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Numerical Investigation of Deformation Influence of Existing Viaduct Piles under MJS Construction Method

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Abstract

To overcome the impacts of pile construction by Metro jet system (MJS) to the adjacent existing buildings, taking Hengqin underground traffic project in Zhuhai, China as engineering background, a numerical model was constructed by using Plaxis 3D technique, and the fluid-solid coupling analysis of the optimized construction scheme was carried out. The predicting model for the settlement of adjacent existing bridge piles by MJS reinforcement was put forward. Results show that the influence of MJS on the existing viaduct piles is gradually weakened from near to far, but the influence on the existing C3 bridge piles with a distance of only 0.75 m is significant. The maximum horizontal displacement is up to 6.5 mm. The horizontal deformation of the bridge foundation caused by MJS is much larger than the settlement, and the horizontal deformation of bridge foundation is mainly inclined to the side of MJS pile. The cement slurry filling ratio has a great influence on the horizontal deformation of the bridge pile, and the influence is the least when the cement slurry content reaches 30%. The conclusions obtained in this study provide a reference for design and application of MJS.

Keywords: Metro jet system (MJS), Viaduct piles, Shield tunnel, Soil reinforcement

1. Introduction

With the development of urban economy, urban traffic congestion affects people's daily travelling. With the maturity of underground construction technology, the underground rail transit has become an effective way to alleviate urban traffic pressure. However, in order to ensure the safe construction of underground engineering and reduce the impact on the surrounding environment, MJS (Metro jet system) pile reinforcement has gradually become the main means of the deep foundation support engineering, shield section and other underground engineering [1-3].

During the construction of urban underground engineering, the construction methods such as shield excavation and support will inevitably cause irreversible damage to the existing structures in the surrounding area. The adjacent existing (structure) buildings have excessive deformation caused by construction, the normal use and the maintenance of the buildings will be affected seriously, and there are serious potential risks and security risks [4-7]. MJS is a construction method that pressurizes and conveys the ingredients of the hardened material mud, sprays, cuts the formation, mixes, forcibly discharges the mud, and concentrates the mud. It can carry out horizontal foundation reinforcement and 360° all-round foundation reinforcement, and has a positive and small impact on the surrounding environment and foundation disturbance.

Therefore, it is of great theoretical significance and practical value to study the influence of MJS pile grouting construction on the stability of the existing bridge foundation. In addition, the study on the deformation characteristics of the adjacent existing bridge foundation caused by the underground construction can provide a basis for the safety evaluation and structural optimized design of the bridge.

2. State of the art

As an effective way of reinforcement, the high pressure jet grouting pile is widely used in soil reinforcement of various fields. The grouting pressure of the high pressure jet grouting pile is generally about 20 MPa, and it is impossible to control the amount of grout discharge and the hole pressure by using the form of natural grout return at the orifice. Especially in some areas such as soft soil reclamation, the soil pressure will rise instantaneously due to the poor drainage, which will cause surface subsidence and excessive deformation of surrounding buildings. Based on the improvement of the traditional high pressure jet grouting process, the MJS method replaced the double pipe with the porous pipe to realize the control integration in the aspects of forced slurry discharge, pressure monitoring and formation pressure, so as to reduce the disturbance of the existing buildings by the project construction [8-11]. To ensure safe operation of the existing stations and tunnels, Zhao and Yang adopted the method of combining subway injection system with artificial ground freezing technology to evaluate the influence of hydration heat of cement paste on the ground freezing process during the removal of supporting walls in subway stations. They found that the end section heat preservation in summer and winter could reduce

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the active freezing time by 53 d and 3 d, respectively [12]. Due to the injection of cement paste, the hydration heat reaction of MJS slurry inevitably increased the artificial ground freezing time. Shi et al. carried out hydration heat reaction tests on the improved soil with different cement content and curing time in MJS construction method. They found that the cement slurry improved the initial setting point of soil, and the curing time and cement content greatly affected the thermal conductivity [13].

