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DEVELOPMENT OF SURFACE SETTLEMENT OF TWIN TUNNELS UNDER THE INFLUENCE OF THE RIVER

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ABSTRACT: Soft soil poses more challenges to the construction of shallow-buried tunnels than other soils: the surrounding rock mass is more easily disturbed, and the tunnel stability is more influenced by groundwater seepage. The research is based on the Zizhi Tunnel project, a shallow-buried twin tunnel in soft soil. This paper divides the research area into the inside and outside river-affected area respectively. From the field monitoring data, the settlement law can be summarized, which found that for a single monitoring point, outside a river-affected area, the entire settlement development stage can be clearly divided into three stages: slow growth, rapid growth stage, and gradual convergence; however, inside the river-affected area, the settlement in the last stage will not converge but will continue to develop. Compared with the vault settlement, the surface settlement inside the river-affected area develops slower than that outside the river-affected area, which shows good consistency with the monitoring data. The synchronization of the sinking rate and stability of vault settlement and surface settlement verifies that the river over the tunnel has an impact on the development of surface settlement by the groundwater seepage in the soft soil. Based on field monitoring data, a numerical model is established to investigate the influence of the river on the surface settlement of the twin tunnels, of which the numerical results show the same development law as the monitoring data.

Keywords: Tunnels, Surface settlement, River, Groundwater seepage

1. INTRODUCTION

An increasing number of subways and tunnels are being built in coastal cities under intricate geological conditions. These structures are typically shallowly buried in soft ground, and their construction, often involving river under-crossing, induces ground movement and can result in damage to nearby structures, especially in soft soil. Therefore, investigating the impact of a river on tunneling-induced deformation in coastal soft soil holds significant importance in controlling excessive settlement and safeguarding surrounding buildings.

So far, scholars have carried out many studies on ground settlement during tunnel construction. Various factors affecting surface settlement, e.g., space and time [1], tunnel shape and depth [2], reinforcement [3], and consolidation settlement [4,5], have attracted widespread attention from scholars at home and abroad. The models in the study help us calculate surface settlement in different soils, but they cannot be used in tunnels with complex geological conditions, mainly because of the influence of groundwater flow.

Groundwater seepage is considered to be one of the risks of tunnel construction. Scholars have studied the influence of geological conditions caused by tunnel excavation on ground settlements. Chai et al. [6] pointed out that land settlement is caused by consolidation caused by the drop in pore water pressure. Shen et al. [7] proposed that groundwater seepage is the cause of long-term tunnel settlement. Yoo et al. [8] found that excessive surface settlement and areas affected by large settlements were caused by groundwater drawdown. Shen and Xu [9] established a numerical model to analyze the relationship between ground settlement, groundwater drawdown, and groundwater level to predict ground settlement caused by groundwater drawdown. Yoo [10] conducted an artificial neural network analysis to qualitatively study the influence of the soil stiffness in the groundwater seepage zone and the permeability coefficient of the shotcrete lining on the surface settlement of the tunnel. Tang et al. [11] based on different cases excavated in low permeability soils found that groundwater seepage in low permeability soils have influence on the settlement trough.

From the research of other scholars mentioned above, it can be found that the development of surface settlement may be different due to the influence of groundwater seepage. This article will analyze and summarize the law of surface settlement caused by the excavation of the double-track tunnel under the influence of the river. Study the influence of rivers on surface settlement caused by tunnel excavation, which may be due to the presence of low-permeability silty clay and mucky silty clay in the affected area. In a soil layer with a low permeability coefficient, groundwater seepage will cause the pore pressure of the surrounding saturated silty clay mixed gravel layer to redistribute, which will further consolidate and settle the overlying layer of the tunnel

[4,10,11]. Meanwhile, as the consolidation stress of the soft soil layer increases, the permeability coefficient will gradually decrease, resulting in a slower consolidation process and an increase in consolidation time [12,13].

2. RESEARCH SIGNIFICANCE

The study proved that the river has a certain influence on the development of surface settlement caused by tunnel construction through the analysis of field measurement data. The influence of the river on the tunneling-induced ground settlement is investigated by field data and numerical analysis. Through numerical analysis, the control effect of cofferdam construction on reducing the surface settlement caused by tunnel crossing the river is investigated, and the construction guidance for the subsequent tunnel crossing the river is proposed.

