Numerical Simulation of Pile Settlement under Large Diameter Submarine Shield Tunnel

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Abstract: In view of the domestic first large diameter shield close Marine environment down wear large bridge project, Shenzhen high-speed along the river shield tunnel under wear before the Shenzhen Sea bridge as the background, the numerical simulation method, in view of the large diameter submarine shield under the bridge pile foundation, through different ways and methods on influence of settlement of pile foundation. The calculation results show that the additional bending moment of the bridge pile is small, the maximum settlement of the bridge pile is within the range of the control standard value, and the maximum horizontal displacement of the bridge pile is within the range of the control standard value, so the bridge will not be damaged. It can be seen that the construction of submarine shield tunnel has a certain degree of influence on the cross-sea bridge, but after applying engineering measures, the impact on the bridge can be effectively reduced to ensure the safety of high-speed railway bridge. The research results can provide reference for the construction design of the type of engineering.

1. Introduction
In the Guangdong-Hong Kong-Macao Greater Bay Area, one of the key economic areas in China, the smooth road traffic plays an essential role in guaranteeing the stable economic development. As the aboveground construction area decreases, the urban traffic is developing downward. Numerous lines pass through each other in the well-connected underground traffic network. It becomes more and more important to ensure the safety of existing buildings and structures. Many scholars both at home and abroad have studied this topic.

Qiao Shijie, et al. \cite{1} established the FLAC3D model for shield tunneling under overpass piles of the Beijing-Kaifeng Express by taking the Metro Line 19 Project as an example. In this model, he simulated and analyzed the settlements of bridge piles without and with ground reinforcement, and suggested to effectively control the settlements of bridge piles and ground surface through surface grouting reinforcement measures, refined control measures, and optimization of muck conditioning parameters.
Li Jigang [2] built a three-dimensional finite element model for Shenzhen Metro Line 5 in the Midas/GTS software, to analyze and predict the settlements and displacements of strata, segments, and pile foundations during the shield construction, and proposed some engineering measures based on the calculation results. Bi Jingpei, et al. [3] studied the impact of the underpass construction on the Nancang Bridge of Beijing-Shanghai High-speed Railway under the Shield Section of Tianjin Soft Soil, and the results revealed that the piles had small additional bending moments, and the maximum settlements of decks, pile caps, bridge piles, were not greater than 2 mm during shield tunneling, and the impact of the shield construction on the bridge piles was under effective control after grouting reinforcement. Zhi Bin, et al. [4] collected the data on the transformation of bridge piles under working conditions with different distances between the shield tunnel and bridge piles to explore the impact of the distance between the shield tunnel to bridge piles on the bridge. Ren Jianxi, et al. [5] researched the impact of the shallow shield + cross diaphragm (CRD) method and bench cut method on adjacent pile foundations at special complex areas in loess regions in Xi’an, and results showed that, compared with the bench cut method, the CRD method imposed less impact on the transformation of pile foundations. Besides, they also explored the transformation of pile foundations after the sleeve valve pipe grouting for reinforcement. Zhang Xiaoguang, et al. [6] studied the impact of the shield tunnel crossing underneath a river on bridge piles under the working conditions without rainfalls, and concluded that the scheme of erecting up temporary inverted arches and grouting under-the-bridge piles for water plugging was feasible and that the grouting effect was critical to the construction of under-the-bridge under-cutting piles. Chen Qiaosong, et al. [7] studied the shield tunnel for a metro line crossing under an urban bridge and a loop road, and effectively solved such problems as shallow tunnel construction and the safety risks to nearby buildings through measures including a temporary steel bridge, WSS full-face grouting, a large pipe-roof, etc. However, these studies and researches focus on overpass piles of expressways and small-diameter shield tunnels. The large-diameter shield tunnels and cross-sea bridges have not been considered. More studies are needed for the simulation and analysis based on complex field conditions of cross-sea bridges.

