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Research Article

Measured Analysis on Surface Deformation and Influence of Cutter Torque for Twin Shield Tunnelling in Silty Sand

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In this study, the field measurement was conducted on the twin shield tunnelling in a shield section of Hangzhou Metro Line 6, where the surface deformation caused by twin shield tunnelling in the silty sand was obtained. The surface deformation law and the applicability of the twin-line Peck formula in the silt area were analyzed. The relationship between the cutterhead torque and the surface deformation in the silty sand was identified. Furthermore, the differences in surface deformation of twin shield tunnelling in the Hangzhou soft soil area were discussed. The results show that the settlement process caused by twin shield tunnelling in silty sand is faster than that of soft soil and has no rebound phenomenon. The twin-line Peck formula is suitable in silty sand, but the prediction of the latter line using this formula is slightly deviated because of the secondary disturbance effect. Due to the secondary disturbance of the soil caused by the construction of the latter line, the soil loss rate of the latter line is higher than that of the former line. Therefore, the reference ratio of the soil loss rate of the latter line and the former line is given. Furthermore, the cutterhead torque of the shield machine was found to be associated with the maximum instantaneous value of the surface deformation.

1. Introduction

In recent years, the development of subway tunnel engineering is very rapid, and tunnel engineering plays a very important role in the development of infrastructure constructions [1, 2]. Among the urban tunnel construction method, the shield method is widely used due to its fast construction speed and simple technology. However, it is inevitable to cause some disturbance to the surrounding soil. This can break the stress-balanced stress state of the original underground space and cause some deformation of the surrounding soil in the process of shield tunneling [3–5], which are particularly obvious in the double-line shield construction. The measurement and analysis of surface deformation is the most common method to study the disturbance of surrounding soil resulted from the shield construction, and the monitoring results can directly reflect the actual surface deformation. Therefore, the measured analysis of ground deformation caused by shield construction has important engineering significance for ensuring construction safety and guiding soil reinforcement [6].

Many scholars have studied the surface deformation caused by shield construction, mainly based on the measurement analysis method [7–12] and the numerical simulation method [13–18]. The research on the deformation of surrounding soil caused by twin parallel shield tunneling mainly relies on the Peck empirical formula, which can be divided into two categories: (1) using the Peck formula to directly calculate the total deformation of surface deformation and (2) using the Peck formula to calculate the surface deformation caused by the former and latter tunnel excavation, respectively, and then the total surface settlement deformation is obtained by superposition. In terms of field measurement and analysis, Ding et al. [19] measured and analyzed the surface settlement caused by twin shield tunnelling in the soft soil area and explored the law of surface deformation and the value of soil loss rate. Wei et al. [20] studied the relationship between surface deformation and cutterhead torque during shield tunneling through the statistical analysis of monitoring data and construction parameters of Hangzhou Metro Line 2 and obtained a suitable calculation method of cutterhead torque value for Hangzhou soft clay soil. Wan et al. [21] carried out research on the difficulties of cutterhead wear, blockage, and surface settlement encountered in the construction of shield machine in the typical water sand cobble layer. They found that the opening rate, maximum opening size, and opening position are the key factors affecting the geological adaptability of the shield machine.

The bearing capacity of silty sand is low, the permeability of the wall is high, and the internal friction angle is large [22]. Therefore, the rotary cutter working in silty sand is often bonded and worn, and even the working face collapses due to the cohesionless dispersion of silty sand material [23]. Moreover, liquefaction is easy to occur under the vibration of shield construction. To ensure the stable and efficient construction of shield in silty sand, it is necessary to reduce the disturbance to the stratum during tunneling and reduce the risk of spewing and blocking during soil discharge. However, at present, there are few studies on the influence of surface deformation and construction parameters caused by twin shield tunneling in silt sand. In addition, the influence of shield tunneling construction parameters on surface deformation is not considered in the abovementioned study. Therefore, it is of great engineering significance to explore the soil deformation caused by twin shield tunneling in silt sand.

Based on the statistical analysis of the measured data of a twin shield tunnel in Hangzhou Metro Line 6, this work studies the surface deformation in the process of twin shield construction in silt sand and makes a comparative analysis with the soft clay area. The application of Peck-based empirical formula and basic assumptions in the process of twin-line excavation in the silty sand area is investigated. The reference ratio between the soil loss rate in the former line and the latter line in the silty sand area is proposed. The relationship between shield construction parameters and surface deformation is discussed.