3. PROJECT OVERVIEW

3.1 General Information

The project is located in the western area of Hangzhou, surrounded by dense residential blocks and commercial buildings, which is the longest urban tunnel in China. Hangzhou Zizhi Tunnel (Zijingang Road – Zhijiang Road) project starts from Zhipu Road in the south and ends at Zijingang Road in the north, with a total length of 14.4 kilometers. The north and south sections of the tunnel are constructed by the shallow tunneling method, and the middle section is constructed by the NATM method. This paper is based on the shallow buried tunnel of the north exit of the Zizhi Tunnel. The layout of the tunnel is 300 m from the north to the south. The parallel tunnel starts from the working shaft and travels along the Zijingang Road to the south along the Yanshan River and Tianmushan Road, which is under the influence of seepage of the Yanshan River and was selected to be the study region in this paper.

3.2 Geological And Geotechnical Conditions

Figure 1 shows the typical longitudinal profile of the twin tunnels around the Yanshan River. The tunnel excavation is mainly laid in the silty clay mixed gravel layer, including miscellaneous fill, plain fill, mucky silty clay, and silty clay. The longitudinal slope of the tunnel is 2.98%, and the thickness of the overburden above the tunnel gradually varies from 9.5 m to 18 m.

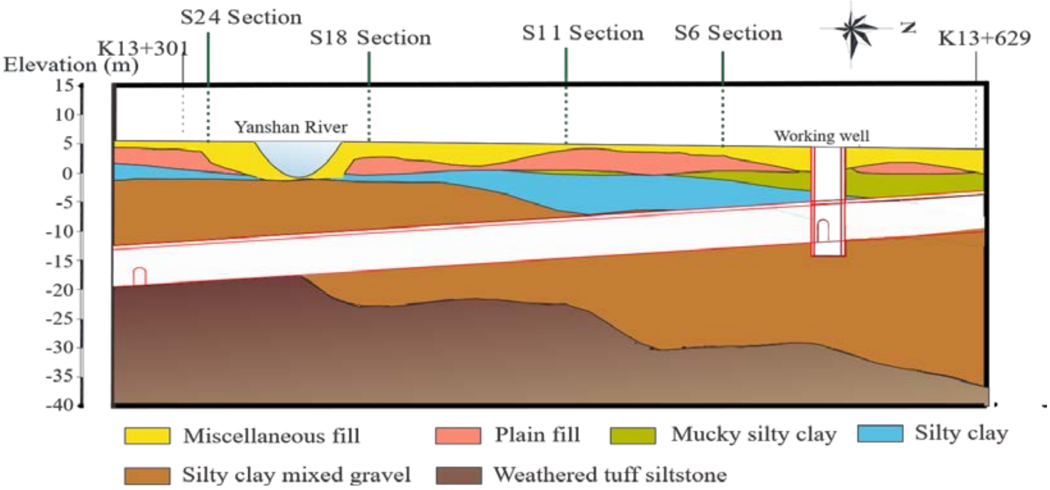


Fig. 1. Typical longitudinal profile [3]

Table 1 Geotechnical properties of soil layers

Soil type	γ (kN/m^3)	e	E_s (MPa)	υ	c (kPa)	φ (deg)	k_v (cm/s)	k_h (cm/s)
Miscellaneous fill	17.5	0.783	2.6	0.33	0	10.0	4×10^{-3}	5×10^{-3}
Plain fill	18.4	0.875	3.5	0.35	10	12.0	6.5×10^{-4}	8×10^{-4}
Mucky silty clay	17.6	1.245	2.5	0.45	11	9.5	4×10^{-7}	5×10^{-7}
Silty clay	19.4	0.721	6.0	0.41	35	16.0	2×10^{-7}	3×10^{-7}
Silty clay mixed gravel	19.8	0.601	10.0	0.38	45	17.0	6×10^{-6}	8×10^{-6}

Note: γ*=unit weight, e=void ratio,* E_s*= modulus of compressibility,* υ*=Poisson's ratio,* c*=cohesion,* φ*=internal friction angle,* k_v*=vertical permeability coefficient,* k_h*=horizontal permeability coefficient.*

Detailed geotechnical properties of each soil layer are obtained through laboratory soil tests. The soil properties are listed in Table 1.