In this paper, a finite element analysis was conducted over the construction of large diameter submarine shield tunnels with the Midas/GTS NX software by taking the Shenzhen Nanping Fast Link to the Express along Zhujiang River crossing under the Bridge of Guangzhou-Shenzhen Express along Zhujiang River (Ramp C/D) as example. The paper also studied the change law and characteristics of site displacement, and pile foundation displacement and bending moment during the construction of large-diameter submarine shield tunnel under the bridge, and summarized the change law of additional stresses of bridge piles during the construction.

2. Project Overview
The Shenzhen Nanping Fast Link to the Express along Zhujiang River Project (Ramp C/D) starts from the reconstructed tunnel of the Expressway along Zhujiang River on the north side of Qianhaiwan in the north, runs southward into Qianhaiwan, enters Qianhai Guiwan District, turns east along the south bank of Shuangjie River, crosses the New City Overpass, and then connects to the bridge section. It has an overall length of about 4,791 m, including 3,380 m long shield tunnel with an outer diameter of 15.5 m. The overall alignment is in circular arc, with the minimum radius R=1,370 m.

The tunnel cross between Piles #75 ~ #76 under the Bridge of Guangzhou-Shenzhen Expressway along Zhujiang River. The minimum horizontal clearance between the tunnel and bridge piles is 1.8 m. The tunnel overburn is 8.7 m thick. Both bridge piles #75 and #76 are in the combined form of pile cap + pile foundation. The upper cap is 9.2 m × 6.3 m × 2.5 m. Underneath the cap, there are four 28.5 m long and φ1.6 m bored piles. The Bridge of Guangzhou-Shenzhen Expressway along Zhujiang River is a cross-sea bridge. The surface water level is 0 m. The buried depth of the main structure roof in the shield tunnel is 25.91 m. The main works are with water in the shield tunnel, so the impact of hydraulic pressure must be considered. The plane and profile positional relations between the expressway and the shield tunnel, is shown in Figs 1 and 2.
3. Numerical Analysis of Shield Tunnel Construction

For shield tunneling under the Bridge of Guangzhou-Shenzhen Expressway along Zhujiang River in the Shenzhen Nanping Fast Link to the Express along Zhujiang River Project (Ramp C/D), according to the design and geological data, the ABAQUS infinite element software was used to model multiple analysis steps to simulate, calculate, and analyze the controlled working conditions during the shield tunneling. The model was 50 m, 80 m, and 100 m respectively along the X, Y, and Z axes. The shield was set to advance toward X axle. In the model, soil masses, piles, shield shell, segments, and grouts were 3D physical units. The overlying silt, silty clay, medium sand, and clay were in the Mohr-Coulomb model. The underlying granite was in the Drucker-Prager model. Others were in the elastic model. Piles and soils were hard contacted normally and in Mohr-Coulomb friction tangentially. The left and right boundaries of the model were bound horizontally; the bottom edge was vertically bound; and the top edge was free. The 3D numerical calculation model is shown in Fig 3.
Table 1 Parameters of Soil Strata and Related Structural Materials

| Material                        | Gravity Density (kN/m) | Elasticity Modulus (MPa) | Cohesion (kPa) | Internal Friction Angle (°) | Poisson's Ratio |
|--------------------------------|------------------------|--------------------------|---------------|-----------------------------|-----------------|
| <3-1> Bay silt                 | 15.2                   | 9                        | 8             | 2                           | 0.49            |
| <5-1> Silty clay               | 19                     | 22.5                     | 31.1          | 5                           | 0.40            |
| <5-3> Gravelly sand            | 19                     | 21                       | 0.2           | 30                          | 0.3             |
| <6-3> Silty clay               | 19.4                   | 21                       | 20.8          | 14.6                        | 0.40            |
| <36-1> Completely-weathered granite | 19.5                | 70                       | 30            | 22                          | 0.3             |
| <36-2-1> Strongly-weathered granite | 22                   | 120                      | 35            | 28                          | 0.3             |
| <36-3> Moderately-weathered granite | 25.0                 | 9470                     | 4800          | 41.9                        | 0.27            |
| <36-4> Slightly-weathered granite | 26.3                  | 19000                    | 7300          | 42.5                        | 0.26            |
| Concrete grout                 | 20                     | 20000                    | /             | /                           | 0.17            |
| Segment                        | 25                     | 34500                    | /             | /                           | 0.17            |
| Shield shell                   | 75                     | 206000                   | /             | /                           | 0.31            |
| Pile cap                       | 25                     | 30000                    | /             | /                           | 0.17            |
| Pile foundation                | 25                     | 30000                    | /             | /                           | 0.17            |