At present, subway jet grouting reinforcement is often used to strengthen and repair the existing structures around the construction. However, due to lack of sufficient theoretical support and engineering basis, the influence of MJS reinforcement method on adjacent existing buildings needs to be further studied. Chen et al. adopted MJS construction method to strengthen the sandy soil layer under the existing double tunnel. In the process of shield penetration, the deformation of the existing tunnel affected by the new tunnel was monitored in real time. The deformation of the existing tunnel went through four stages: settlement, uplift, secondary settlement and stable state [14]. Through the analysis of the applicability of MJS in Ningbo soft soil and the soil squeezing effect of MJS construction on the surrounding environment, combined with the building deformation data during construction, Ye et al. analyzed the influence of MJS construction on the surrounding buildings [15]. De et al. adopted the horizontal pile reinforcement method of MJS to study the internal deformation characteristics of the shield through the existing tunnel in water-rich sand and the formation effect of MJS pile. They found that the settlement of the overlying existing tunnel showed a Gaussian curve distribution law, and the influence on the surrounding environment was relatively small in the MJS horizontal pile reinforcement area [16-17]. Luo et al. strengthened the existing tunnel disturbed by MJS pile construction through field tests and carried out a numerical simulation analysis of the reinforcement system combined with the direction of seismic waves. They found that the MJS pile reinforcement could effectively reduce the settlement and the radial deformation of the existing tunnel, and the seismic wave had a significant effect on the settlement deformation of the tunnel [18-19].

MJS construction method is widely used in adjacent subway foundation pit, however, there is a lack of understanding of the construction parameters and pile quality of MJS construction method under different soil environmental conditions [20-21]. Li and Yang established the finite element model of the tunnel shield construction, and they used the omnidirectional high-pressure jetting pile to simulate the tunnel through the existing elevated pile foundation, and analyzed the influence of MJS pile construction on the deformation and the bearing capacity of the existing pile foundation in short distance [22]. To study the disturbance influence of subway foundation pit excavation on the existing bridge piles, Yang et al. established a three-dimensional numerical model of the deep foundation pit adjacent to the subway to simulate the excavation, and studied the bridge pile and the ground settlement by changing the construction parameters of MJS pile. They found that the optimum distance from MJS pile to wall was 0.225 times of the excavation depth of foundation pit. In addition, the settlement deformation of the surface and the wall could be effectively reduced by changing elastic modulus of MJS pile [23]. Li et al. established a numerical model of tunnel excavation with upper soft and lower hard composite strata combined with field monitoring data, and they evaluated the reinforcement effect of the subway jet system adjacent to the existing viaduct piles [24]. Song established the numerical model of the shield tunnel to simulate the excavation, and studied the influence of the lower tunnel excavation on the upper high-speed railway roadbed. They not only analyzed the horizontal reinforcement mechanism and the construction control technology of MJS, but also revealed the settlement characteristics of the ballastless-track roadbed of high-speed railway [25].

Combined with the actual engineering situation of Hengqin underground traffic project in Zhuhai, China, a numerical simulation model of pile foundation by the MJS construction method was established by using Plaxis 3D technique in this study. Considering the factors such as the displacement and the pore pressure, the construction technical parameters were set, and the fluid-solid coupling simulation analysis of the optimized construction scheme was carried out. Through the real-time monitoring of the settlement of the bridge pier and the deep horizontal displacement of the soil around the bridge pile, the structural evolution and the deformation characteristics of pile foundation near the existing bridge during the grouting reinforcement of MJS pile were studied, and the simulation results were verified by the monitoring data. The research results can provide the theoretical basis for stability evaluation and deformation control of the adjacent existing bridge piles, and provide the technical support for the similar projects.

The rest of this study is organized as follows. Section 3 introduces the engineering background, numerical simulation model, site construction and monitoring scheme. Section 4 analyzes the simulation and test results, and finally, the conclusions are summarized in Section 5.

3. Methodology

3.1 Engineering background

The Hengqin underground rail transit project in Zhuhai is located in the coastal area, and the clearance of the tunnel is 7.0 m, and the buried depth of the tunnel is about 17 m. The length of the shield is 890 m, and the outer diameter of the segment is 7.7 m, and the thickness of the segment is 350 mm, and the width of the segment is 1.2 m. The side of the shield passes through Lianhua bridge, and the lower part of the shield passes through the 460 m wide Shizimen waterway, and then reaches the shield receiving working well. The nearest distance from the shield excavation edge to the C3 pile of Lianhua bridge is only 0.75 m, as shown in Fig. 1.