2. On-Site Monitoring Experiment

2.1. Project Overview. This study takes the double-track single-round shield section of Shuangpu station to Heshan Road Station of Hangzhou Metro Line 6 as the research object. The section line is located along Kehai Road, Shuangpu Town, Xihu District, Hangzhou, China, with a total length of 2486 m. The left and right lines of the section adopt a V-shaped slope, and the buried depth of the tunnel top is 9.0~15.5 m. Shi Chuan island shield machine is adopted, with an opening rate of 45%. As the shield machine in this section passes through the sandy soil, the cutterhead panel is cut off to become a spoke cutterhead. Increasing the opening rate of the cutterhead is conducive to the slag entering the soil bin. The lining structure of the tunnel adopts prefabricated reinforced concrete segment lining, with an inner diameter of 5.5 m, an outer diameter of 6.2 m, and a width of 1.2 m, which is staggered joint assembly.

The distribution and parameters of the soil layer are shown in Table 1. In the table, W is the moisture content of soil layer, γ is the wet gravity, e is the void ratio, E_S is the compression modulus, ρ is natural density, K_0 is the static side pressure coefficient, ϕ_{cq} is internal friction angle, and V is Poisson's ratio. The geological section of shield tunneling is shown in Figure 1.

2.2. Layout of Measuring Points. In order to understand the surface deformation of the silty sand shield section in the process of tunneling, the monitoring points are arranged at the construction site. The layout of the monitoring points is as follows: several longitudinal monitoring points are arranged at intervals along the advancing direction of the tunnel on the central axis of the tunnel, and the transverse monitoring section is arranged perpendicular to the axis direction. A monitoring face is set every 35 meters on the tunnel axis and every 25 meters within 120 meters of the shield starting section. In special cases, a monitoring face is set, such as the place where the geological conditions change greatly and the places, where many buildings exist above the soil layer. Each monitoring surface is symmetrically arranged with the axis as the center to 1.5 m, 5 m, 7.5 m, 10 m, 13.5 m, 18.5 m, and L m (adjusted according to the tunnel buried depth). The layout of some monitoring sections is shown in Figure 2.

3. Analysis of Experiment Results

3.1. Analysis of Transverse Surface Deformation Law. Based on the measured data of surface deformation of each monitoring section, the variation trend of each monitoring cross section in the process of twin shield tunneling in the Hangzhou silty soil area is analyzed. It is found that the final settlement curve generally presents a "W" shape and is asymmetrical. Three typical sections were selected in this study. The former tunnel and the latter tunnel were located on the left and right sides of the middle line, respectively. As shown in Figures 3–5, the abscissa in the figure represents the amount of surface deformation, and the abscissa represents the horizontal distance between the monitoring point and the middle line of the tunnel. The maximum surface settlement above the latter line is obviously larger than that of the former line. The maximum surface deformation caused by the latter tunnel is larger than that of the former tunnel. The main reason is the superposition disturbance effect of the latter tunnel on the soil. There is a little difference in the secondary disturbance effect of each section.

Figure 6 shows the measured surface deformation curve of a section of Hangzhou Metro Line 2. The shield mainly passes through the soft soil layer. Compared to Figures 3–5, it is found that the final settlement trend of surface

Table 1: Parameters of soils.

Soil properties	W (%)	γ (kN/m^3)	e	E_S (MPa^{-1})	ρ (g/cm^3)	K_0	ϕ_{cq} (°)	V
③ 3 Sandy silt with silt	26.0	19.5	0.742	0.100	1.95	0.40	28.0	0.29
③ 31 Silt	25.4	19.6	0.716	0.083	1.96	0.34	30.0	0.29
③ 5 Sandy silt	25.3	19.7	0.706	0.100	1.97	0.37	29.0	0.29
③ 6 Silt	25.3	19.5	0.721	0.086	1.95	0.32	31.0	0.26
⑤ 33 Silt	23.5	19.7	0.687	0.096	1.96	0.32	31.5	0.26

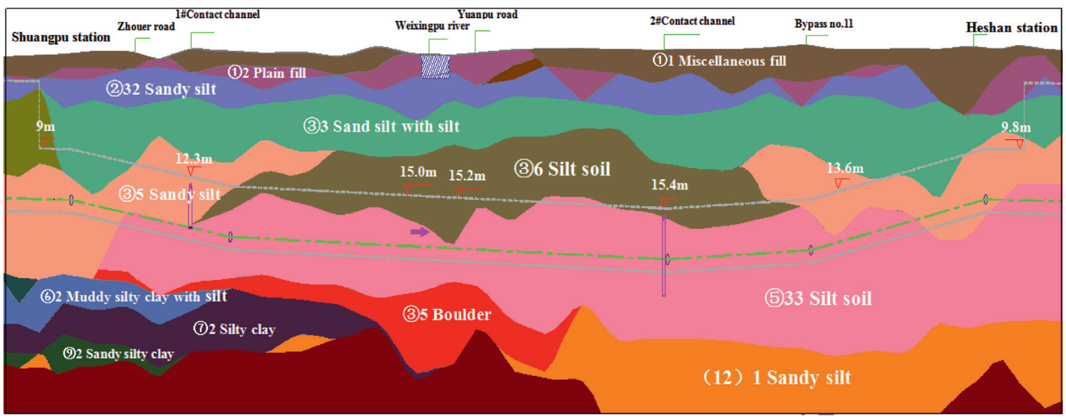

Figure 1: Geological profile of shield tunnel under construction.