4. Analysis of Calculation Results for Shield Tunnel Construction

4.1. Statistics of Simulation Calculation Analysis Steps
Multiple analysis steps were established to simulate the shield tunnel construction process and the transformation of bridge pile foundations at different stages. The main working conditions of shield excavation, is referred to the following table.
| Main Working Conditions          | Boundary Condition                                                                 | Simulated Condition                                                                 |
|---------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Ground stress balance analysis  | Set the contact between piles and soils as being smooth Passivate the shield shell,  | Original ground stress state                                                          |
| step                            | segments, grouting, and other units                                                  |                                                                                      |
| Analysis of step 1              | Excavate the soil mass in the first segmental ring area                              | The shield advances into the area where the bridge pile foundations are affected      |
| Analysis of step 2              | Excavate the soil mass in the 6th segmental ring area The shield tail comes off from | Activate the shield shell at the position of the first segmental ring Passivate the   |
|                                 | the first segment Back-fill grouting after the first segmental ring                  | shield shell at the position of the first segmental ring Activate the first segmental   |
| Analysis of step 3              | Excavate the soil mass in the 11th segmental ring area The shield tail comes off from| Activate the shield shell at the position of the first segmental ring Passivate the   |
|                                 | the 6th segment Back-fill grouting after the 6th segmental ring                     | shield shell at the position of the first segmental ring Activate the first segmental   |
| Analysis of step 4              | Excavate the soil mass in the 16th segmental ring area The shield tail comes off from| Activate the shield shell at the position of the first segmental ring Passivate the   |
|                                 | the 11th segment Back-fill grouting after the 11th segmental ring                   | shield shell at the position of the first segmental ring Activate the 11th segmental   |
| Analysis of step 5              | The shield tail comes off from the 25th segment Back-fill grouting after the 25th   | Activate the shield shell at the position of the 25th segmental ring Passivate the     |
|                                 | segmental ring                                                                       | shield shell at the position of the 25th segmental ring Activate the 25th segmental    |

4.2 Analysis on Settlements of Pile Foundations When the Shield Tunnel Crosses under the Bridge

The calculation results of the above 5 analysis steps were obtained, considering that the shield tunnel passes through the middle area under the pile foundations of two bridge piers on both sides and the top of the shield is 5.1 m from the pile foundations. As the tunnel skewed downward through the bridge piles, if the pile on the left side far away from the shield was Pile #1, and that on the right side close to the shield was Pile #2, different piles were subject to different impacts because their distance to the shield varied. When the shield advanced into the area where the pile foundations were affected, the...
calculation result of the pile foundation settlement was shown in Fig 4. Under the impact of shield tunneling, the pier pile foundations on both sides subsided, and such settlement decreased gradually from the heading face to the periphery. The settlement went to the peak -- 0.93 mm -- at Pile #2. As the shield advanced toward the piles, when the first segmental ring was assembled and grouted, the maximum settlement of bridge piles reached 3.33 m. At the same time, Pile #1 uplifted slightly under the extrusion impact, as shown in Fig 5.