The groundwater in the construction section is mainly Quaternary pore phreatic water, replenished by atmospheric precipitation runoff and laterally replenished along the Yanshan River with relatively large content. The static water level is 0.6 - 3.5 m, and the annual variation range is 1 - 2 m. 15 piezometers (SW1~SW15) are set up at the river construction site to observe the water level changes in the water-rich soft soil layer with the spacing of 30 m. Figure 2 shows the evolution of the phreatic level of SW9, SW11 and SW12 during construction.

In Fig. 2, the groundwater levels has large fluctuations from 60 to 90 days. This was due to the high rainfall brought by the typhoon during this period. However, with the good drainage measurements, the short-term changes in groundwater level did not have a significant impact on surface settlement.

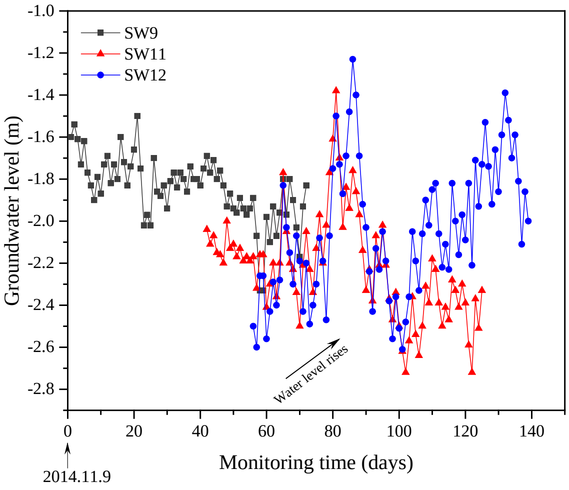


Fig. 2 Groundwater level variation curve with time

3.3 Settlement Measurements

To grasp the degree of influence of tunnel construction on the surrounding environment, the monitoring and measurement of the northern section of the shallow tunnel of Zizhi tunnel was carried out, and measurements results were averaged three times. The monitoring items were mainly surface settlement, crown settlement and groundwater level, as shown in Table 2.

Fig. 3 shows the layout of 28 surface settlement monitoring sections within 300 m of the northern section of Zizhi tunnel. Outside the affected area of the river, a total of 18 monitoring sections (S1~S15, S26~S28) are arranged at a spacing of 10 m. Inside the affected area of the river, a total of 12 monitoring sections (S15~S26) are set at an interval of 5 m for S19~S23 and 10 m for others. The arrangement of measuring points is divided into two categories: one is only one measuring point directly above the central axis of the tunnel, and the other is a row of measuring points arranged at a spacing of 5 m directly above and on both sides of the central axis and the arching line of the tunnel.

Table 2 Monitoring items and indexes

Item	Instrument	Frequency
Surface settlement	Levels	$L > 5S$, 1 time/week $L < 5S$, 1 time/2 days $L < 2S$, 1~2 times/day
Vault settlement	Levels steel rulers	after excavation: 1~15 days, 1~ 2 times/day 15~30 days, 1 time/2 days 1~3months,1~2times/week After 3 months, 1~3times/month

Note: L = interval of excavation face and measurement section, S = tunnel span.

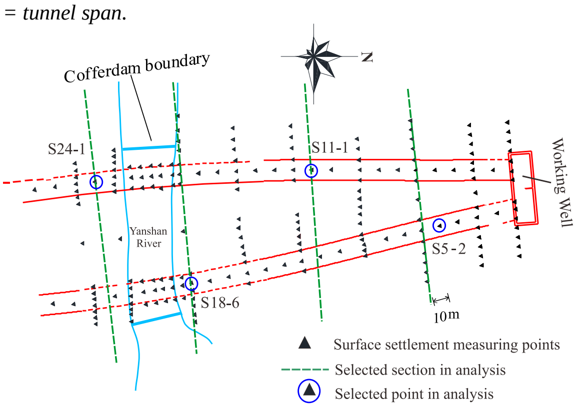


Fig. 3 Arrangement of monitoring points

4. MEASUREMENT

4.1 Surface Settlement of Single Point

Outside the river-affected area, taking the settlement development curves of measuring points S5-2 and S11-1 as an example, Figs. 4 and 5 plot the development process of the development of surface settlement. The moving average method is used to smooth the settlement rate curve, of which the settlement rate is the average value of the actual settlement rate on the current day and three days before and after, so as to avoid excessive fluctuations in the original data.

