Analysis of the Influence of Train Dynamic Load on the Side-Crossing Bridge Pile Subway Tunnel

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Abstract. In order to explore the influence law of train dynamic load on the side-crossing bridge pile foundation subway tunnel, taking Xi’an Metro Line 14 underneath the Datong-Xi’an High-speed Railway Bridge Project as the background, three-dimensional finite element numerical simulations have been carried out on four working conditions: the subway tunnel shield is not constructed, the shield is constructed to the high-speed rail bridge, the subway right line tunnel is completed, and the subway tunnel is double-line completed. The analysis results show that the train dynamic load is transferred to the tunnel structure of 11.0m underground through the bridge, pile foundation and surrounding strata, the maximum position of the tunnel structure dynamic response is at the haunch, the response of the double-line tunnel is greater than that of the single-line tunnel; the train dynamic load has the greatest impact on the pile top of the bridge pile foundation and the least impact on the pile bottom; the subway tunnel adjacent to the bridge pile reduces the train dynamic response of the pile foundation, when there is no tunnel on the side of the pile foundation, the dynamic response of the bridge pile foundation is the largest, the single-line tunnel comes second, and it is the smallest when there is the double-line tunnel.

Keywords: high-speed train; dynamic load; shield construction; pile; tunnel.

1. Introduction
By the end of 2019, a total of 40 cities in mainland China have opened urban rail transit operations, operating line mileage reaches 6736.2km, the total operating mileage of subway lines is 5180.6km, accounting for 76.9%, and the newly-increased operating line mileage is 974.8 km[1]. With the rapid development of subway construction, it is inevitable that the subway will cross the high-speed railway, the underpass subway tunnel construction affects the stress and deformation of the railway bridge structure; the train dynamic load will also affect the subway tunnel.

Many scholars at home and abroad have carried out a lot of research on the problem of train vibration. Balendra et al. [2] (1991) proposed a semi-analytical plane strain model through the dynamic substructure method when studying structural and tunnel vibration problems, the model first obtained the impedance matrix of the building and the tunnel, and then combined the vehicle-rail-building model to seek the solution of the dynamic response, and then predict the ground building vibration caused by the
train vibration. T. Birrer [3] (2007) built the semi-analytical discrete model for ground vibration problem caused by motion loads, obtained the results of transient ground motion and steady-state ground motion in combination with Green's function, and compared with the analytical solution, found that the model is valid for any homogeneous, isotropic and linear elastic medium. Gao Guangyun et al. [4] adopted the semi-analytical numerical model to analyze the ground vibration caused by the train dynamic load on the viaduct pile foundation, the research results found that when the high-speed train runs at 260 km·h⁻¹ or more, increasing the pile diameter can effectively reduce ground vibration caused by high-speed trains. Chen Xing et al. [5] studied the dynamic response law when running parallel in the same direction at close distances in high-speed rail tunnels and subway tunnels, the study found that the dynamic response amplitude of the railway tunnel section gradually increased from top to bottom when the train was running. Liang Zili et al. [6] adopted the method of numerical simulation to study the "soil arching effect" of the pile net structure under the train dynamic load, and found that the impact of the train dynamic load on the soil arching effect is relatively small, the smaller the stiffness of the soil body among the pile foundations, the more obvious the "soil arching effect". In order to obtain the dynamic characteristics of railway tunnels, Yang Wenbo [7] adopt approach combining model tests and numerical calculations to conduct research, the research result showed that the area with the greatest vibration attenuation in the horseshoe-shaped tunnel section is located between the inverted arch and the haunch, there is an increasing trend between the haunch and the vault. Xu Lihui[8] et al., in order to explore the damage law of circular tunnels under train dynamic load, carried out the secondary development of the finite element software based on ANSYS, which improved the accuracy of the fatigue life prediction of the tunnel structure, the study showed that the damage position is mainly located at the inverted arch under long-term repeated action of train load.

In this paper, combined with Xi'an metro line 14, subway shield tunnel underneath Datong-Xi'an High-speed Railway across Xi'an-Tongchuan high-speed bridge project, the approach of numerical simulation was used, four typical working conditions: the subway tunnel shield is not constructed, the shield is tunneled under the high-speed rail bridge, the subway right line tunnel is completed and the double line is completed, were selected, combined with two different train operating speeds: 250 km·h⁻¹ and 350 km·h⁻¹, the influence law of the train dynamic load on the subway shield tunnel was analyzed.