The buried depth of groundwater table is 2.0 m. The geological conditions of the site from top to bottom are as follows:

(1) Plain fill: brownish yellow or brown red, mainly composed of clayey soil, mixed with 10%-20% medium-coarse sand, partially sandwiched with macadam, thickness of 2.0-3.5 m, the average hammering number is 3.81.

(2) Silt: grayish brown or dark gray, flow plastic, containing a little rot, shell and fine sand, the thickness is 6.9-20.0 m, and the average hammering number is 1.06.

(3) Silty clay: brownish yellow or brown red, malleable, partially sandwiched with medium coarse sand, the thickness of 12.0-24.0 m, average hammering number is 10.05.

(4) Medium sand: grey or brown yellow, saturated, slightly dense state, particle composition is mostly quartz,

the thickness of 2.0-7.0 m, the average hammering number is 12.

(5) Gravelly sand: grayish white or brown, saturated, medium dense, mainly composed of quartz sandwiched with 10%-30% soil, the thickness of 3.0-12.0 m, the average hammering number is 19.

The key technical index of interval reinforcement is to ensure the reinforcement effect without affecting the normal use of the bridge and the safety of the bridge structure. Compared with triaxial mixing pile and high pressure rotary jet grouting pile, the MJS pile has the following remarkable advantages: large flow rate and nozzle pressure, stable coaxial high pressure air, precise and controllable ground pressure, high degree of mechanization, full monitoring of rotational speed and lifting speed. The influence of MJS on existing buildings is much less than that of high pressure rotary jet grouting pile by using the special discharge valve to control the discharge volume of slurry.

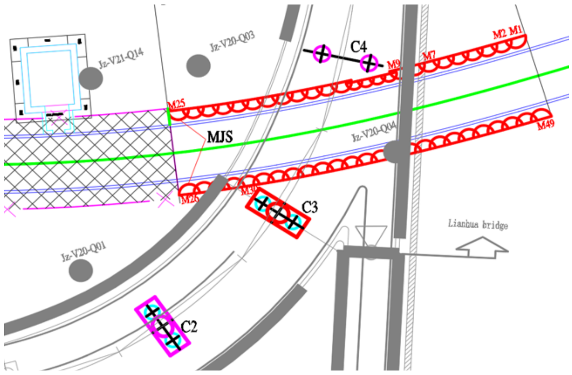

Fig. 1. Schematic diagram of tunnel and bridge pile.

According to the geological conditions and the engineering practice, considering the effect of reinforcement and the influence factors of the bridge, the construction parameters of MJS pile are shown in Table 1.

Table 1. Construction parameters of MJS pile.

Name	Pressure of cement slurry (MPa)	Main air pressure (MPa)	Inverted suction pressure (MPa)	Control coefficient of underground pressure	Lifting speed (m/min)	Slurry flow rate (cement slurry)	Water cement ratio
This project	40 ± 2	0.65	20-25	1.5	0.1	100-130	1:1
Literature data[20]	37	0.7	20-30	1.4-1.6	0.1-0.2	80-160	1:1

3.2 Numerical simulation analysis

3.2.1 The computational model

A three-dimension finite element numerical model including the MJS pile and the surrounding multi-layer soil of bridge foundation was established using the Plaxis 3D (V21 version) technique [26, 27]. The model is 50 m long, 30 m wide and 75 m deep. The stratum distribution of the model is shown in Fig. 2. The constitutive model of soil near the bridge piles of C2 , C3 and C4 is Hardening Soil model, and the arrangement of bridge piles and the spatial position of MJS piles are shown in Fig. 3. A total of 49 MJS piles were set up in the engineering model. The fluid-solid coupling method was used to analyze the squeezing effect of each MJS pile grouting on the surrounding soil in the construction, that is, the coupling changes of displacement, pore pressure and other factors are considered in the simulation process of each MJS pile.