For the settlement development, it can be seen from Figs. 4 and 5 that the entire settlement development stage can be clearly divided into three stages: the slow growth stage in the early stage, the rapid growth stage in excavation stage and the gradual convergence stage in the last stage. In the first stage, because the tunnel face is far from the excavation face, the development of settlement is relatively slow; in the second stage, due to the tunnel excavation, the development of settlement grows faster; in the third stage, as the tunnel face is farther away from the excavation surface, the surface settlement increases slowly until it converges.

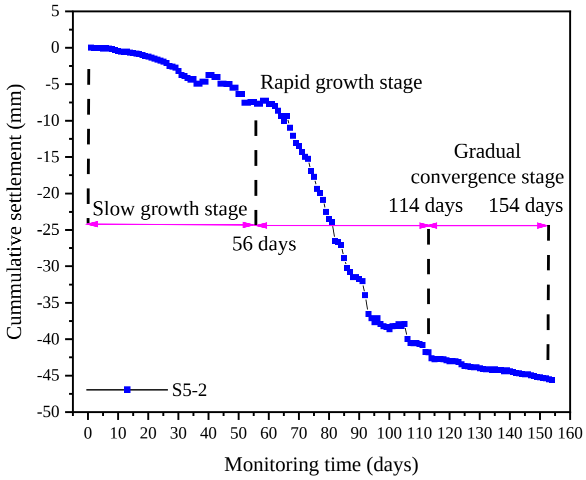


Fig. 4 Settlement of S5-2 point

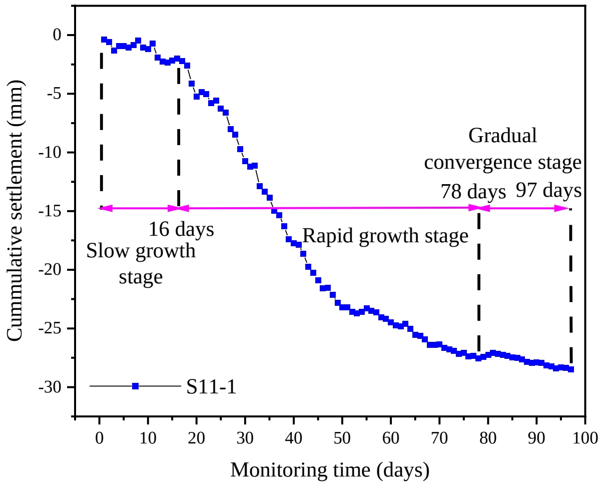


Fig. 5 Settlement of S11-1 point

Inside the river-affected area, taking the settlement development curves of measuring points S18-6 and S24-1 as an example, it can be seen from Fig. 6 and Fig. 7 that there is a significant difference between the settlement development curve inside river-affected area and that outside river-affected area. Due to the late start of settlement monitoring, the measured data for the slow growth stage in the early stage was very short, and the gradual convergence stage in the later stage became a continuous growth stage. During the entire monitoring time, the surface settlement continued to increase without a convergence.

The main reason for the continued growth of surface settlement is due to the consolidation and deformation of the soft soil around the riverbed. Because the permeability coefficient of the soft soil near the riverbed is very small, the consolidation cannot be completed in a short time, and the surface settlement continues to increase at a low rate.

