Surface Deformation Law of Cixian Section of the South-to-North Water Transfer Project

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Abstract. The disturbance of ground deformation caused by pipe jacking construction has become one of the important factors affecting the safety of the surrounding buildings and environmental changes. The construction of the sewage pipe network, which is in the Cixian section of the South-to-North Water Diversion Middle Route, is taken as an example. Theoretical prediction and field tests are conducted to research the ground settlement deformation caused by the disturbance of pipe jacking construction. Research indicates that the surface settlement near Hexie Avenue in Ci County meets the engineering safety requirements when the volume loss rate of the local layer is controlled within 6.9%. And the maximum surface settlement within the construction range of the Cixian section of the South-to-North Water Diversion Project was within 2.5-4 mm, which did not break the safety threshold. Suggested values for the formation loss rate and settlement trough width coefficient index are proposed for similar working conditions, which are 3.31% and 0.525 respectively. Relevant research results provide a reference for the study of ground deformation prediction under similar working conditions.

Keywords. Pipe jacking tunnel, ground deformation, field test, formation loss rate.

1. Introduction
With the deepening of the Chinese urbanization process, a large number of municipal projects such as underground passages and sewage discharge pipelines have been extensively developed [1]. Because the pipe jacking method has the characteristics of environmental protection, safety, and low disturbance impact, it is widely used in the construction of municipal engineering [2]. The impact of pipe jacking under the building construction disturbance is the current research focus.

Researchers at home and abroad have conducted many studies on such problems utilizing numerical simulation, theoretical analysis, model testing, and field measurement. For example, Liu Bo et al. [3] take an underground walking passage in Nanjing as the research object and use the method of numerical simulation and field monitoring to predict and analyze the deformation of the tunnel and surface caused by pipe jacking construction. Based on the theory of circular hole expansion, Zhao Wen et al. [4] put forward the calculation equation of the plastic zone around the tube with flange plate;
S.L. Shen [5, 6], and L. Zhen et al. [7] have analyzed the laws of surface deformation and deep soil deformation under the disturbance of pipe jacking construction. Shi Peixin et al. [8] studied the calculation and evaluation method of pipe jacking force. Wang Bin et al. [9] analyzed the disturbance degree of pipe jacking construction in sand and clay formations. Li Fangnan et al. [10] proposed a method of considering the influence of grouting pressure. Pan Weiqiang [11] relied on the pipe curtain section project of Guiqiao Road Station of Shanghai Line 14 to monitor and analyze the ground settlement during the pipe jacking construction process. The above research results provide a better technical paradigm and method for the study of formation deformation during pipe jacking construction. However, in the western part of Handan, especially in the Cixian section of the middle route of the South-to-North Water Transfer Project, the impact of pipe jacking construction on formation deformation in sandy gravel formations has not yet been reported.

Based on this, this article takes the Cixian sewage pipe network in the west of Handan as the engineering background, adopts the method of combining theoretical analysis and field measurement to study the surface and highway pavement deformation during the pipe jacking construction process, and optimize the theoretical prediction calculation parameters to modify the theoretical model of surface settlement and deformation. It is hoped that the related research results will provide technical and theoretical reference for other project construction in this area.

2. Project Overview
The sewage pipeline project of Hexie Avenue is located in the west of Ci County, Handan City, which is about 100 meters away from the Cixian section of the central route of the South-to-North Water Transfer Project. The pipe is jacking construction mainly traverses Hexie Avenue in Cixian County, which is a supporting project for the sewage pipeline network to cross the mainline of the Vietnam Water-North Diversion Project, show as in figure 1. The diameter of the pipeline is 1m, the buried depth is 6.13m, the length of a single pipe section is 2m, and the thickness is 0.1m. The length from the working shaft to the receiving shaft is about 46m.