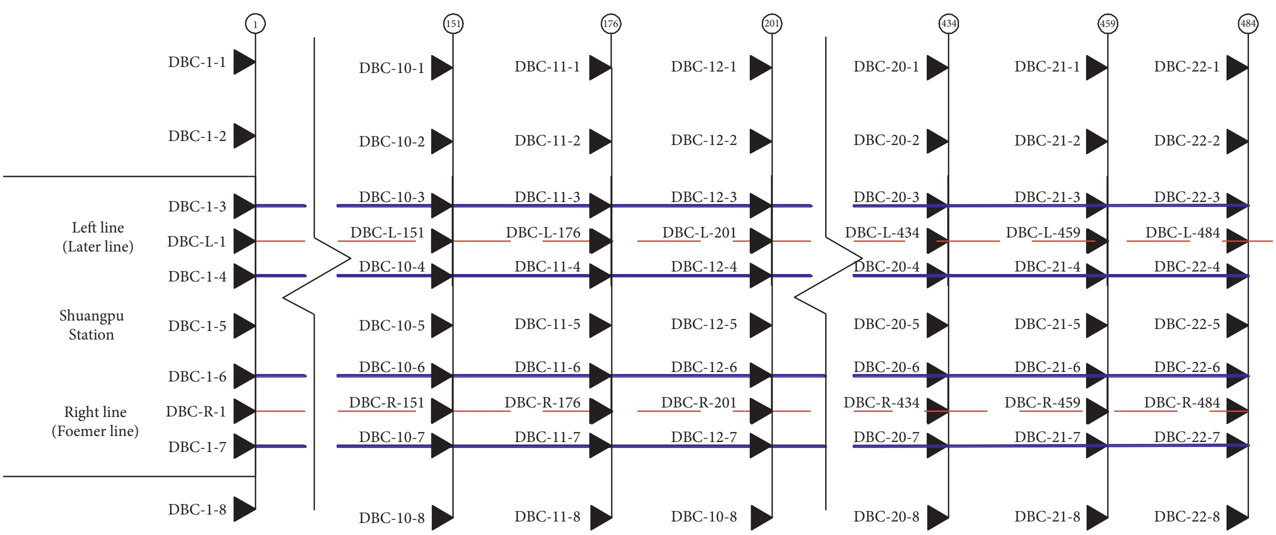

Figure 2: Layout of partial measuring points.

transverses deformation caused by twin shield tunneling in the soft soil area, which still conforms to the above rules. The average settlement of the latter line in the soft soil area is about 1.5 times bigger than that of the former line, while it is about 2 times in the silty sand area. It can be seen that the secondary disturbance effect produced by shield tunneling in silty soil area is stronger than that in soft soil, which indicates that the secondary disturbance phenomenon has a greater impact on silty soil than that in soft soil. Therefore, when the twin shield tunnelling is not properly controlled in the Hangzhou silt soil area, the surface deformation value is easy to exceed the alarm value, thus affecting the construction safety. The reason that the additional settlement caused by the secondary disturbance effect of shield construction in silty soil area is more obvious than that in the soft soil area obtained from the field monitoring. This is related to the porosity and permeability of silty soil. Compared with soft soil, silty sand soil has larger void and lower cohesion [24]. Therefore, the self-stability of silty sand is worse and the effect of disturbance is greater.

3.2. Analysis of Surface Deformation with Time. In the process of shield construction, the surface will change with the different advancing stages. The measurement points with the largest deformation in the tunnel section during the

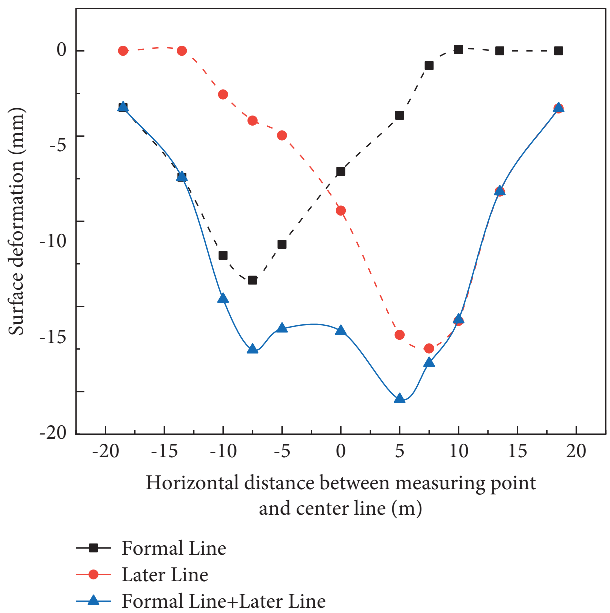

Figure 3: Surface deformation of section DBC10.