2. Project Survey
The Xi'an Subway Line 14 project (Beike Station-Heshao Village), spanning 13.76km, all of which are underground lines. The section between Shangxian Road Station and Xuefu Road Station (hereinafter referred to as Shangxue Section) is the second section of this line, after the line is led out from Shangxian Road Station, it heads east along Kaifa Road, then turns south, cross the Datong-Xi'an High-speed Railway Cross-Xitong Highway Bridge from north to south, the bridge is a 32m-span simply supported box girder, bored concrete pile foundation, and the pile foundation diameter is 1.25m; the outer diameter of the shield tunnel in the subway section is 6.3m, the PIPE segment thickness is 0.3m, and the position relationship between the shield tunnel and the bridge pile foundation is shown in Fig.1.

![Fig.1 Schematic diagram of the relationship among the high-speed viaduct piles underneath the section](image-url)
3. Model Survey

3.1. Selection of model parameters
The finite element model relies on the Xi'an Metro Line 14 Xuefu-Shangxian section subway underneath the Datong-Xi’an High-speed Railway bridge group pile section for modeling, the subway tunnel maintains trend with a small curve of 350mm radius, and the railway bridge structure is arranged based on the actual position of the project; Xi’an Metro Line 14 adopts the shield construction method, the diameter of cross section of the shield tunnel is 6.3m, the buried depth is 11m, and the pipe segment thickness is 0.30m, considering the actual engineering situation, combining the research of numerical simulation experts [9] in this aspect, the model size is selected as 160m (length) × 60m (width) × 80m (height), it contains totally 7 layers of soil, and the depths of each layer are: 1.7 m, 1.3 m, 3.8 m, 2.5 m, 4.3 m, 14.1 m, and 52.3m, the three-dimensional finite element model is built based on the selected size.

The stress and strain characteristics of each soil layer obey the Mohr-Coulomb Criteria, the train track is simulated by beam element, and the material is steel, the cross section adopts 60kg steel rail section, the pile foundation of high-speed railway bridge is simulated by beam element and adds pile interface element, the material is C40 concrete, the diameter of cross section is 1.25m in accordance with the project reality, the pile caps, piers, and bridge boards are all simulated by solid elements, and the materials are all C40 concrete. All materials are homogeneous, continuous and isotropic. The soil parameters are selected in accordance with the geological exploration data, and the steel rail and concrete parameters adopt empirical values, as shown in Table.1.

| name                  | Density (g/cm-3) | dynamic modulus of elasticity/Mp | dynamic Poisson's ratio | cohesion/Kpa | internal friction angle/° |
|-----------------------|-----------------|----------------------------------|------------------------|--------------|--------------------------|
| miscellaneous soil    | 1.8             | 168                              | 0.341                  | 10           | 10                       |
| silt                  | 1.68            | 199                              | 0.31                   | 0            | 29                       |
| medium sand           | 1.73            | 281.9                            | 0.293                  | 0            | 31                       |
| silty clay            | 1.93            | 368.7                            | 0.303                  | 22           | 20                       |
| medium sand           | 1.97            | 563.5                            | 0.290                  | 0            | 32.5                     |
| silty clay            | 1.91            | 358.5                            | 0.303                  | 23           | 20.5                     |
| medium sand           | 2.06            | 610.7                            | 0.287                  | 0            | 34                       |
| track                 | 7.835           | 210000                           | 0.3                    |              |                          |
| pile, pier, pile cap, bridge deck | 2.5       | 34020                           | 0.2                   |              |                          |
| pipe segment          | 2.5             | 35500                           | 0.2                   |              |                          |

3.2. Dynamic Load Simulation of High-Speed Train
At present, the trains operated in the Datong-Xi’an High-speed Railway include CRH2A trains, CRH380 series powered car train-set and powered car train-set "Fuxing". In this chapter, combined with the actual situation of Datong-Xi’an High-speed Railway, the relevant parameters of CRH380B model were selected to simulate the train load.

In this paper, by consulting the relevant information of the CRH380B powered car train-set, then revising in combination with the actual situation of Datong-Xi’an High-speed Railway, the node power train load table software Midas GTS was adopted, and the vehicle fixed distance, axle load, speed and other parameters of the CRH380B powered car train-set were output in the train load table, and finally the dynamic load of the CRH380B powered car train-set was generated.
4. Calculate Working Conditions

Four typical working conditions: the subway tunnel shield is not constructed, the shield is constructed under the high-speed rail bridge, the right line is completed, and the two lines are completed, are selected, as shown in Fig.2.