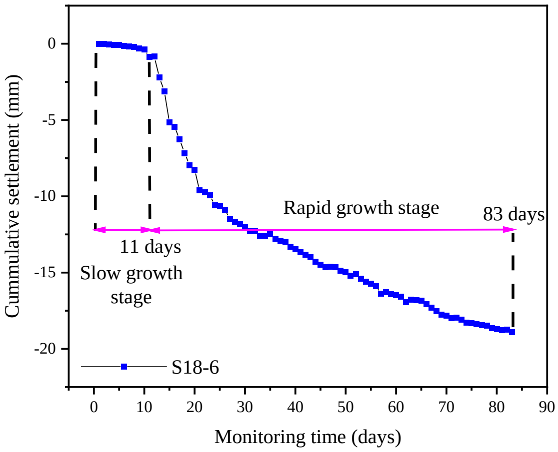


Fig. 6 Settlement of S18-6 point

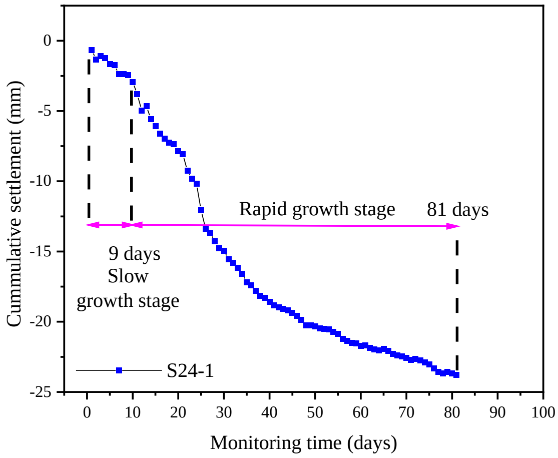


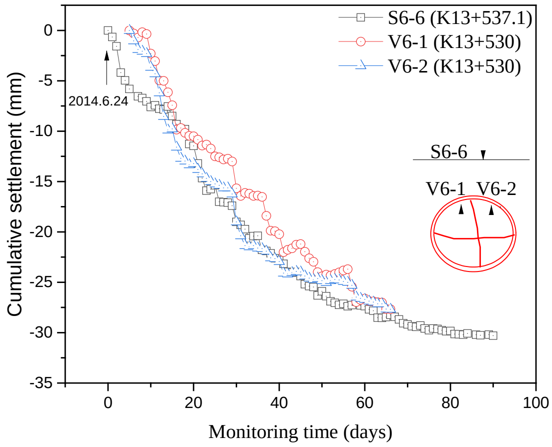
Fig. 7 Settlement of S24-1 point

4.2 Surface Settlement And Vault Settlement

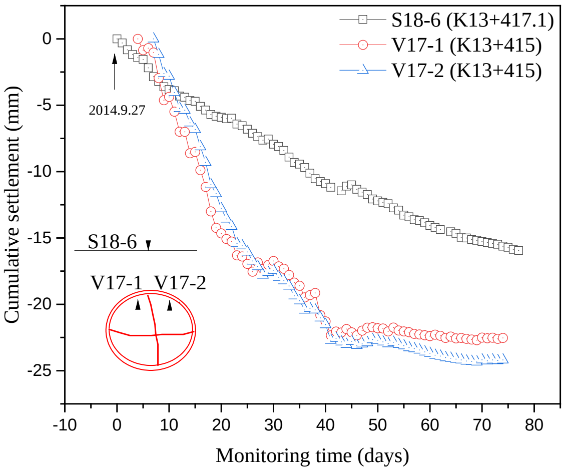
Figs. 8a and 8b compare the settlement development of the surface points above the central axis of the tunnel with that of the vault points in two different monitoring sections of S6 and S18, which are outside and within the river-affected area respectively. In the initial stage of monitoring, the settlement rate of the vault is greater than that of the ground surface. As the distance between tunnel faces and monitoring section becoming larger, the decrease in the settlement rate of the vault is higher than that of ground surface. Then two types of development laws on the surface settlement above the tunnel can be observed, possibly attributing to the construction of Yanshan River cofferdam.

As can be observed in Fig. 8a, outside the river-affected area (S6), the sinking rate of the vault is close to the surface settlement rate and tends to be stable at the same time. In the river-affected area (S18), the vault sinking is larger than the surface settlement. After the vault sinking is basically stable, surface settlement continues to develop (see Fig. 8b). The vault sinks at the same rate inside and outside the river-affected area, which is caused by soil loss. The surface settlement develops slower inside the river-affected areas. The synchronization of the sinking rate and stability of vault settlement and surface settlement indicates that the groundwater seepage caused by the river has a significant impact on the surface settlement of the tunnel.