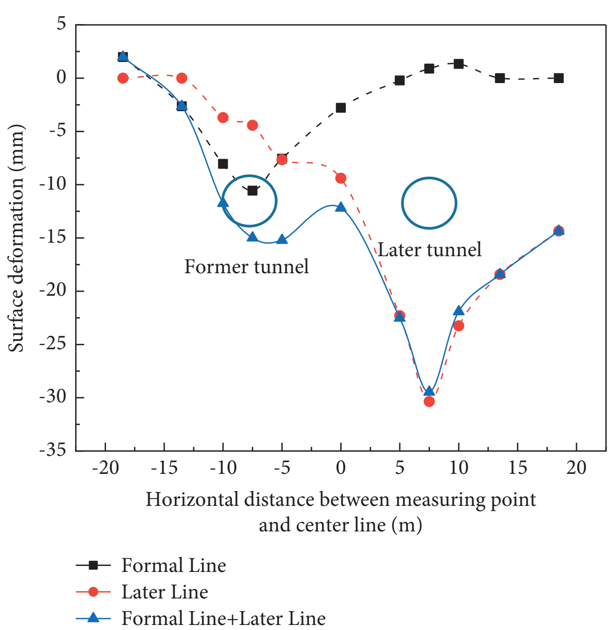

Figure 4: Surface deformation of section DBC26.

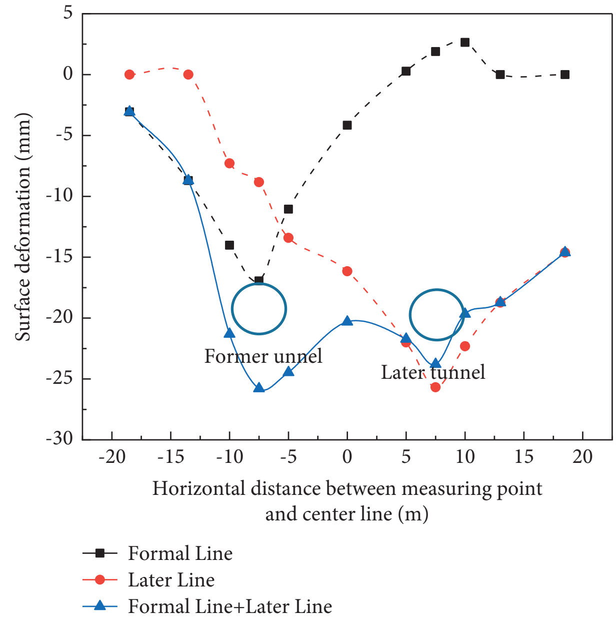

Figure 5: Surface deformation of section DBC35.

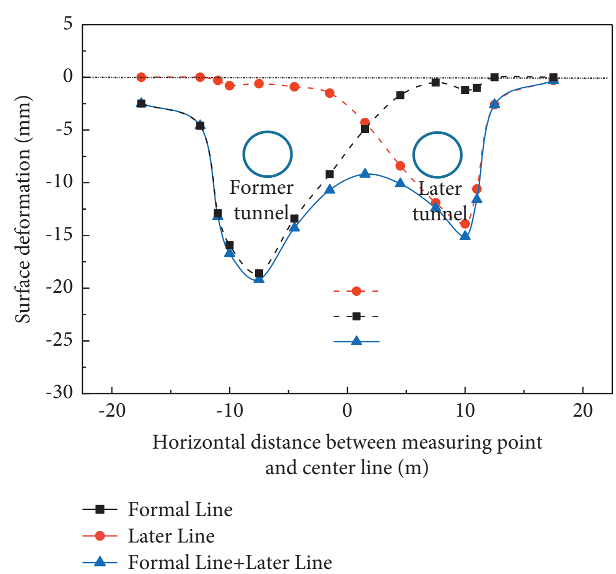

Figure 6: Measured curve of surface deformation of a section of Hangzhou Metro Line 2.

construction process are selected, respectively. As shown in Figures 7 and 8, the cumulative deformation curves of the largest deformation points in section DBC6 and section DBC26 are recorded. In the figures, the ordinate represents the amount of surface deformation, and the abscissa represents the time for the shield to pass through the monitored section. The negative value of the abscissa represents the days when the shield has not reached the monitoring section, and the positive value represents the days when the shield has crossed the monitoring section.

