannot be carried out at the same time. The amount of time a tunnel can support itself without any added support structures before the rock mass around the tunnel begins to collapse is called the stand-up time (Lauffer 1958; Nguyen 2015). Because of the poor self-stability of the fractured surrounding rock and its short stand-up time in this case, the support system cannot be established in the section quickly enough to prevent tunnel instability and collapse (Huang et al. 2019). Therefore, tunnel excavation cannot be completed in one step or using the long step method. Considering the weakness of the rock surrounding the tunnel, the appropriate excavation methods include the short step method, ring excavation reserved core soil method, cross-intermediate wall method, and glasses method. The deformation and failure of the tunnel crown are related to the instability of the tunnel face. Normally, the treatment to reduce the deformation of the tunnel

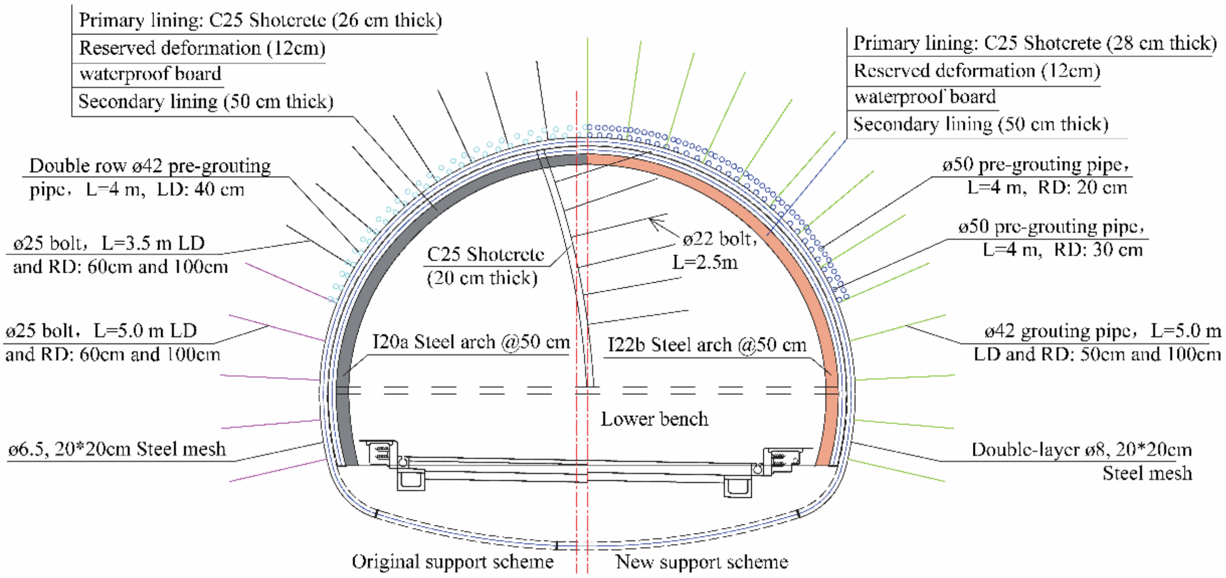

Figure 13 Sketch map before (left) and after (right) treatment. Note: in this figure, all units of diameter are written in mm; L represents length, LD represents lateral distance, RD represents radial distance.

face includes setting front face anchors and reserving a core soil at the face.

In the chainages of YK126+244 to YK126+234, the CD excavation method was performed. During the excavation of the fractured surrounding rock, based on the bench method, the tunnel section was divided into left and right parts, and each part was excavated and supported to form an independent closed unit using the CD excavation method. The excavation of the tunnel surface was performed using the procedure shown in Figure 14a. The excavation methods were adjusted according to monitoring data and the properties of the surrounding rock. During the weak surrounding rock excavation process, the CRD method was used. In this case, both sides of the tunnel were excavated in a few steps so that the short bench and tunnel cross-sections were covered and supported by temporary inverted arches in each step. The last step in the process was to excavate the remaining rocks of the center section to maintain a soil core and reduce the deformation of these rocks, as shown in Figure 14b. In addition, the tunnel was excavated by workers and machines that removed 0.5 m of material in each working cycle. The inverted arch closely followed the lower bench with a length range of 3 m to 5 m and was closed in time to form a stable support system.

For the shallowly buried granitic soil tunnel, the support measures vary with the excavation methods. Advanced support before excavation is a necessary measure to control the deformation of the surrounding rock and prevent collapse accidents. The CD method was adopted for excavation; specifically, the left part was excavated first, the support structure was added in a timely manner, and then the right side was excavated. Notably, each part of the excavation was fixed with an anchor rod to form a stable closed loop. The results show that the initial construction method and support structure could not meet the safety requirements of tunnel construction, and the level of risk was extremely high, so the construction method needed to be adjusted in a timely manner. For the CRD method, a suitable bench and excavation length were taken, and the smaller part of the excavation block was formed into a ring; with the excavation along with the presupport, the removal of the temporary support structure allowed the surrounding rock deformation to reach basically stable conditions. Generally, in the excavation of shallow tunnels, regardless of which of these two methods is adopted, the installation of the support structure should follow the excavation sequence. The selection of the excavation method and the determination of the support structure strength should be based on the deformation of the surrounding rock based on monitoring data.

