Ground Response to Pipe-Roof Tunneling of a Large Underpass in Shanghai Soft Soil

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Abstract. Pipe roof method is an effective way for urban underpassing scheme. Due to the successive jacking of multiple pipes, the characteristics of ground response are distinctly different from single pipe or twin pipes. In this paper, the gradual ground loss by successive pipe-jacking and the causes of settlement are analyzed. The conclusions drawn from this paper show that: (1) The maximum incremental was right above the pipe axis which could be controlled within 1mm. (2) The shield effect of the former pipe on the latter one resulted in a 50% reduction of maximum incremental settlement. (3) The distribution of cumulative settlement curve was reflected by superimposed effect of staged ground settlements. (4) The results of settlement monitoring illustrated that the field measured settlements were basically tally with those of the simulated values, the goodness of fit was more than 85%.

Keywords. Pipe roof, ground settlement, superimposed effect.

1. Introduction
During the construction process of the pipe roof-box culvert method, the box culvert is jacked under the protection of a previously created pipe roof structure. This method has less influence on the ground transportation, generally requires no removal of underground pipelines, and can avoid excessive ground settlements [1-3]. However, when compared with single pipe or twin pipes, the ground response of pipe roofs is more complicated. Many researchers had focused on the controlment of settlements and attitude of pipes [4-7], for instance, Kotak et al. [4] explored the impact of back fill grouting on surface settlement and proposed that grouting can help to slow the development of settlements. Furuyama et al. [5] predicted the settlement induced by pipe jacking in special geological condition of North America. Yamaguchi et al [6] improved the evaluation method of interaction between proximal pipes. Hence, the current reported studies are still lacking in the evolution of ground loss specific to multiple pipes’ jacking. Based on a pipe-roof engineering case in Shanghai, the ground response to pipe-roof tunneling of a large underpass is analyzed in this paper. The relevant conclusions drawn from the paper can provide practically targeted references for engineers in similar projects.

2. Project Description
The pipe-roof project of an underpass was consisted of 62 parallel pipes under urban expressway in Shanghai, China. These steel pipes with external diameter of 824 mm were jacked over 85 m in soft ground by four slurry pipe jacking machines at a depth of 6.3 m under the urban expressway. As figure...
shows, the scale of pipe roof structure was 21.648m wide and 8.148m high, consisted by 24 top pipes (No. S1~S24), 7 left pipes (No. Z2~Z8), 7 right pipes (No. Y1~Y7) and 24 bottom pipes (No. D1~D24). The top pipes started to be jacked after the completion of bottom pipes and bilateral pipes. After the formation of pipe roof frame, the box culvert can be continuously jacking in an isolated area.

Table 1 shows the physical and mechanical parameters of soils, the underpass was mainly jacked in mucky silty clay and mud clay which is featured as high water content, high sensitivity and low strength.

| No. | Soil layers     | $\gamma$ (kN/m$^3$) | $\omega$ (%) | $c$ (kPa) | $\phi$ ($^\circ$) | $E_s$ (MPa) |
|-----|-----------------|----------------------|--------------|-----------|------------------|-------------|
| 1   | Silty clay      | 18.5                 | 32.2         | 19.0      | 19.0             | 4.46        |
| 2   | Mucky silty clay| 17.6                 | 40.6         | 12.0      | 18.0             | 3.09        |
| 3   | Mud clay        | 16.8                 | 50.0         | 11.0      | 11.5             | 2.20        |
| 4   | Silty clay      | 17.9                 | 35.9         | 14.0      | 19.0             | 3.79        |
| 5   | Silty clay      | 18.0                 | 35.1         | 15.0      | 19.0             | 4.33        |
| 6   | Sandy silt      | 18.5                 | 28.9         | 5.0       | 31.5             | 9.43        |

3. Finite Element Analytical Model

Considering the sphere of influence of pipe roof jacking, the geometric size of the model was set as 90m×40m (figure 2). Due to the tiny amount of space between adjacent pipes (<0.1m), the analytical model of pipe roof was simplified as a no gap junction structure. According to the engineering practice, the bottom pipes are jacked from the middle to both sides and the bilateral ones are jacked from top to bottom simultaneously. At last, the top ones started to be jacked until the frame was closed. So in the numerical model, 62 steel pipes were jacking by total 48 steps, the initial pipes and terminal pipes of four sides were marked by rhombus and triangle respectively (figure 3).
4. Ground Response to Pipe Roof Jacking

4.1. Incremental Settlement of Individual Jacking
The incremental settlements meant the difference between two adjoining steps. According to the jacking steps illustrated in figure 3, the incremental settlement induced by individual pipe of bottom ones and top ones was shown in figure 4 and figure 5. The distribution curves of incremental curves were in accordance with the peck curve [8], the maximum magnitude of incremental settlements were less than 1mm which was located directly above the pipe axial line. Along the horizontal direction from middle to the two sides, the incremental settlement gradually decreased, falling by about 50%. This phenomenon lay in the shield effect of the former pipe on the latter one, the existing pipe of bilateral sides sheltered the propagation of current jacking.

4.2. Cumulative Settlement of Pipe Group
Figure 6 revealed the cumulative settlement curves induced by pipe group jacking, ground settlements were accumulated continuously with the successive jacking of pipe group, eventually reaching to 22.5mm. The distribution of the settlement curve was rendering as superposition of phased ground settlements. The settlement trough evolved into a bowl-shaped curve, reflecting the superimposed effect of pipe group jacking.
Figure 6. Cumulative settlements induced by pipe group jacking.

Figure 7 shows five critical steps of the pipe group jacking process. As the first pipe, the ground response induced by D13 was very small, the maximum settlement was only 0.8 mm. Pipe Z8 was the initial one of left side, the corresponding settlement increased to 1.4 mm and the settlement trough was transited from flat pattern to bimodal pattern which peak points were above pipe Z8 and Y7. Meanwhile, the width coefficient of settlement trough increased to 14 m. Pipe D19 and Z2 represented the completion of bilateral jacking, significantly increasing settlement from 1.4 mm to 10 mm. The settlement trough turned into groove type, with the maximum settlements symmetrically distributed from -6 m to 6 m in horizontal direction. Pipe D3 was he terminal pipes of bottom row and S10 was the closed pipe of the frame, there was no obvious change in the distribution of settlement curves, the width coefficient of settlement trough kept as 14 m. When the jacking process of total 62 pipes was completed, the maximum settlement could reach 22.5 mm.

Figure 7. Cumulative settlements of critical steps

The monitoring points of ground settlement were arranged as shown in figure 8. As figure 9 shows, after jacking of 38 bottom and bilateral pipes, the results of field test illustrated that the field measured settlements were basically tally with those of the simulated values. However, due to excessive amounts of secondary grouting, the left half of the measured curve had an obvious uplift.

Figure 8. Arrangement of monitoring points
5. Conclusions

Based on an underpass project in Shanghai, the gradual ground loss by successive pipe-jacking and the causes of settlement are analyzed. Some conclusions are summarized as follows:

(1) In this project, the distribution curves of incremental settlements induced by individual pipe well fitted to the peck curve. The maximum increment was right above the pipe axis which could be controlled within 1 mm.

(2) Due to the shield effect of the former pipe on the latter one, the existing pipe of bilateral sides sheltered the propagation of current jacking, resulting a 50% reduction of maximum incremental settlement.

(3) The distribution of cumulative settlement curve was reflected by superposition of phased ground settlements and the settlement trough finally evolved into a bowl-shaped curve.

(4) The results of settlement monitoring illustrated that the field measured settlements were basically tally with those of the simulated values, the goodness of fit was more than 85%.

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