The geological section, which is revealed by the excavation of the working well on the north side of Hexie Avenue, shows that the pipe jacking construction is mainly located in the sandy gravel stratum, and there is the phenomenon of interbedded silty clay with gravel and sandy gravel stratum, as shown in figure 2. The main physical and mechanical parameters of each layer are shown in table 1.

| Strata         | Natural severity /KN/m³ | Compression modulus/MPa | Poisson's ratio(ν) | Cohesion /kPa | Friction angle (φ/°) |
|----------------|-------------------------|-------------------------|--------------------|---------------|----------------------|
| Pebble silty clay | 19.7                    | 33.5                    | 0.33               | 25            | 28                   |
| Pebble         | 21.0                    | 50.6                    | 0.28               | 0             | 36                   |

Table 1. Physical and mechanical parameters of the formation.

Figure 1. Overview of the project.  
Figure 2. Stratum section.
3. Field Test of Surface Deformation Induced by Pipe Jacking Construction

3.1. Measured Solution

The surface settlement is measured by the level method. During the pipe jacking construction process, monitoring points are arranged within 10 m in front of the jacking. Between the working well and the receiving well, there are 23 monitoring sections arranged every 2 m, which is DJC1–DJC23. With the pipeline axis at the center, 9 monitoring points are arranged at equal intervals on each section, and the interval between each monitoring point is 1m, as shown in figure 3.

![Figure 3. Schematic diagram of ground settlement monitoring points.](image)

3.2. Analysis of Measured Results

The law of surface deformation during pipe jacking construction is shown in figure 4. The analysis in the figure shows that the maximum surface settlement is about 3 mm after the pipe jacking construction; Under this working condition, the impact of pipe jacking construction on stratum deformation has the characteristics of “immediate disturbance”, that is, the amount of surface deformation at the jacking face is relatively large, while the stratum in front of the jacking face is relatively less affected by disturbance. Compared with the surface deformation in front of the fixed roof working face, the surface deformation at the working face shows a "drop" increase.

![Figure 4. Variation of the settlement of different monitoring sections during the jacking process.](image)

After the pipe jacking construction is completed, the cumulative settlement and deformation of the ground surface are shown in figure 5. It can be seen from the analysis in the figure that along the cross-section of the pipeline, the surface settlement varies between 1.5 mm and 4 mm, and the maximum settlement of pipe jacking occurs above the axis; along the longitudinal section of the pipeline, the surface settlement deformation is relatively stable; The settlement of the road surface of
Hexie Avenue is relatively small. Due to the relative rigidity of the road surface and the roadbed, the surface settlement slightly increases when it reaches the receiving shaft.

![Graph](image)

Figure 5. Changing the curve of the surface settlement of each monitoring section.

4. Ground Deformation Prediction and Model Modification

4.1. Existing Prediction Models

Peck obtained the approximate horizontal settlement curve of the surface by using probabilistic analysis on a large number of measured data.

\[ S(x) = S_{\text{max}} \exp\left(-\frac{x^2}{2i}\right) \]  

(1)

where \( S(x) \) is the settlement of any point on the ground; \( S_{\text{max}} \) is the maximum settlement of the surface, \( S_{\text{max}} = \frac{V_s}{2.5i} = \frac{4DV_i}{2.5i} \); \( V_s \) is the stratum volume loss, \( V_i \) is the stratum loss rate; \( D \) is the diameter of the tunnel; \( x \) is the level distance from the calculation point to the center of the settlement curve; \( i \) is the horizontal distance from the center of the settlement curve to the inflection point of the curve, which is called the width coefficient of the settlement trough.