The surface settlement in the river-affected area develops slower than the vault settlement, continues to develop, and differs greatly from the vault settlement. This may be due to the existence of low-permeability silty clay and mucky silty clay in the affected area. In the soil layer with a low permeability coefficient, the groundwater seepage will cause the pore pressure redistribution of the surrounding saturated silty clay mixed gravel layer, causing further consolidation and settlement of the overburden layer on the tunnel [6, 8, 11]. Meanwhile, the permeability coefficient will gradually decrease with the consolidation stress in the soft soil layer, leading to slower consolidation process and increasing consolidation time [12, 13]. It is consistent with the slower convergence rate of surface settlement within the river-affected area in Fig. 8b.



(a) Outside the river-affected area



(b) Inside the river-affected area

Fig. 8 Comparison of surface settlement and vault settlement development

5. NUMERICAL ANALYSIS OF TWIN TUNNELS

5.1 Numerical Model

The tunnel model is shown in Fig. 9. The size of the model is 140 m, 80 m, and 60 m in the x, y, and z directions, respectively. The parameters of the soil are shown in Table 3. The specific construction steps are to establish the stress field and seepage field in the initial state and then simulate the construction according to the actual excavation of the Zizhi Tunnel. The entire construction process includes a total of 55 calculation cycles. Each calculation cycle includes pre-grouting and tunnel excavation, adding initial support lining, intermediate wall, temporary invert, and consolidation calculation in the case of groundwater seepage. Each calculatation is 2m, of which the construction speed is 1m/d, and the consolidation calculation time is set to 2 days.

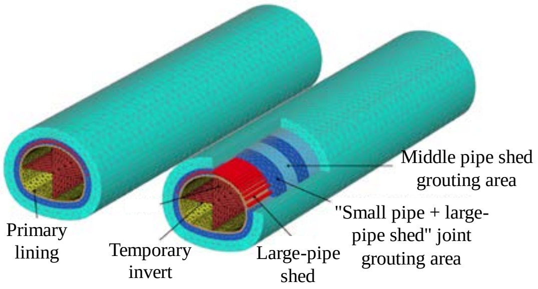


Fig. 9 Numerical model

Table 3 Parameters for numerical model

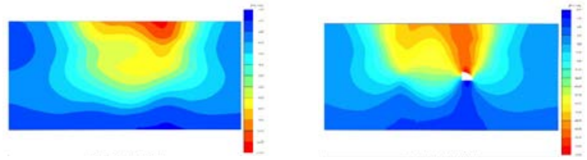
Soil type	E_{50}^{ref} /MPa	E_{oed}^{ref} /MPa	E_{ur}^{ref} /MPa	c' /kPa	φ' /°	G_0^{ref} /MPa	K_0	m	$\gamma_{0.7}$
③	2.7	2.25	18	10	27	63	0.5	0.8	0.0001
④	6.48	5.4	43.2	8	28	/	0.5	0.8	/
⑤	10.8	9	72	10	23	/	0.5	0.8	/

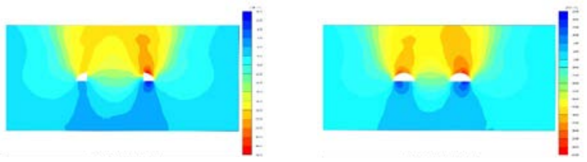
Note: E_{50}^{ref} *=secant stiffness in standard drained triaxial test;* E_{oed}^{ref} *=tangent stiffness for primary oedometer loading;* E_{ur}^{ref} *=unloading / reloading stiffness from drained triaxial test;* c'*=effective cohesion;* φ'*=effective friction angle;* G_0^{ref} *=reference shear modulus at very small strains;* K_0 *=coefficient of lateral earth pressure (initial stress state); m=power for stress-level dependency of stiffness;* $\gamma_{0.7}$*=threshold shear strain.*