Fig 4 Settlement Nephogram of Pile Foundations Under Working Condition 1 When the Shield Tunnel Crosses Under the Bridge

Fig 5 Settlement Nephogram of Pile Foundations Under Working Condition 2 When the Shield Tunnel Crosses Under the Bridge

When the shield advanced closest to the bridge pile foundation directly under the middle area between two pier pile foundations, both Piles #1 and #2 were subject to certain settlements. The settlement went to the peak, about 4.96 mm, at Pile #2, as shown in Fig 6. As the shield tunneling route skewed downward through the piles, Pile #1 farther away from the tunnel was less affected by the heading face, and its settlement was only about 43% of that of Pile #2.

Fig 6 Settlement Nephogram of Pile Foundations Under Working Condition 3 When the Shield Tunnel Crosses Under the Bridge
From Fig 7, as the shield moved away from the middle area between two pier pile foundations, and the segments were assembled and grouted, the maximum settlement declined gradually to about 4.62 mm. As the shield crossed directly under the middle area between two pier pile foundations, the impact of shield tunneling upon Pile #1 was augmenting. This was because after skewing through the bridge piles, the heading face got closer to Pile #1 and brought larger impact on Pile #1. When the shield gradually moved out of the area where the piles were affected, as shown in Fig 8, Pile #2 uplifted further, and the maximum settlement decreased further to 3.83 mm. Pile #1 also uplifted to a certain degree as the shield moved away.

Fig 7 Settlement Nephogram of Pile Foundations Under Working Condition 4 When the Shield Tunnel Crosses Under the Bridge

Fig 8 Settlement Nephogram of Pile Foundations Under Working Condition 5 When the Shield Tunnel Crosses Under the Bridge

4.3. Analysis on Settlement of Pile Foundations When the Shield Tunnel Crosses under One Side of the Bridge

The calculation results of the above 5 analysis steps were obtained considering that the shield tunnel crosses under the pile foundation of Pier #1 and the top of the shield is 5.1 m from the pile foundation. When the shield advanced into the area where the bridge piles were affected, the pile settlement was as shown in Fig 9. The resulting differential settlement between two bridge piles was quite small, only 0.21 mm, because the heading face was far away from these piles. When the first segmental ring was assembled and grouted, as shown in Fig 10, bridge piles on both sides were subject to obvious differential settlement as the heading face got closer to the piles. The pier column farther away from the heading face in Pier #2 uplifted slightly. This was because the large thrust resulting from the heading face squeezed the surrounding soil masses.
When the shield moved closest to the bridge pile foundation directly under Pier #1, there was an obvious differential settlement between Pile #1 and Pile #2. As shown in Fig 11, the settlement of Pile #1 increased up to 5.32 mm, and Pile #2 uplifted increasingly. Because the shield tunneling route skewed downward through bridge piles, resulting in certain differential settlement between different piers, an additional subsidiary stress was generated.

From Figs 12 and 13, as the shield moved away from the middle area between two pier pile foundations, and after the segments were assembled and grouted, the bridge piles subsided continuously to the maximum 13.34 mm. The differential settlement between Pile #1 and Pile #2 continued to increase. Pile #2 uplifted, while Pile #1 subsided. The differential settlement declined between different columns of a same pile. The uplift of Pile #2 was mainly caused by the large thrust of the heading face which squeezed the surrounding soil masses, while Pile #1 continues to subside after the shield passes by.
When the shield gradually moved out of the area where the piles were affected, the maximum settlement of Pile #1 substantially remained the same, while Pile #2 uplifted further.

Fig 12 Settlement Nephogram of Pile Foundations Under Working Condition 4 When the Shield Tunnel Crosses Under One Side of the Bridge

Fig 13 Settlement Nephogram of Pile Foundations Under Working Condition 5 When the Shield Tunnel Crosses Under One Side of the Bridge