Through the sampling from the borehole of Jz-V20-Q1, Jz-V20-Q3, Jz-V20-Q4 near the bridge pile of C2, C3 and C4, the geotechnical engineering investigation results were properly generalized, and the soil of the site was reduced to 5 layers. The main physical and mechanical parameters of rock and soil are obtained from the laboratory tests. The geometric dimensions and material types of bridge piles, caps and other components are determined according to the relevant design drawings. Considering the load of the upper pier and the box girder on the cap, through the calculation, the load of C2 cap was about 550 kN/m^2, and the load of left side of C3 cap was about 560 kN/m^2, and the load of right side of C3 bridge pile was about 1930 kN/m^2, and the load of C4 bridge pile was about 1820 kN/m^2.

3.2.2 Construction parameters of MJS pile

In the MJS construction, the diameter of the nozzle is 2.8 mm, and the default drill pipe center is the pile center, that is, the distance from the nozzle to the pile center is 71 mm and the grouting pressure is 40 ±2 MPa. In the finite element model, the soil squeezing effect is simulated by applying uniformly distributed pressure on the hole wall of MJS pile. The pressure of the high pressure jet is expressed by the following formula [28]:

$$p_m = K d_0^{0.5} p_0 / x^2 \quad (1)$$

where, p_m is the pressure of the nozzle, d_0 is the nozzle diameter, p_0 is the pressure at the exit of the nozzle, x is the axial distance along the nozzle, K is the coefficient related to the medium, which is generally taken as 0.1 in the soil.

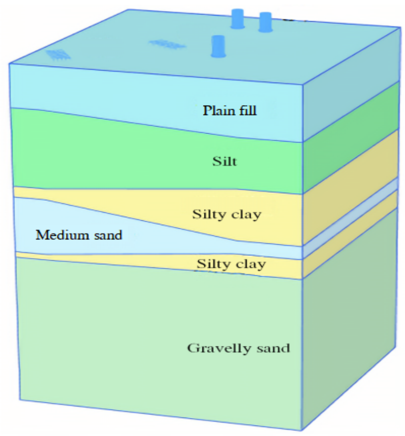

Fig. 2. Finite element model.

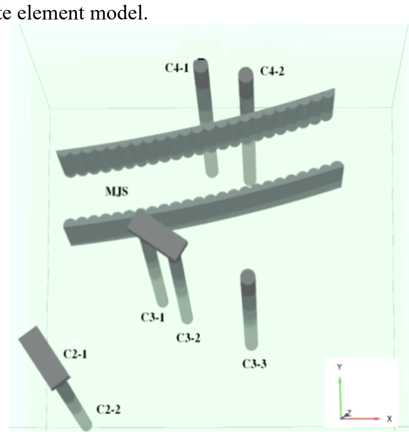

Fig. 3. Finite element model of MJS pile.

According to Eq. (1), the grouting pressure at 1000 mm from the pile center (at the hole wall of MJS pile) is 246 kPa, and the grouting duration time is 4 h. The Concrete constitutive model is often adopted, in which the strength and the elastic modulus increase with time. In this constitutive model, the compressive strength of the pile after curing of 28 d is 1.0 MPa, and its elastic modulus is 100 MPa. It is assumed that after construction of 1 d, the strength and the elastic modulus of MJS pile are 30% and 50% of the curing of 28 d respectively. The grouting time of each pile is 4 h, and the construction progress of each day is 3 piles

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3.3 Site construction and monitoring scheme

According to the optimized design scheme, there were 49 MJS piles in the reinforcement area, and the MJS piles were the occlusal piles with 1.5 m diameter and 45 m length. To reduce the impact on the surrounding environment, the form of "half pile" was adopted for reinforcement, and the "jumping method" was selected for construction, with odd piles and then even piles. To reduce the disturbance to the strata, the hole-cutting water device of the drilling pipe was not be opened within 10 m depth, and was dealt with according to the drilling situation in the range of 10 m to 45 m, and was not be opened for normal drilling until it was difficult to drill. At the beginning of shotcreting, the process parameters were set according to the pre-construction. Before injection, the water suction device, the air suction device and the mud discharge valve were open, and the soil pressure was closely monitored during the injection. If the pressure was abnormal, the size of the discharge valve would be adjusted in time to control the ground pressure within the safe range, as shown in Fig. 4.