When the tunnel diameter \( D \) is constant, the stratum volume loss rate and the settlement trough width coefficient \( i \) are the key factors affecting the result of surface settlement deformation. There are many research results on the estimation method of the width coefficient \( i \) of the settlement trough. According to the correlation between the value of \( i \) and the friction angle of the stratum soil, the buried depth \( z_0 \) of the tunnel, and the radius \( R \) of the tunnel, the following empirical estimation methods are refined and summarized [12]:

(a) Knothe estimation method.

\[ i = \frac{z_0}{\sqrt{3\pi} \tan(45^\circ - \frac{\phi}{2})} \]  

(2)

(b) Clough and Schmidt estimation method.

\[ i = R(z_0 / 2R)^{0.8} \]  

(3)
(c) O’Reilly and New estimation method.

\[ i = Kz_0 \]  \hspace{1cm} (4)

where \( K \) is the width coefficient index of the settlement trough, combined with the suggestions in the literature [13], the width coefficient of the settlement trough in this paper is calculated as 0.48.

The stratum loss rate depends on factors such as stratum type, groundwater conditions, construction methods, support timing, and construction control quality. It usually values based on the local construction experience. Generally, the stratum loss rate ranges from 0.22% to 6.9%. Assuming that the formation volume loss rate in this project is between 0.22~6.9%, the maximum surface settlement can be calculated according to equations (1), (2), (3), and (4), as shown in table 2. It can be seen from the table analysis that when the volume loss rate of the formation in the construction area is controlled within 6.9%. The maximum surface variable is about 10.3 mm, which meets the requirements of formation stability.

| Method of prediction | \( i / m \) | \( S_{\text{max}} / \text{mm} \) | \( V_l = 0.22\% \) | \( V_l = 1\% \) | \( V_l = 2\% \) | \( V_l = 6.9\% \) |
|---------------------|-------|----------------|----------------|----------------|----------------|----------------|
| Knothe              | 4.8   | 0.14          | 0.65           | 1.3            | 4.5            |
| Clough              | 2.1   | 0.33          | 1.5            | 3.0            | 10.3           |
| O’Reilly            | 2.9   | 0.23          | 1.07           | 2.16           | 7.4            |

4.2. Correction of a Prediction Model Based on Measured Data
In this paper, the Gauss function is used to perform regression analysis on the measured results to obtain the maximum surface settlement \( S_{\text{max}} \) and the width coefficient \( i \) of the settlement trough at different monitoring sections. Further inversion, the formation volume loss rate was obtained, and the O’Reilly and New estimation method were used to invert the distribution range of the settlement trough width coefficient \( K \). The form of the Gauss function is shown in equation (5).

\[
y = y_0 + \frac{A}{w\sqrt{\pi}/2} e^{-\frac{(x-x_c)^2}{w^2}}
\]  \hspace{1cm} (5)

By comparing the form of the equation (1) and equation (5), it is found that the maximum surface settlement \( S_{\text{max}} \) and settlement trough width coefficient \( i \) predicted by the peck equation can be expressed by Gauss function parameters as:

\[
S_{\text{max}} = y_0 + \frac{A}{w\sqrt{\pi}/2} \left\lfloor \frac{w}{2} \right\rfloor
\]

\[
i = \frac{w}{2}
\]  \hspace{1cm} (6)

Besides, \( x_c \) is the horizontal coordinate correction term of the surface settlement curve. Using the equation (5) to perform a regression analysis on the measured data of monitoring sections DJC1~DJC15, the regression and inversion results of model parameters are shown in table 3. The analysis of the data in table 3 shows that when the pipe jacking method is used for the construction of the underground passage in the Cixian area in the west of Handan, the maximum surface settlement varies from 3.02 to 3.72; the stratum volume loss rate \( V_l \) varies from 1.17% to 5.45%. It is 3.31%, the formation loss rate is less than 6.9%, and the formation deformation meets the safety requirements; the variation range of the settlement trough width coefficient \( K \) is 0.17~0.88, with an average of 0.525, which is slightly larger than the research suggested by Han Xuan et al. [12].
Table 3. Inversion analysis results of surface deformation prediction parameters.