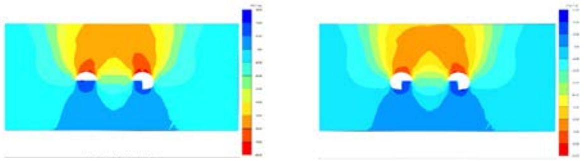
5.2 Numerical Results

The numeirical results of the settlement ouside river-affected area is shown in Fig. 10. The width of the tunnel surface settlement trough was basically set when the upper face of the west tunnel was 1.0 Hz (Hz is the height of the tunnel) from the center of the twin tunnels, and the surface settlement above the west tunnel reached 29.4% of the total settlement when the upper face of the west tunnel reached the distance from the center of the twin tunnels; 58.8% of the total settlement was reached when the excavation of the upper face of the west tunnel and the upper face of the east tunnel was completed. The surface settlement reached 82.3% of the total settlement after the excavation of the west tunnel and the east tunnel. The largest phase of tunnel surface settlement was caused by the excavation of the upper part of the east and west tunnels, which accounted for 45.9% of the total surface settlement, of which the excavation of the upper face of the west tunnel accounted for 29.4% of the total surface settlement. The excavation of the lower part of the tunnel accounts for 23.5% of the total surface settlement. Settlement at the center of the twin tunnels after the passage of the east and west lines accounted for 17.7% of the total settlement.

It can be seen from Fig. 10 that outside of the river-affected area, the main factor for the development of the tunnel surface settlement is the excavation of the upper face of the tunnel. The settlement when the tunnel face is fully excavated accounts for the main part of the total settlement. After all the tunnel face passes through the excavation face, the settlement will continue to increase by about 20%, which may be caused by the consolidation of surrounding soils.


(a) 15 steps (b) 20 steps


(c) 22 steps (d) 25 steps


(e) 29 steps (f) 31 steps

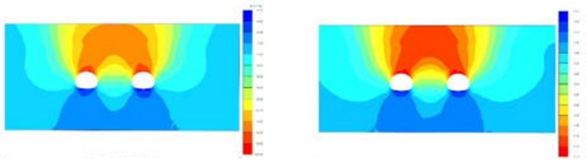
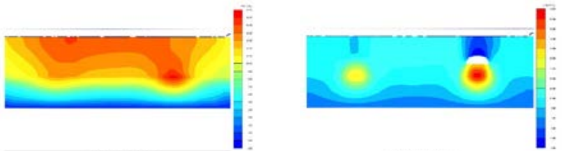
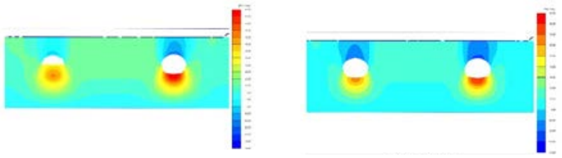

(g) 35 steps (h) 55 steps

Fig.10 Settlement ouside river-affected area

Fig. 11 shows the nmerical results of settlement inside river-affected area with cofferdam. It can be seen from Fig. 11 that after the upper face of the west tunnel reaches the center of the twin tunnels, the surface settlement is concentrated within the high-pressure piles on both sides of the tunnel, and at this time, the surface settlement above the west tunnel reaches 16% of the total settlement. When all the excavation of the twin tunnels is completed, the settlement of the ground surface above the west tunnel is 52%.

Compared with the numerical model calculation results outside the river affected-area (see in Fig. 10), the settlement is increased by 34.3%, which may be due to the decrease of the water level of the river in the middle section caused by the construction of the cofferdam above the tunnel, and the existence of a certain amount of groundwater seepage inside the soil. The reason for tunnel settlement in addition to the soil stress release induced by tunnel excavation, the groundwater seepage process is also a main cause for settlement. The small permeability coefficient of the soils around the river makes the settlement and consolidation time of the surrounding soils slower compared to the settlement caused by the excavation of the tunnel's face, which gradually stabilizes over time.