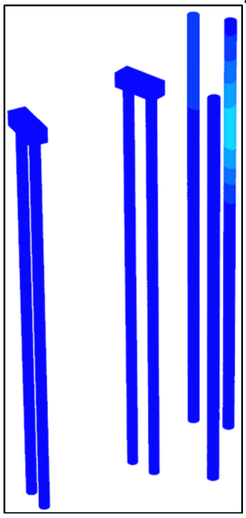
Fig. 4. Construction site of MJS pile.

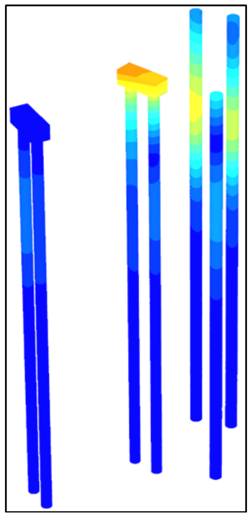
Some monitoring was set in the reinforced area, including the pier settlement, the pier inclination, the horizontal displacement at the top of pier, the internal force of bridge box girder, the internal force of pier, the void water pressure, the earth pressure, and the soil inclination. This study focused on the real-time monitoring data of pile foundation deformation during the pile construction of MJS.

4. Results analysis and discussion

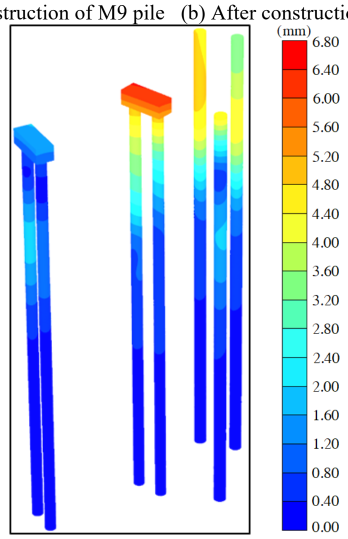
4.1 Deformation characteristics of bridge pile foundation

The numerical simulation was carried out strictly according to the on-site construction sequence of MJS pile. The two pile machines worked at the same time, with a total of 24 analysis steps, and the "jumping method" consistent with the actual engineering was used for pile construction: first play odd piles, then even piles, and the two pile machines alternately promoted the construction. During the MJS pile grouting construction, the deformation characteristics of the existing viaduct piles disturbed by the surrounding construction are shown in Fig. 5.





(a) After construction of M9 pile (b) After construction of M30 pile



(c) After construction of M49 pile

Fig. 5. Displacement field of bridge pile after MJS pile grouting.

In Fig. 5(a) the soil disturbance influence on the surrounding environment in the initial stage of MJS pile construction is relatively small, only small deformation occurs at the pile foundation of C4-2 closest to M9 pile, and other bridge piles are still in a stable state without obvious deformation. As the MJS pile machine continued to construct alternately, the construction of the M30 pile foundation was completed, and the deformation characteristics of the adjacent existing bridge piles were shown in Fig. 5(b). Compared with Fig. 5(a), the disturbance degree and the scope of MJS pile construction to the surrounding environment increased sharply. In addition, in Fig. 5(b) the maximum deformation of bridge pile caused by MJS pile construction was located at the top of C3-1 pile, and the total deformation was more than 5 mm. The deformation of other adjacent pile foundations was mostly concentrated within the corresponding length of MJS pile, and the construction had little influence on the parts above the ground and deeper parts of the bridge pile. After the construction of MJS pile, the deformation of C2-1 and C2-2 was further disturbed, and the deformation of bridge pile near the MJS pile foundation increased sharply. At the same time, the deformation of the bridge pile extended gradually from the middle upper part to the top. The maximum deformation was located at the pier of C3-1 and C3-2, and the maximum deformation reached 6.8 mm.