(a) The shield is not constructed

(b) The shield is constructed under the high-speed rail bridge

(c) The right line is completed

(d) The two lines are completed

Fig. 2 Typical stages of shield construction
Relevant data shows that the design speed of the Datong-Xi’an High-speed Railway is 250 km•h\(^{-1}\), the reserved design speed is 350 km•h\(^{-1}\), therefore, two speeds: 350 km•h\(^{-1}\) and 250 km•h\(^{-1}\) are selected, respectively, in the four typical stages of shield construction, eight calculated working conditions are defined as shown in Table.4.

Table. 2 Calculates the working conditions

| Working condition | Speed (km•h\(^{-1}\)) | Construction situation |
|-------------------|------------------------|------------------------|
| Working condition 1 | 250                    | Not constructed        |
| Working condition 2 | 350                    | Not constructed        |
| Working condition 3 | 250                    | Working face is under the bridge |
| Working condition 4 | 350                    | Working face is under the bridge |
| Working condition 5 | 250                    | Right line is completed |
| Working condition 6 | 350                    | Right line is completed |
| Working condition 7 | 250                    | Left line is completed  |
| Working condition 8 | 350                    | Left line is completed  |

5. Result Analyses

5.1. Selection of vibration pickup point
The propagation law of train dynamic load was conducted on the three typical positions: the top, middle and bottom of the pile closest to the subway tunnel after shield excavation, as shown in Fig.3. Three typical positions: tunnel vault, haunch and inverted arch are selected for analysis, as shown in Fig.4.
5.2. Result analysis

Taking the condition of the subway tunnel shield without construction as an example, suppose that the ground train runs along the high-speed railway bridge at 250 km•h⁻¹ in both directions, the model of this paper, the train enters at 0.24s, the train fully acts on the section at 4.00s, and the ground train leaves the section at 7.84s.

According to the time history curve of the vibration pickup point of the pile foundation in Fig.5, when the train enters the section at 250km•h⁻¹, the vertical displacement of the pile gradually increases as the train gradually approaches, it gradually decreases as the train gradually moves away, the vertical displacement, velocity, and acceleration gradually decrease from the top to the bottom along the pile. The peak values of vertical displacement, velocity, and acceleration of the pile are located on the pile top, and the maximum values are 1.59mm, 10.82mm•s⁻¹, and 267mm•s⁻², respectively.

(a) vertical displacement
Fig. 5 Time-history curve of pile foundation in vibration pickup at 250km•h$^{-1}$ per hour

According to the time-history curve of the tunnel section in Fig. 6: after the left and right line tunnels are completed, when the train enters the section at 250km•h$^{-1}$, the vertical displacement of the tunnel section gradually increases as the train approaches, it gradually decreases as the train moves away, the vertical displacement, velocity, and acceleration are the largest at the haunch, the vault comes second, and inverted arch is the smallest. The peaks of maximum vertical displacement, velocity, and acceleration of the tunnel section are located on the haunch, and the maximum values are 0.97mm, 7.10mm•s$^{-1}$, and 145.05mm•s$^{-2}$, respectively.
5.3. Influence analysis

The peak results of the eight working conditions calculated are summarized, and the results are shown in Table.3.

Table. 3 Summary of peak results of pile in construction process

| working condition                        | driving speed (km•h⁻¹) | position of pile maximum | dynamic displacement peak (mm) | dynamic velocity peak (mm•s⁻¹) | dynamic acceleration peak (mm•s⁻²) |
|------------------------------------------|-------------------------|---------------------------|------------------------------|-------------------------------|-----------------------------------|
| not constructed                          | 250                     | pile top                  | 1.59                         | 10.82                         | 267.00                            |
| not constructed                          | 350                     | pile top                  | 1.59                         | 18.52                         | 550.67                            |
| right line is constructed under the bridge | 250                     | pile top                  | 0.71                         | 5.60                          | 111.15                            |
| right line is completed                  | 350                     | pile top                  | 0.77                         | 8.32                          | 295.28                            |
| right line is completed                  | 250                     | pile top                  | 0.69                         | 5.38                          | 107.37                            |
| right line is completed                  | 350                     | pile top                  | 0.75                         | 7.87                          | 278.31                            |
| double line is completed                 | 250                     | pile top                  | 0.69                         | 5.33                          | 109.86                            |
| double line is completed                 | 350                     | pile top                  | 0.74                         | 7.86                          | 299.15                            |

Fig.6 Time-history curve of tunnel section at 250km•h⁻¹ per hour

(b) vertical velocity

vertical acceleration (mm•s⁻²)

c) vertical acceleration
As can be found from summary of the rules in Table.3, on the whole, with the construction of the subway tunnel shield, the influence of the ground train dynamic load on the bridge pile foundation is significantly reduced, and the most affected position is at the pile top from the position of the pile. 

