Correction and Regularity of Influence Coefficient for Double-Line Tunnel Settling

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Abstract: In the construction of most double-tunnel subways and postexcavation tunnels, settlement deformation is an important problem. In this study, we analyzed the problem using monitoring data from the Huai’anqiao-Xisanjiao section (an anhydrous sand layer) of the first phase of China’s Shijiazhuang Rail Transit Line 3 project. First, FLAC3D software was used to establish a numerical model. Grouting pressure was assumed to be uniformly distributed. The settlement value of a measured point was calculated as the test data, and the range of the correction factor was obtained by an influence coefficient formula. The correction factor was revised in accordance with the measured data, and the correction factors for the properties of Shijiazhuang sand were obtained. For the first tunnel measuring point, the correction factor was −0.2; for the rear of the tunnel point the correction factor was 0.2. Finally, different numerical models were established, and the influence on the correction factor of such factors as tunnel depth and horizontal spacing, slope ratio, and tunnel spacing were established by using a control variable method.

1. Introduction

With China’s support for narrowing the gap between urban and rural communities, the construction speed and scale of subways have become a measure of the development of a city. To promote the development of Shijiazhuang City, the capital of Hebei Province, central and local support will be provided to build six subway lines. As of July 17, 2017, the first phase of Shijiazhuang Metro Line 1 (mainly along the Shijiazhuang Zhongshan Road) and the third phase of the project (mainly along the streets of China) have begun. Because the lines pass primarily through the downtown areas of Shijiazhuang, surface subsidence caused by construction has become a serious problem (Wenhua 2013, Haibing et al. 2009, Qimin et al. 2014, Fangbiao et al. 2012).

Based on the influence coefficient proposed by Peck (1969) for predicting two-lane tunnel settling, we used the finite element model to calculate the approximate value of the settling by using the analytical formula as the test data. We then combined the formula with field-measured data as a correction factor to obtain a specific value. Finally, the influence of such factors as the tunnel depth \( H \), the tunnel horizontal distance \( d' \), the slope ratio \( c \), and the row spacing distance \( x \) on the correction
factor was analyzed by establishing different numerical models.

2. Engineering Introduction and Model Establishment

2.1. Project Overview
For construction of Huai’an Bridge to West Three Teaching Section by Shield Method, the starting distance of the right-line shield tunnel was DK8 + 763.952, the end distance DK9 + 693.621, and the shield length 929.669 m. The shield machine had four simultaneous grouting points, each with a grouting pressure and grouting volume display. The synchronous grouting volume was 2.5 m$^3$ to 3 m$^3$, and grouting pressure control was 0.2 to 0.3 MPa.

2.2. Establishment of Finite Element Model
The size of the double-line model was established to be 60 m × 60 m × 60 m, and the tunnel radius took into account the segment and grouting conditions, which were 2.7 m, 3.0 m, and 3.2 m. The horizontal spacing was 15.2 m, and the depth was 16.4 m. The grouting pressure was applied using simultaneous grouting. Because different grouting pressures affect surface subsidence, the grouting pressure in the model was set at 0.3 MPa and was evenly distributed. We assumed the grouting slurry’s gelation time to be at an initial setting of 3 h, its intensity to be 0.05 MPa, its final setting time to be 8 h, and its strength to be 0.3 Mpa. The model is shown in Fig. 1.

3. Brief Introduction to the Influence Coefficient of Double Lines
Based on many engineering examples (Peck 1969), the coefficient of influence between the first tunnel and the second tunnel may be expressed as:

$$W_{mod} = 1 + \left[M \left[1 - \frac{d'}{2K_1Z^*} \right] \right]W$$

(1)

In (1), $M$- the correction factor; $d'$-the horizontal axis spacing of horizontal double tunnels; $X$-the distance between the tunnels; $A$-half of the width coefficient of the sedimentation tank; $K_1$-stiffness coefficients of the first tunnel; $Z^*$-vertical distance between the center of the tunnel and the measuring point; $W$-the sedimentation values of the first tunnel for the measurement points of the two tunnels.