From the comparison of Figs. 5(a), 5(b) and 5(c), the influence of grouting construction of MJS pile on the disturbed deformation of the adjacent existing bridge was gradually weakened from near to far, and the horizontal bending deformation first occurred in the corresponding depth of MJS pile. With the grouting construction continuation of MJS pile, the deformation of the existing bridge pile was gradually transferred to the top, which caused damage to the upper bridge structure and brought safety risks to the normal use and the maintenance of the bridge.

4.2 Deformation characteristics of existing bridge foundation along depth direction

After the grouting construction of MJS pile, the variation curves of the displacement components of the adjacent existing bridge pile foundation along depth direction are shown in Fig. 6. In Fig. 6(a), the upper part of pile foundation of the existing bridge is inclined to the side of the MJS pile (the positive direction of x), and the closer to the MJS pile is, the greater the inclined deformation degree of pile foundation of the existing bridge is.

In Fig. 6(b), the existing bridge pile foundations on both sides of MJS pile are inclined to the side of MJS pile, and the deformation is symmetrically distributed along the direction of MJS pile, that is, the bridge pile foundations of C4-1 and C4-2 incline in the negative direction of *y*, while the bridge pile foundations of C3-1 and C3-2 incline to the positive direction of *y*, and the maximum deformation value is not much different, both of which are about 5 mm.

In Fig. 6 (c), during the grouting construction of MJS pile, the existing bridge foundations all have settlement deformation of different degrees, and the maximum deformation is located at the bridge pile top of C3-1 and C4-2, which are close to MJS piles. In addition, with the buried depth increasing, the settlement deformation of bridge foundation gradually decreases, which satisfies the distribution characteristics of Slogisticl function. The settlement curve was fitted as Eq. (2):

$$y = \frac{a}{1 + e^{-k(x-b)}} \tag{2}$$

where, y is the settlement of the bridge foundation, x is the depth variable, and a, b and k are the constant, respectively.

In Fig. 6, the maximum of horizontal deformation of bridge foundation of C3-1 at 0.75 m away from MJS pile is the largest, and the maximum deformation in x and y direction is 3.5 and 5 mm, respectively. In the vertical direction, the settlement of the bridge foundation is less than 1.5 mm. The horizontal deformation plays a leading role in the influence of grouting construction of MJS pile on the existing pile foundation. In addition, because the pile body and the buried depth of MJS are relatively small, the impact of grouting construction on the bridge pile deformation is mostly concentrated in the upper half. At the buried depth of 45 m, the deformation of the bridge pile foundation in three directions is less than 0.1 mm. Therefore, for the stable state of the bridge pile foundation with a buried depth of more than 45 m, the grouting construction of MJS pile can be regarded as no influence.

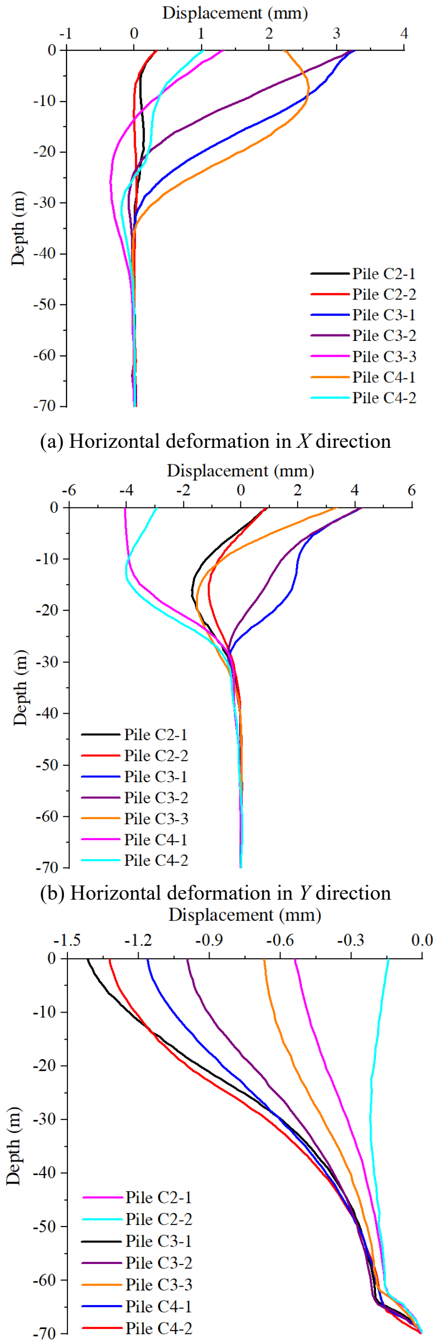


Fig. 6. Deformation curves of bridge pile along the depth direction.