It can be seen from the analysis of Figures 7 and 8 that when the shield machine reaches the monitoring section, the soil begins to settle rapidly. During the process of the shield machine passing through the monitoring section, the soil continues to settle, and the settlement speed gradually slows down after the shield tail passes through the monitoring section and finally tends to be stable. This is consistent with the stratum deformation law in the sandy silt area obtained from the research in literature [25–27]. Compared to Figure 9, different from the conclusion of [19] in the study of shield tunneling in soft soil areas, silty sand does not begin to settle one day earlier than soft soil, and there is no obvious rebound. The settlement in silty soil areas tends to be stable about 2 days

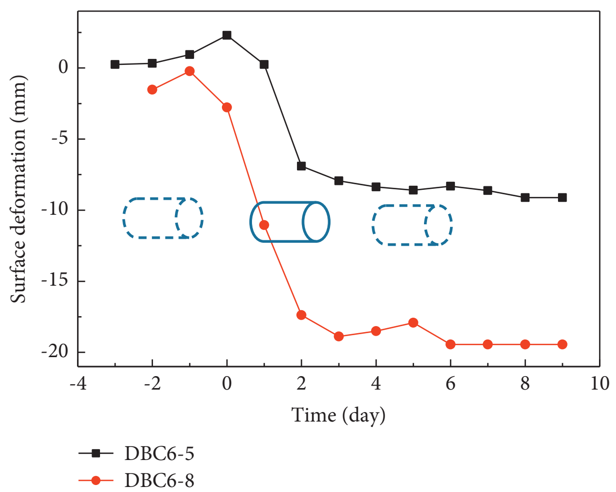

FIGURE 7: Deformation of monitoring points in section DBC6.

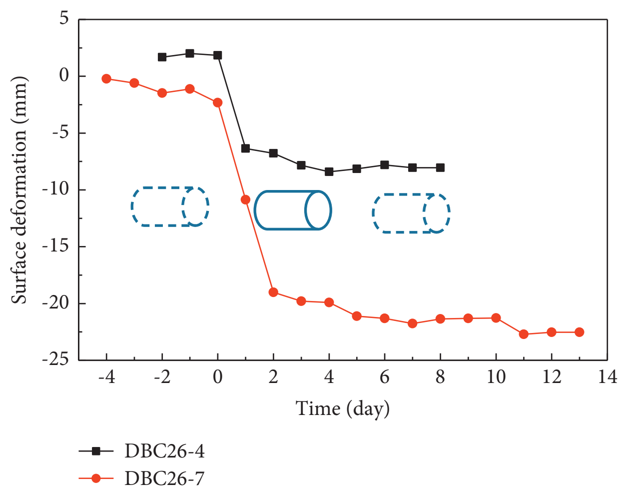

FIGURE 8: Deformation of monitoring points in section DBC26.

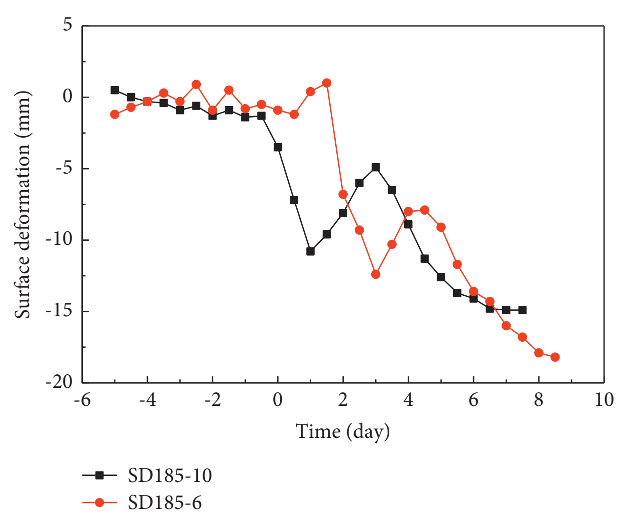

FIGURE 9: Accumulated deformation curve of SD185 section in Feng-Gu section of Hangzhou Metro Line 2.

after the shield machine reaches the cross section, while it tends to be stable in soft soil areas for a longer time. The reason is that the permeability coefficient of silty sand is larger and the pore water pressure dissipates faster after being disturbed by shield construction [28].

By comparing the cumulative surface deformation of the former line and the latter line in the process of shield tunneling in silty soil and soft soil, it is found that the soil deformation of the latter line is more obvious under the action of the second disturbance. As shown in Figures 7 and 8, the maximum settlement of the latter line of the monitoring section in the silty soil area is 2.11 times and 2.75 times that of the former line, which is significantly larger than that in the soft soil area about 1.5 times that of the former line [17]. Compared with soft soil, the seepage characteristics of silt soil are one of the potential causes of larger soil deformation and failure [29]. This is related to shear strain, sliding fraction, volumetric strain, particle displacement, and the cohesive failure zone of silt soil. From a microscopic point of view, the deformation characteristics of silt soil are affected by the pore size, distribution, shape, and arrangement of the silty clay at the bottom and side of the tunnel [30]. It proves the conclusion that the influence of secondary disturbance on silt soil is greater than that on soft soil. Therefore, special attention should be paid to the settlement of the latter line during construction. At the same time, the settlement of silty sand changes rapidly, so it is necessary to do a good job in the early prevention, which can provide a reference for construction and field monitoring.