(a) 11 steps (b) 16 steps


(c) 18 steps (d) 20 steps

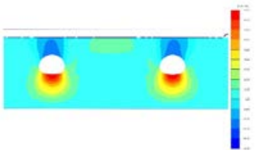
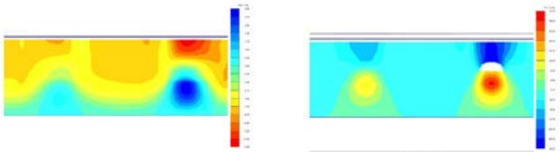

(e) 36 steps

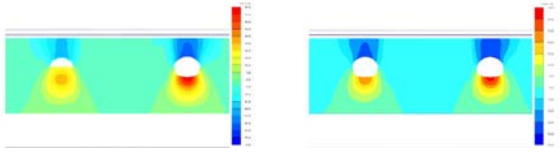
Fig.11 Nmerical results of settlement inside river-affected area with cofferdam

Fig. 12 shows the nmerical results of settlement inside river-affected area without cofferdam. Comparing the numerical results of Figs. 11 and 12, the influence of construction of cofferdam could be analyzed. From Figs. 11 and 12, it can be seen that the construction of tunnel cofferdam to reduce the water level of the river can make the surface settlement compared to the non-construction reduced by 39%. The instantaneous settlement of the tunnel is smaller with the cofferdam than that without the cofferdam, and nearly half of the surface settlement is developed after the whole tunnel face is passed, accounting for 52% of the total surface settlement. The surface settlement of the tunnel without the cofferdam increases faster when the tunnel face passes and increases slower after the tunnel face passes away. Therefore, the construction of the cofferdam should pay more attention to the subsequent settlement. When there is no diversion treatment under the river, more attention should be paid to the tunnel of the pre-grouting support and try to minimize the instantaneous settlement of the tunnel excavation.

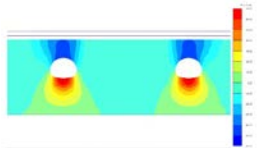
From Figs. 11 and 12, the tunnel cofferdam construction can reduce the surface settlement by 51.2% compared to the un-constructed construction, and the surface settlement after the tunnel passes through the excavated face is increased by 27.6% compared to the un-constructed construction. Surface settlement in the un-constructed tunnel is faster in the excavation of the tunnel face than in the cofferdam construction, and the amount of surface settlement after the tunnel face is completed is smaller than in the cofferdam construction.



(a) 11 steps (b) 16 steps



(c) 18 steps (d) 20 steps



(e) 36 steps

Fig.12 Numerical results of settlement inside the river-affected area without cofferdam

For the area affected by the river, the surface settlement of the tunnel after the construction of the cofferdam passes through the excavation surface due to the impact of groundwater seepage at 52%, which is an increase of 34.3% compared to the area outside the river (see in Fig. 11). During the construction process, more attention should be paid to the subsequent settlement development of the tunnel, and timely monitoring should be achieved. At the same time, the secondary lining strength of the tunnel should be reasonably designed to avoid further increases in surface settlement and cause engineering accidents.

6. CONCLUSIONS

This paper investigates the ground surface settlement during the excavation of a large-diameter shallow-buried twin tunnel in soft soil under the influence of a river. The main findings are summarized as follows:

1. Affected by the river, there are different settlement laws inside and outside the river-affected area. For a single monitoring point outside the river-affected area, the entire settlement development stage can be clearly divided into three stages: the slow growth stage in the early stage, the rapid growth stage in the excavation stage, and the gradual convergence stage in the last stage. However, inside the river-affected area, the settlement in the last stage will not converge but will continue to develop.
2. Compared with the vault settlement, the surface settlement inside the river-affected area develops slower than that outside the river-affected area, which shows good consistency with the monitoring data. The synchronization of the sinking rate and stability of vault settlement and surface settlement verifies that the river over the tunnel has an impact on the development of surface settlement by the groundwater seepage in the soft soil.
3. A numerical model is established to verify the correctness of the settlement law summarized above, which shows a trend consistent with the monitoring data. The existence of the river has an influence on the development of surface settlement, which may be due to the consolidation caused by groundwater seepage.
4. To better control the settlement caused by a tunnel undercrossing a river, reinforcements such as a cofferdam and pre-grouting support could be applied.

7. ACKNOWLEDGMENTS

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