4.3 Strengthening effect of MJS pile

4.3.1 Horizontal deformation of bridge pile and soil

The deep horizontal displacement of the soil around the viaduct pile foundation was monitored and analyzed. To obtain the horizontal deformation data of the soil around the bridge pile foundation, the inclination holes with a depth of 70 m were set up at the piers of C2, C3 and C4 respectively to monitor the horizontal displacement of deep soil. The monitoring results are shown in Figs. 7 and 8. In Figs. 7 and 8, the horizontal deformation of piers of C2, C3 and C4 in y direction is larger than that in x direction after the construction of MJS pile, and the horizontal deformation of soil near the C2 bridge pile is the smallest. The maximum horizontal displacement of soil near the C3 bridge pile in x direction is 4.42 mm, and the maximum horizontal displacement in y direction is 6.07 mm. The maximum horizontal displacement of soil near the C4 bridge pile in x direction is 3.63 mm, and that in y direction is 5.62 mm.

From the field monitoring results, it can be seen that the horizontal distance to MJS pile is still the key factor affecting the deformation of the adjacent existing bridge pile. When the distance from the bridge pile to the MJS pile is more than 3 m, the influence on the bridge pile is negligible, and when the distance is from 2 m to 3 m, the horizontal deformation is less than 1 mm. When the distance is from 1 m to 2 m, the horizontal deformation is less than 2 mm. When the distance is 1 m, the influence is the greatest, and the horizontal deformation is about 4 mm. From the vertical distance analysis, when the depth of pile is 45 m, the maximum of downward influence range is about 5 m, and the influence more than five meters on the bridge pile foundation is negligible. In the process of lifting MJS pile, to achieve the reinforcement effect, the pressure of range of shield tunnel is large, and the amount of grouting is large, and the lifting speed is slow. Therefore, the maximum of vertical deformation is located in the depth of 15 m to 30 m. When the depth is more than 15 m, the grouting pressure decreases gradually, and the deformation of the bridge pile is relatively small. In addition, through the field test, it is known that the cement slurry filling rate and the grouting pressure are important factors affecting the deformation of the bridge pile foundation, and the grouting pressure should be controlled between 10 MPa and 40 MPa during the construction, and the influence on the bridge pile is the minimum when the cement slurry content reaches 30%.

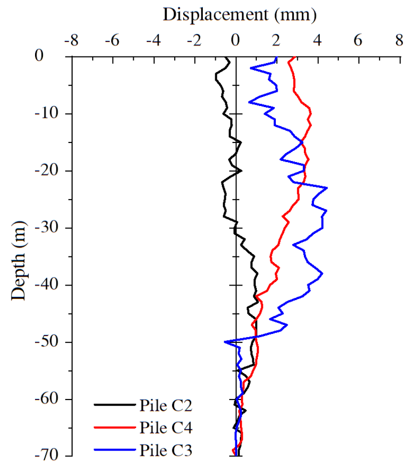


Fig. 7. Horizontal displacement of soil in *x* direction of bridge pile.

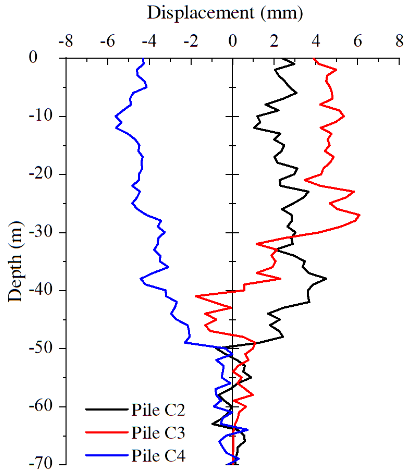


Fig. 8. Horizontal displacement of soil in y direction of bridge pile.