4. Applicability Analysis of Peck Formula

Peck [7] statistically analyzed a large number of measured data of surface deformation caused by subway construction. Considering that the soil loss causes stratum movement, he proposed that the soil is in an undrained state during ground settlement, and the volume of soil loss is equal to the volume of the settlement tank. The surface settlement trough above the tunnel is in accordance with the normal distribution, and the horizontal settlement formula of the surface is obtained as follows:

$$S(x) = S_{\max} \exp\left(-\frac{x^2}{2i^2}\right),$$
$$S_{\max} = \frac{V_{\text{loss}}}{i\sqrt{2\pi}} = \frac{\pi R^2 \eta}{i\sqrt{2\pi}}, \qquad (1)$$

where x is the horizontal distance from the tunnel axis; $S(x)$ is the surface settlement at the location x; $S_{\max}$ is the maximum surface settlement above the tunnel axis; i is the width coefficient of the ground settlement tank; V_{loss} is the soil loss per unit length; R is the tunnel excavation radius; and η is the soil loss rate. On the basis of the Peck formula, Suwansawat and Einstein [31] studied the ground deformation formula of a double-line shield tunnel.

$$\delta(x) = \frac{\pi R^2 \eta_1}{\sqrt{2\pi} i_1} \exp\left(-\frac{(x - D/2)^2}{2 i_1^2}\right) + \frac{\pi R^2 \eta_2}{\sqrt{2\pi} i_2} \exp\left(-\frac{(x + D/2)^2}{2 i_2^2}\right), \quad (2)$$

where i_1 is the width coefficient of the ground settlement slot of the former tunnel; D is the soil loss rate of the former tunnel; D is the width coefficient of the ground settlement slot of the latter tunnel; η_2 is the soil loss rate of the latter tunnel; and D is the distance between the two tunnel axes.

Wei [32] summed up the value method of the width coefficient of the tunnel ground settlement trough based on a large number of literature studies. The value method of the width coefficient of the ground settlement trough is divided into three categories. According to the applicable conditions, three types of formulas suitable for silty sand are selected as follows:

$$i = (1 - 0.02\varphi)h, \quad (3)$$

$$i = 0.25(h + R), \quad (4)$$

$$i = kh. \quad (5)$$

In the formula, h is the depth from the tunnel axis to the ground; φ is the internal friction angle of the soil above the tunnel axis; and R is the outer radius of the tunnel, in which, in formula (3), φ takes 35° to 40° and in formula (5), k takes 0.2 to 0.3.

In this study, the surface deformation is predicted based on the condition of monitoring section DBC10. The i obtained by formulas (3) and (5) is 3~4.5, and the i obtained by formula (4) is 4.5. Therefore, i the former line takes 4.5, and if the value is assumed to be proportional to the final settlement, i the latter line takes 5.84. The predicted settlement curve is drawn by substituting it into the formula. The predicted results and measured surface deformation are shown in Figures 10 and 3.

Comparing the curves in Figures 10 and 3, it is found that the measured deformation curve and the predicted curve of section DBC10 present "W" shape, and the measured deformation curve and the predicted curve of other monitoring sections are basically similar in shape, with a high degree of coincidence, but there are some differences between the surface settlement values of the latter line of some sections and the predicted values. It can be seen that using the two-line Peck formula to predict the surface deformation caused by twin shield tunneling in the Hangzhou silt soil area has a certain reference value.

At present, there is no reasonable method to calculate the soil loss rate. In this study, according to the back analysis method described by Wei [33], combined with the measured data of surface settlement, formula (6) is used to calculate the value of η. When the back-calculation points are selected according to the measured data, only the sections whose measured surface deformation conforms to the prediction of the peck formula are selected.

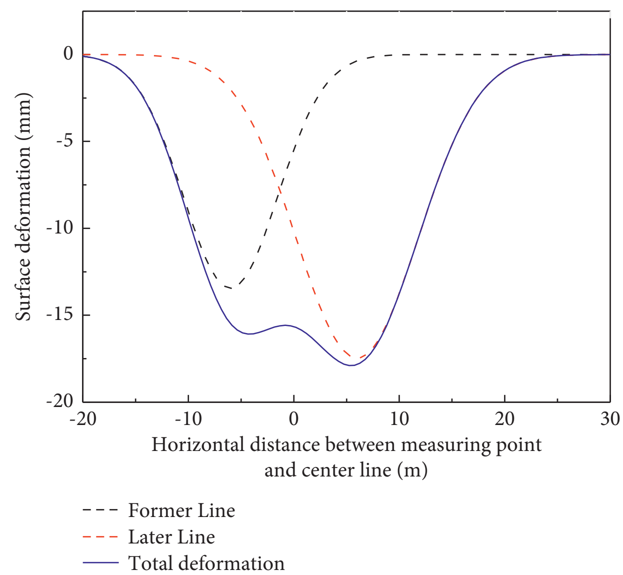

Figure 10: Prediction of surface deformation of section DBC10.