The $W$ and $W_{mod}$ values required in the formula need to be calculated by numerical simulation; the settling groove width is obtained by the following formula (Yukun et al. 2009):

$$\frac{1}{R} = 1.15 \left( \frac{H}{2R} \right)^{0.6}$$

(2)

After the numerical simulation is completed, the $W$ and $W_{mod}$ values are obtained as the tentative data, and the value of the correction factor $M$ is obtained by fitting the coefficient formula, as shown in Table 1.
Table 1. Numerical simulation points for $M$ values

| Point number | Final value | $W$ /m | $W_{mod}$ /m | $X$ /m | $d'$ /m | $M$  |
|--------------|-------------|--------|-------------|--------|---------|------|
| D1           | 0.0071      | 0.0038 | 0.0033      | 60     | 15.2    | -0.13|
| D2           | 0.008       | 0.0046 | 0.0032      | –      | –       | -0.2 |
| D3           | 0.0076      | 0.0051 | 0.0025      | –      | –       | -0.13|
| D4           | 0.0073      | 0.0056 | 0.0017      | –      | –       | 0.18 |

4. Field-Measured Data

After inspecting the final layout of the distribution map for the construction of the Shijiazhuang Metro Line 3, Huai’an Bridge station to XiSanjiao station, we concluded that there were 25 sections where there was a monitoring point for soil settlement between the two-lane tunnels, as shown in Table 2. Fig. 2 shows three sections of the initial shield construction for the Shijiazhuang City Rail Transit Line 3, the first phase of the project schedule for Huai’an Bridge.

Table 2. Control sections of measuring points of Huai Xi interval two-lane tunnel

| Left line | Intermediate | Right line | Rings |
|-----------|--------------|------------|-------|
| DB8764-3  | DB8764-4     | DB8764-7   | DB8764-9   |
| DB8784-1  | DB8784-2     | DB8784-4   | DB8784-5   |
| DB8804-2  | DB8804-3     | DB8804-5   | DB8804-6   |
|           |              |            | GXC03-04   |
|           |              |            | GXC03-06   |

Fig. 2. Construction schedule for left and right lines

The following use the specific values of $-0.2$ and $0.2$ based on the measured data to obtain the measured value of the $W_{mod}$ calculated value, compared with the actual monitoring values; see in Fig. 3.

Fig. 3. Absolute error curve of calculated values and measured values

Fig. 3 shows that with the correction factor values of $-0.2$ and $0.2$, the absolute error is greater than $3$ mm in only four cases, the minimum is $-0.95$ mm, and most of the $1$ mm or less errors are minimal.
5. The Effect of Each Factor on the Correction Factor

We established the actual soil layer model by changing the slope of the model (horizontal, uphill 2%, and downhill 2%) in accordance with the correction factor obtained from the measured data. The model was established by using FLAC3D finite difference software. Depths (9.4 m and 16.4 m), horizontal spacing (15.2 m and 9 m), line spacing (48 m and 60 m), and other factors were used to determine the effect of each factor on the correction factor. The grouping is shown in Table 3.

| Model | Depth /m | Horizontal spacing /m | Pitch /m | Slope /m |
|-------|----------|-----------------------|----------|----------|
| Model 1 | 9.4      | 15.2                  | 60       | 0%       |
| Model 2 | 9.4      | 15.2                  | 60       | +2%      |
| Model 3 | 9.4      | 15.2                  | 60       | -2%      |
| Model 4 | 16.4     | 15.2                  | 60       | 0%       |
| Model 5 | 9.4      | 15.2                  | 48       | 0%       |
| Model 6 | 9.4      | 12                    | 60       | 0%       |

**Fig. 4** shows that the slope of the correction factor is not affected by the correction factor when there is a change only in the slope. This is because the depth of the slope and the depth of the settling tank change. A change in the slope cannot exist as an independent influencing factor. **Fig. 5** shows the change in $M$ when the burial depth is changed. It can be seen that a change in burial depth will affect the correction factor of the tunnel survey point, and the influence on the tunneling point is not obvious. **Fig. 6** shows that the differences before and after the $M$ value of the trend and the specific value are very close, so they have almost no effect. **Fig. 7** shows the trend of the change in $M$ when the horizontal spacing of the two-line tunnel differs. When the change trend is basically the same, the left and right farthest point of the double hole is the $M$ value corresponding to the settlement value of the ground measuring point. It is a large gap and can be used for further research.
6. Conclusion
(1) We obtained the numerical settlement of the measured value by fitting the formula. The correction factor was −0.2 for the first tunnel survey and 0.2 for the other tunnel.
(2) By comparing the change trend in the $M$ value, we can conclude that the distance and slope have no appreciable effect on $M$, and the $M$ value obtained by most of the measured points at different depths is also consistent with the change trend.
(3) Finally, when the horizontal distances differ in, the correction factor of the measuring point above the arch of the left and right tunnel changes greatly when the change trend of the correction factor is basically the same; this can be used for further research.

Acknowledgments
This study was supported by the Natural Science Foundation of Hebei Province (Grant No. E2019210126), the Natural Science Foundation of Hebei Province (Grant No. E2019210304), the Science and Technology Research Project of Universities in Hebei (Grant No.ZD2020336), and the Science and Technology Project of Hebei Province (Grant 16215408D).

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