4.3.2 Settlement deformation of bridge piers

The settlement deformation curves of adjacent existing piers during the construction of MJS pile are shown in Fig. 9.

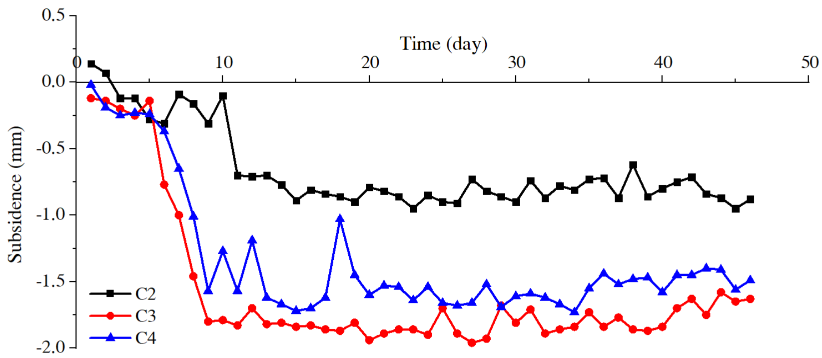


Fig. 9. Duration sinking curves of bridge pier.

In Fig. 9, the settlement deformation of the adjacent existing piers increased sharply during the first week construction of MJS pile. In the subsequent construction period, the settlement deformation of the piers fluctuated slightly, but the deformation was small. After the completion of the construction, the adjacent existing pier with the largest settlement was C3, and the maximum settlement deformation was 1.96 mm. In addition, during the construction of MJS pile, the traffic on the bridge deck was normal, and the bridge structure was always in a safe and stable state. Since the foundation treatment depth of MJS pile was far less than that of bridge pile, the influence of the friction between the bridge pile body and the soil was small, and the influence of construction disturbance on pier settlement could be ignored. The field monitoring data showed that the horizontal deformation of the bridge pile caused by MJS pile was much larger than the settlement deformation. In the deformation reinforcement of the bridge pile, the horizontal deformation should be controlled first to ensure driving safety of the nearby bridge. This is consistent with the numerical analysis results and verifies the accuracy of the numerical analysis results.

5. Conclusions

To study the stability and the deformation characteristics of the existing bridge pile near the grouting construction of MJS pile, taking the Hengqin line of Zhuhai light rail as the engineering background, the numerical simulation analysis of the MJS pile construction adjacent to the existing bridge was carried out. The deformation characteristics of the pile foundation of the existing bridge in different construction stages were monitored and analyzed, the deformation evolution mechanism of the pile foundation of the existing bridge near the MJS pile was revealed, and the numerical simulation analysis was verified. The main conclusions are as follows:

(1) The disturbance deformation of the adjacent existing bridge foundation gradually weakens from near to far in the grouting construction of MJS pile. The closer is the distance to the MJS pile, the greater is the deformation of the bridge foundation. The first failure place of the bridge foundation on both sides of MJS pile is the middle upper part of the adjacent existing bridge foundation.

(2) The horizontal deformation of the bridge foundation caused by MJS pile construction is much larger than the settlement deformation, and the horizontal deformation of bridge foundation is mainly inclined to the side of the MJS pile, so the horizontal deformation of bridge foundation should be controlled first. The cement slurry filling ratio has a great influence on the horizontal deformation of the bridge foundation, and the influence is the least when the cement slurry content reaches 30%.

(3) The initial stage of MJS pile construction has a great influence on the settlement deformation of the existing bridge foundation. In the later construction, the settlement of bridge foundation fluctuates slightly and the deformation is small. For predicting the settlement deformation of the existing bridge foundation near the MJS pile along the depth direction the model was proposed, and the choices of parameters value in the model were closely related to the distance from the MJS pile to the bridge foundation.

Due to the construction of underground rail transit project in the city, the surrounding environmental conditions are complex and diverse, so the impact of MJS pile grouting construction on the existing structures foundation is different. In the future, the disturbance influence and the deformation characteristics of MJS pile construction on the adjacent existing buildings foundation under the different working conditions will be further studied.

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