$$\eta = \frac{S_{max} i \sqrt{2\pi}}{\pi R^2}. \quad (6)$$

The distribution of soil loss rate of each section is listed in Table 2, and the variation law of soil loss rate during double-line shield construction in silty soil area is analyzed. It can be seen from Table 2 that the main distribution range of soil loss rate of each effective monitoring section in this test is 0.2%~0.8%, accounting for 88.46% of the total, of which 0.2%~0.5% is the most, accounting for 57.69% of the total, which is similar to the situation of Hangzhou silt area. Further analysis shows that the average soil loss rate of the latter line is 1.83 times that of the former line, and 11.54% of the soil loss rate of the latter line reaches 0.8~1.2%, which is because the soil loss rate of the latter line is increased due to the influence of secondary disturbance. Therefore, when the two-line Peck formula is used to predict the surface deformation of silty soil area, it is suggested that the soil loss rate of the latter line should be 1.8 times that of the former line.

Table 3 shows the distribution of soil loss rate of shield construction in a soft soil section of Hangzhou Metro Line 2. Compared to the distribution of soil loss rate in the silty sand section in Table 2, the soil loss rate of the former line of silty sand is less than that of soft soil, and that of the latter line is close to or even greater than that of soft soil, which is consistent with the conclusion that silty sand is more affected by secondary disturbance.

In this study, the soil loss rate of each section of the former line and the latter line is drawn according to the ring number, as shown in Figure 11. The soil loss rate has no obvious change rule because the construction parameters in the process of shield tunneling have a great impact on the soil loss rate, and the slight change of construction parameters will greatly affect the soil loss rate.

Table 2: Distribution of loss rate in silt soil region in Hangzhou Metro Line 6.

Soil loss rate	0.2~0.5		0.5~0.8		0.8~1.2		Average value
Range (%)	Number	Proportion (%)	Number	Proportion (%)	Number	Proportion (%)	
Former line	9	34.62	5	19.23	0	0.00	0.42
Latter line	6	23.08	3	11.54	3	11.54	0.77
Total	15	57.69	8	30.77	3	11.54	0.6

Table 3: Distribution of loss rate in soft soil region in Hangzhou Metro Line 2.

Soil loss rate	0.2~0.5		0.5~0.8		0.8~1.2		Average value
Range (%)	Number	Proportion (%)	Number	Proportion (%)	Number	Proportion (%)	
Former line	7	58.33	4	33.33	1	8.33	0.49
Latter line	6	42.86	6	42.86	2	14.28	0.61
Total	13	50.00	10	38.46	3	11.54	0.55

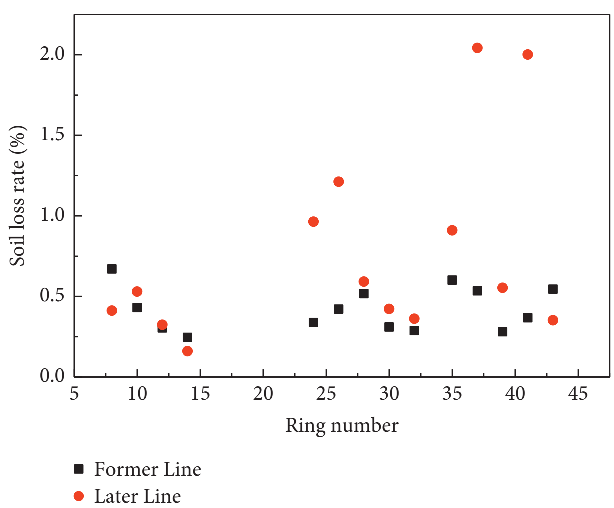

Figure 11: Loss rate of all sections.

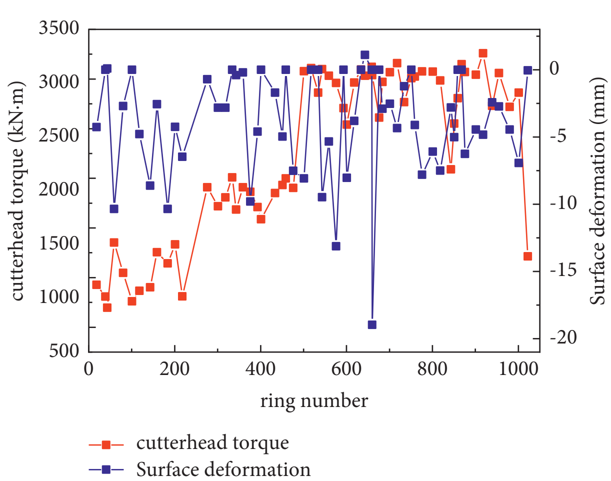

Figure 12: Relationship between displacement and torque of the former line.