(1) Under the train load of 250 km$\cdot$h$^{-1}$, the dynamic response of the bridge pile foundation is the largest when the tunnel is not constructed. The maximum of displacement, velocity and acceleration of the pile top are 1.59mm, 18.52 mm$\cdot$s$^{-1}$ and 550.67 mm$\cdot$s$^{-2}$, respectively.

(2) Under the train load of 250 km$\cdot$h$^{-1}$, the dynamic response of the bridge pile foundation is the smallest after the double-line tunnel is completed. The maximum of displacement, velocity and acceleration of the pile top are 0.73mm, 5.84 mm$\cdot$s$^{-1}$ and 115.43mm$\cdot$s$^{-2}$, respectively.

| working condition                      | driving speed (km$\cdot$h$^{-1}$) | position of section maximum | dynamic displacement peak (mm) | dynamic velocity peak (mm$\cdot$s$^{-1}$) | dynamic acceleration peak (mm$\cdot$s$^{-2}$) |
|--------------------------------------|----------------------------------|-----------------------------|--------------------------------|-------------------------------------------|---------------------------------------------|
| right line is constructed under the bridge | 250                              | haunch                      | 0.93                           | 6.74                                      | 111.15                                     |
| right line is constructed under the bridge | 350                              | haunch                      | 0.93                           | 6.99                                      | 247.42                                     |
| right line is completed               | 250                              | haunch                      | 0.82                           | 5.91                                      | 116.52                                     |
| right line is completed               | 350                              | haunch                      | 0.83                           | 5.61                                      | 193.05                                     |
| double line is completed              | 250                              | haunch                      | 0.70                           | 5.70                                      | 112.74                                     |
| double line is completed              | 350                              | haunch                      | 0.81                           | 5.44                                      | 189.96                                     |

It can be found from summary of the rules in Table.4 that the dynamic load of ground train affects the underground subway shield tunnel structure, and the maximum of dynamic response of the tunnel structure is at the haunch. From the construction process of subway tunnels, the response of the double-line tunnel is greater than that of the single-line tunnel; when the left and right tunnels are completed, the dynamic response of the tunnel structure is the largest, under the train load of 250 km$\cdot$h$^{-1}$, the peak displacement, velocity and acceleration of the tunnel haunch are 0.93mm, 6.99 mm$\cdot$s$^{-1}$ and 247.42mm$\cdot$s$^{-2}$, respectively.

6. Conclusion

By combining with Xi’an Subway Line 14, numerical simulation method was adopted in the subway shield tunnel underneath the Datong-Xi’an High-speed Railway cross-Xitong high-speed bridge project, four typical working conditions were selected: the subway tunnel shield is not constructed, the shield is tunneled under the high-speed rail bridge, the subway right line tunnel is completed and the double line is completed, the analysis of the influence of train dynamic load was carried out on the subway shield tunnel.

(1) The subway tunnel adjacent to the bridge pile foundation reduces the train dynamic response of the pile foundation. When there is no tunnel on the side of the pile foundation, the dynamic response of the bridge pile foundation is the largest, the single-line tunnel comes second, and it is the smallest when there is the double-line tunnel.

(2) The ground train dynamic load can affect the underground subway shield tunnel structure, and the position of dynamic response maximum of the tunnel structure is at the haunch.
(3) The train dynamic load is transferred to the tunnel structure of 11.0m underground via the bridge, pile foundation and surrounding stratum, the response of the double-line tunnel is larger than that of the single-line tunnel; the maximum response position of the tunnel is the haunch. Under the train load of 250 km•h\(^{-1}\), the peak displacement, velocity and acceleration of the haunch of the double-line tunnel are 0.93mm, 6.99 mm•s\(^{-1}\) and 247.42mm•s\(^{-2}\), respectively.

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