3.4 Information feedback

The potential arch crown settlement and ground deformation are hazardous factors that must be considered in shallowly buried tunnel excavation. In general, three methods are used to obtain the deformation of the rock surrounding the tunnel: mathematical formula prediction (Chou and Bobet 2002; Shi et al. 2019), numerical simulation (Chakeri et al. 2011) and site monitoring (Kavvadas 2005; Janine et al. 2012). Among them, the last method is the most commonly used for selecting the excavation and support systems and establishing early warning systems for tunnel accidents. Due to the complexity of the surrounding rock properties and the difference in construction technology, the actual

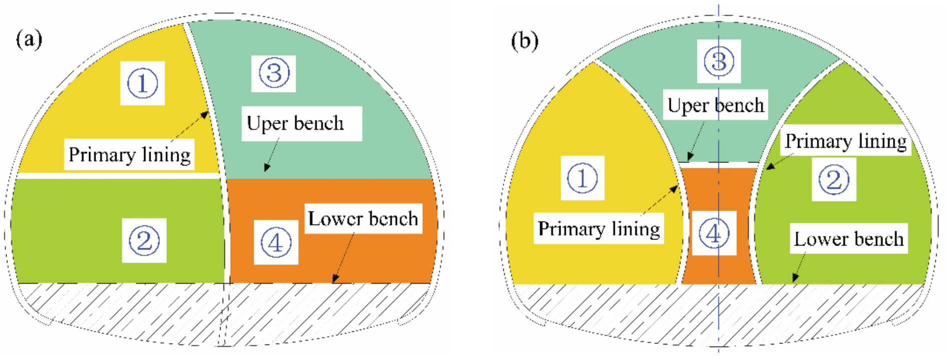

Figure 14 Sketch of excavation method. (a) Center diaphragm excavation method; (b) Cross diaphragm excavation method.

deformation pattern of the surrounding rock during tunnel excavation can differ from calculation results, which increases the safety risks and costs of tunnel construction. The monitoring data collected on-site can be used to monitor the deformation of the surrounding rock in real time and to judge whether the initial support structure and construction method are appropriate according to advanced criteria; this is known as the information feedback method (Wang 1990; Ye 2007). Using this method, the deformation of the surrounding rock can be determined in a timely manner during tunnel excavation to optimize the construction method and strengthen the support structure to control the deformation. Therefore, the information feedback method based on monitoring data not only monitors the deformation of the surrounding rock during tunneling but also promotes safety management, cost effectiveness and construction time efficiency. With the emphasis on monitoring and measurement, engineers should focus on the prediction of geological conditions and on the monitoring and measurement of deformation during the excavation of tunnels in shallowly buried areas. Furthermore, the frequency of monitoring and the number of monitoring points should be increased. During the excavation of a tunnel in granitic soil, the analysis of the monitoring data should be reported on a daily basis to ensure that workers or construction enterprises have access to and use this information. When the deformation of the surrounding rock is abnormal, they should be notified, and effective measures should be taken in a timely manner to prevent accidents.

Moreover, accumulating considerable professional knowledge and work experience (Storseth et al. 2012; Casse et al. 2019), which can improve the accuracy of data analysis and predictions of tunnel deformation, are seen as particularly important for construction safety in shallowly buried tunnels. As in this case, when the excavation reached the shallowly buried section, the deformation of the surrounding rock clearly increased, so the information was fed back to the decision makers, who optimized the initial construction scheme, but they failed to account for the poor conditions of the granitic soil and infiltration of heavy rainfall, which resulted in a tunnel collapse. In the absence of sufficient on-site monitoring data, other approach should have been taken into account, such as seismic signal recognition (Yan et al. 2020). Fortunately, an early warning was sent in a timely manner by experienced monitoring engineers, and no one was injured or killed in this accident.

4 Conclusions

This article analyzes the impacts of poor geologic conditions, groundwater infiltration and tunnel excavation on the deformation of surrounding rock, provides an analysis of the deformation mechanism of the weak surrounding rock, and then suggests measures to control this deformation. The deformation process of the rock surrounding a shallowly buried tunnel can be divided into three stages, namely, the rapid deformation stage, the slow deformation stage and the stabilization stage. In the stage of rapid deformation, the stress release caused by excavation and the support structure does not form a closed ring, which leads to the continuous crown subsidence and surface settlement of the surrounding rock at a fast deformation rate, and this stage generally lasts for 5-7 days after excavation. In the slow deformation stage, when the support structure is closed into a ring and its strength is sufficient, the deformation rate of the surrounding rock decreases, and this stage generally lasts for 10 days. If the deformation rate remains high for a long time, it is necessary to strengthen the monitoring effort, optimize the construction method and strengthen the tunnel support when necessary. In the stable stage, the deformation of the surrounding rock tends to stabilize within 30 days after excavation. During the first stage, the deformation rate of the tunnel crown is the highest, and the tunnel is susceptible to partial collapse, so close attention should be paid to tunnel construction in the first stage to ensure construction safety during tunnel excavation. Tunnel collapse endangers workers' lives and prolongs the tunnel excavation process during the construction period. To reduce the risk of secondary disasters caused by accidents, treatments can be applied in three ways: (1) enhancing the monitoring of surrounding rock and surface deformation and providing information feedback to help decision makers decide whether to continue excavation, (2) increasing the bearing capacity of the support structure and improving the surrounding rock conditions, and (3) selecting a reasonable construction method for excavation in fractured or soft surrounding rock. Among these treatments, information feedback is very important for controlling the deformation of the surrounding rock and reducing losses caused a collapse.

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