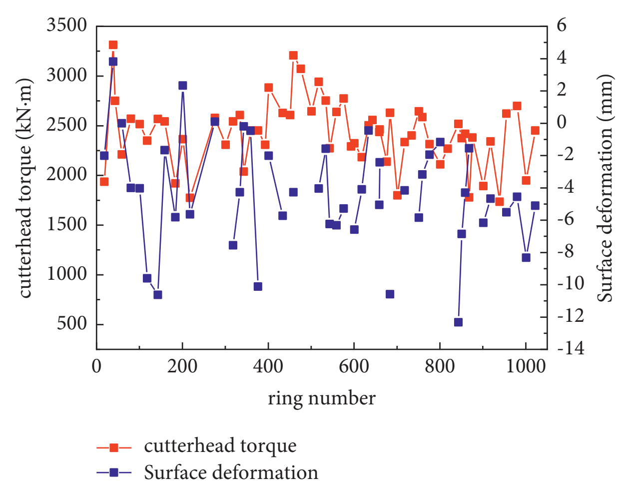

Figure 13: Relationship between displacement and torque of the latter line.

5. Correlation Analysis of Cutterhead Torque and Surface Deformation

The correlation between the instantaneous ground heave (the maximum deformation of the measuring point 12 hours after the shield machine passing) and the cutterhead torque of the shield machine is studied. The instantaneous deformation value and corresponding cutterhead torque value of each monitoring point at the arrival of the shield machine on the former line and the latter line are recorded, as shown in Figures 12 and 13.

Comparing Figures 12 and 13, it can be found that the absolute value of the maximum deformation value of the latter line is about 1.3 times bigger than that of the former line. At the same time, there is a similar proportion between the average torque of the former line and the latter line. The average torque of the latter line is 2645 kN·m, and the average torque of the former line is 2073 kN·m. This indicates that the maximum surface deformation value is related to

Table 4: Maximum torque values of different cases.

Case	Cutterhead diameter (m)	Soil properties	Maximum torque (kN·m)
Hangzhou Metro line 6	6.2	Silty sand	3366
Metro Izmir, Turkey	6.52	Sandy gravel	5200
London Heathrow Airport Tunnel	9.15	London clay	18842
Hangzhou Metro line 2	6.17	Muddy silty clay	2082

the average torque during the shielding process. The main reason for the difference between the average torque of the former line and the latter line and the surface deformation is that the second disturbance is carried out during the driving process of the latter line, which increases the soil loss rate, especially for the silt soil. The porosity is higher. The pore size between the soil particles is uneven, and the influence of the construction disturbance is greater.

In this study, the cutterhead diameter and maximum torque of the shield machine in several engineering cases are selected for comparative analysis. It can be seen from Table 4 that the cutterhead excavation diameters of Hangzhou Metro Line 6 and Line 2 are basically the same. However, the soil layer changes from silty sand to muddy silty clay, and the maximum cutterhead torque is reduced to 0.62 times the original. The diameter of the London Heathrow Airport Tunnel is about 1.5 times bigger than that of the others, while the maximum torque is far more than that of other cases. It can be seen that the cutterhead excavation diameter and the excavation soil condition have a significant impact on the cutterhead torque, and the author speculates that the main reason is that the cutterhead diameter and the strength indexes of the shield tunneling soil are important parameters for calculating the cutterhead torque.

6. Conclusion

This study investigated and studies the surface deformation and the influence of cutterhead torque caused by twin shield tunneling in silt sand. The following results and conclusions are obtained as follows:

(1) The transverse deformation of the cross section of twin shield tunneling presents a "W" shape, whether in silt or soft soil. In the silty soil area, when the shield tunneling reaches the monitoring section, the soil settles sharply, which is different from the soft soil area. After the shield tail passes through, the soil continues to settle and the settlement speed slows down and finally becomes stable. In the silt soil stratum, the secondary disturbance effect of twin shield tunneling is stronger than that in the soft soil area, which should attract more attention in construction.

(2) By combining the measured data analysis with the theoretical formula, this work puts forward the hypothesis that the width coefficient of settlement slot of twin shield tunnel is related to the final settlement. The applicability of the two-line Peck formula in the Hangzhou silt soil area is verified.

(3) Compared to the soft soil area, the secondary disturbance effect produced by shield tunneling in silty soil area is more obvious, and the reference ratio of the soil loss rate of the latter line and the former line is proposed. In addition, the soil loss rate is difficult to be determined in the process of shield tunneling because of the variable construction parameters and great impact on the soil loss rate law.

(4) There is the same proportion between the ratio of the instantaneous maximum settlement and the average torque of the former line and the latter line. Through combining with the measured data and comparing with other cases, it is found that the cutterhead excavation diameter and soil conditions have a greater impact on the cutterhead torque, which should be paid attention to in shield construction.

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 regarding the publication of this paper.

Acknowledgments

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