| Section | \( y_0 \) | \( A \) | \( w \) | \( x_c \) | \( S_{\text{max}} \) | \( i \) | \( V_0/\% \) | \( K \) |
|---------|------|------|------|------|-------|------|-------|------|
| DJC1   | -1.46 | -7.49 | 3.73 | 0.29 | -3.06 | 1.865 | 1.82  | 0.30 |
| DJC2   | -1.76 | -7.06 | 3.41 | 0.25 | -3.41 | 1.705 | 1.85  | 0.28 |
| DJC3   | -1.48 | -10.67 | 4.9  | 0.01 | -3.22 | 2.45  | 2.51  | 0.40 |
| DJC4   | -2.03 | -6.79 | 4.27 | -0.45 | -3.30 | 2.135 | 2.24  | 0.35 |
| DJC5   | -1.56 | -9.59 | 5.23 | -0.07 | -3.02 | 2.615 | 2.52  | 0.43 |
| DJC6   | -1.77 | -5.89 | 3.87 | -0.03 | -2.98 | 1.935 | 1.84  | 0.32 |
| DJC7   | -1.88 | -7.44 | 4.32 | -0.01 | -3.25 | 2.16  | 2.24  | 0.35 |
| DJC8   | 1.93  | -69.02 | 10.82 | -0.28 | -3.16 | 5.41  | 5.45  | 0.88 |
| DJC9   | -2.05 | -6.25 | 3.94 | -0.68 | -3.32 | 1.97  | 2.08  | 0.32 |
| DJC10  | -1.29 | -13.94 | 5.34 | 0.25 | -3.37 | 2.67  | 2.87  | 0.44 |
| DJC11  | -1.52 | -9.75 | 3.95 | 0.31 | -3.49 | 1.975 | 2.20  | 0.32 |
| DJC12  | -1.29 | -9.84 | 4.35 | 0.38 | -3.10 | 2.175 | 2.14  | 0.35 |
| DJC13  | -1.98 | -4.01 | 2.08 | -0.03 | -3.52 | 1.04  | 1.17  | 0.17 |
| DJC14  | -1.92 | -8.97 | 3.97 | -0.25 | -3.72 | 1.985 | 2.35  | 0.32 |
| DJC15  | -0.62 | -24.51 | 6.96 | -0.32 | -3.43 | 3.48  | 3.80  | 0.57 |

Using the parameter value results obtained by the above regression analysis, the monitoring section DJC16–DJC23 is used for predictive analysis. The comparative analysis of the measured data and the model predictive results are shown in figure 6. From the analysis in the figure, it can be seen that the measured surface settlement data of the monitoring sections DJC16–DJC23 are all located between the upper and lower limits of the model prediction results, and the average prediction results are more consistent with the measured results of the overall surface deformation. Therefore, when similar pipe jacking works are carried out in the Cixian section of the Middle Route of the South-to-North Water Transfer Project in the future, it is recommended that the width coefficient index of the settlement trough should be 0.525 and the formation loss rate should be 3.31% in the prediction and calculation of surface settlement.

![Figure 6. Revised model verification.](image-url)
5. Conclusion
Theoretical prediction and analysis show that when the volume loss rate of the stratum of the project is controlled within 6.9%, the surface settlement and deformation can meet the safety requirements of relevant regulations.

Under this working condition, the impact of pipe jacking construction on stratum deformation has the characteristics of “immediate disturbance”, that is, the amount of surface deformation at the jacking face is large, while the stratum in front of the jacking face is relatively less affected by the disturbance, and the maximum surface settlement is The measured value is between 2.5 mm~4 mm, which is within the safety threshold of surface deformation.

After the regression optimization analysis of the measured data, it is recommended that under the disturbance of pipe jacking construction in the Cixian section of the South-to-North Water Transfer Project, the stratum loss rate should be 3.31% and the settlement trough width coefficient $K$ should be 0.525.

Acknowledgments
This work was supported by Open Research Fund of State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Grant NO.Z018022, and supported by Opening Research Fund of National Engineering Laboratory for Surface Transportation Weather Impacts Prevention.

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