4.4 Fitting Analysis of Relation Curve between Longitudinal Settlement of Pile Foundations and Tunneling Distance

Fig 13 shows the relation between the maximum settlement transformation of bridge piles and the tunneling distance when the shield tunnel crosses under the piles and on the side of the piles. From the overall tendency of the curve as shown in Fig 14, when the shield tunnel crosses under the middle area of two piles, the maximum settlement of piles is much less than that when the shield tunnel crosses under one side of the piles. This is because the resulting maximum settlement is right above the tunnel, and the settlement caused by crossing under the middle area between two piles is only 37% of that caused by crossing under one side of the piles. If the shield tunnel drives under the middle, the pile settlement goes to the peak when the shield approaches closest to the piles. If the tunnel runs under one side of the piles, the settlement reaches its maximum after the shield passes through the piles. It can be seen that the subsequent grouting after tunnel excavation will largely relieve the settlement at the upper part on the heading face. Some methods like grouting can elevate soil masses in the front top, but the settlement at this place is lagged to some degree and will reach to the final level as time elapses.
Sagaseta [8] (1987) proposed an equation to calculate the longitudinal surface settlement caused by tunnel excavation based on the elastic strain theory, as shown in Equation 1.

\[
\delta_s(y) = \delta_s(y) \left(1 + \frac{y-V_s}{\sqrt{y^2 + H^2}}\right)
\]  

(1)

Where, \( y \) is the distance to the heading face; \( \delta_s(y) \) is the vertical displacement of the soils on the plane parallel to the tunnel axis; \( V_s \) is the volume of the ground loss due to the tunnel excavation per unit length; and \( H \) is the buried depth of the tunnel.

Wang Xiaojun, et al. [9] corrected the longitudinal development coefficient based on the above equation, and obtain the corrected longitudinal settlement equation based on \( V_s = AV_i = \frac{2}{4}D^2V_i \), as shown in Equation 2.

\[
\delta_s(y) = \frac{D^2V_i}{8H} \left(1 + \frac{y-B}{\sqrt{y^2 + H^2}}\right)
\]  

(2)

Where, \( B \) is the longitudinal development coefficient.

The working conditions when the shield tunnel runs under the middle area between two bridge piles are fitted to those when the tunnel stretches under one side of the piles based on Equations 1 and 2, as shown in Figs 15 and 16. From these Figs, when the tunnel runs under one side of the piles, there is no large difference between the solution of the Sagaseta equation and that of the corrected Sagaseta equation. Both equations can effectively simulate the longitudinal settlement of the tunnel. However, when the tunnel runs under the middle area between two piles, the solution of the Sagaseta equation largely differs from the numerical simulation result, while the solution of the corrected Sagaseta equation matches with the simulation result. This is mainly because the solution of the Sagaseta equation is the analytical solution of the maximum surface settlement caused by the shield tunneling, and the simulation for the front-top surface settlement is not accurate and needs correction.
5. Conclusion

Upon studying the pile foundation settlement of the Bridge of Guangzhou-Shenzhen Expressway along Zhujiang River after the shield tunnel construction and the change law of longitudinal settlements caused by shield tunneling, the following conclusions are drawn:

(1) When the shield tunnel crosses through the middle area under two pier pile foundations, pile foundations on both sides will subside. When the top of the shield is 5.1 m from the pile foundation, the settlement goes to the peak, about 4.96 mm. At this moment, the shield sits directly under the middle area between two pier pile foundations. When the shield tunneling is completed at this section, the final settlement will be 3.83 mm. In accordance with the Code for Design of High Speed Railway (TB 10621—2014), the above values are acceptable and will not bring any destructive impact on the bridge.

(2) When the shield tunnel crosses under the pile foundations on one side of the bridge piers, the pile foundations are subject to the transformation in the following law: the pile foundation on this side is subject to the maximum settlement of about 13.55 mm, and that on the other side uplifts up to around 1.56 mm. In this case, the maximum settlement and differential settlement are much larger than those when the shield tunnel crosses under the middle area between two piles.

(3) Both the Sagaseta equation and corrected Sagaseta equation can be fitted effectively to obtain the working conditions when the shield tunnel crosses under pile foundation on one side of the bridge piers. However, when the shield tunnel crosses under the middle area between both pier pile foundations, it is difficult for the Sagaseta equation to produce the matching results, but the corrected Sagaseta equation still works well.
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