Jacking precision control of pipe roof and large box culvert below urban expressway-a case study of a large underpass in Shanghai

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Abstract. Pipe roof-culvert box method is an effective way for shallow buried tunnel passing beneath important facilities. In soft ground, the culvert can be jacked under the pre-reinforcement of pipe roof. This paper presents an investigation on the precision analysis and control of a large-scale pipe roof jacking (the scale of this structure is 21.648m*8.148m) of an underpass, which passes beneath the Mid-Ring expressway in Shanghai. The conclusions drawn from this paper show that: (1) In this project, more than 70 percent of the deflection values of jacking machines and pipes are controlled within 20mm. (2) During the process of pipe jacking, the deflections of pipes tend to lag behind the machines’ about 3~10m. 68 percent of the rangeability of pipes’ deflection are 50%~100% of the corresponding machines’ deflection. (3) Due to Stiffness effect of pipeline, posture of pipe is difficult to be rectified during the stages of pipe starting and receiving. A compelling rectification will result in overlarge deviation and increase the difficulty of subsequent operation. (4) For two adjacent pipes, the posture of latter pipe is positively related by the stiffness of prior pipe. The Pearson correlation coefficient of horizontal pipes and vertical pipes can be 0.46 and 0.68 respectively. (5) Considering the interspace between top pipes and box culvert, the control criterion of vertical deviation of box culvert is recommended as 5cm.

Keywords: pipe roof, urban expressway, precision analysis, posture control

1. Introduction

From the early 1990s, Shanghai had begun to build the urban expressway transportation system for alleviating the increasing traffic pressure [1]. As Figure 1(a) shows, the urban expressway network is
mainly consisted of three circle lines (Inner Ring Road, Middle Ring Road and Outer Ring Road) and two cross lines (South-North Viaduct and Yan'an Viaduct). However, due to lacking of unified traffic planning, lot of surface roads are separated as so called “dead end roads” by the city expressways, leading to the inconvenience of commuting, even a sever to the transportation of the local network [2]. For example, Fig. 1(b) illustrates a typical case of dead end road which is separated by Mid-Ring Road and trigger the traffic chaos of the local area. In order to connect these two separated parts of the dead end Road, an underpass scheme is preferred for its advantages of little impact on operating traffic flow and surrounding environments in densely inhabited districts.

Figure 1. The distribution of urban expressway in Shanghai and an example of dead end road

Compared with other underground excavation methods, RBJ (Roof-Box Jacking) method is proved to be a relatively reliable and effective way for shallow buried undercrossing in soft ground. Under the pre-supporting of pipe roof, the box culvert can be jacked in an enclosed area. Thus this method can minimize the disturbance to existing underground utilities and ground transportation. In recent decades, this technique has been successfully used in many undercrossing projects, e.g., Capital International Airport underpass project in Beijing [3], Fuhsing North Road undercrossing project in Taipei [4], Jihua utility tunnel in Jilin [5], South-to-North Water Transfer Crossing Project in Tianjin [6] and the Beihong vehicular undercrossing in Shanghai, China [7].

Pipe roof can reduce the effect of ground loss, and create a boundary of high stiffness between ground and box. However, once the jacking deviation exceeds clearance limit between pipes and box culvert, the structural collision is inevitable and obstruct the smooth construction of box culvert. On the other hand, an overlarge interspace between pipes and box culvert could likely cause large ground loss during box culvert jacking. Therefore, the jacking precision of pipe roof is critical which has a direct influence on the jacking process of box culvert. In this paper, the precision of the pipe jacking is analysed and the control criterion of height deviation of box culvert jacking is proposed based on this underpass project. The relevant conclusions drawn from the paper can provide practically targeted references for engineers in similar projects.

2. Project profile
This underpass project is a reconstruction of the dead end road, stretching from Gumei Road to Guiping Road with a total length of 696m. For the planning of the underpass, the most crucial is to keep the
uninterrupted operation of Mid-Ring Road and have no impact on the service of intersections. As Figure 2 shows, the underpass is consisted of two open sections and a buried section. The buried section with a length of 290m is extending from west side of Mid-Ring Road to east side of Guiguo Road. The RBJ method is applied to the section undercrossing Mid-Ring Road and the rest of the project is constructed by open-cut method. As shown in Figure 3, the depth of underpass is about 6.3m under the Mid-Ring Road and the underpass is mainly jacked in mucky silty clay and mud clay which is featured as high water content, high sensitivity and low strength.
As Figure 4 shows, the scale of pipe roof structure is 21.648m wide and 8.148m high. According to the design axis, the interspace between top pipes and box culvert is only 100mm. 62 φ800mm steel pipes are jacking as a sequence of bottom pipes, bilateral pipes and top pipes by four slurry pipe jacking machines. Every pipe is jacking successively according to the order from prover pipe, standard pipe to closed pipe. The interpolating T-shape interlocks between pipes can improve integrity of pipe roof structure and provide accurate orientation for pipe jacking. After the formation of pipe roof frame, the box culvert can be continuously jacking in an isolated area.

3. Precision analysis of pipes
Because these pipes are successively jacked by pipe jacking machines and formed integrally by interlocks. The posture of a single pipe is not only affected by the corresponding posture of jacking machine head, but also affected by the posture of its prior pipe. The influences on the precision of pipes are mainly reflected in two aspects of deflection lag effect and stiffness effect.

3.1. Deflection lag effect of pipeline
During the jacking process of pipe jacking machine, the position precision of a steel pipe is largely depended on the trajectory deviation of the machine head. When the position of machine is deviated from the design axis, the measure of deflection correction is taken (Figure 5) to ensure the precision of pipes.

Figure 5. Illustration of deflection correction

At different jacking distances, the horizontal and vertical deviation of pipe jacking machine mainly ranged from -20mm to 20mm as shown in Figure 6(a). The data indicated that more than 73 percent of the deviation values between machine deflected trajectory and designed axis can be controlled less than 20mm. Correspondingly, Similar to Figure 6(a), 72 percent of the horizontal and vertical deviation of pipes are also centralized within ±20mm (Figure 6(b)). But along the jacking direction, the deflection of pipe will lag behind the machine about 3~10m. Taking D9 and D18 as examples, the trajectory curves of machine and pipe are showed in Figure 7 when the Jacking process is completed. As Figure 7 shows, the deflection correction of machine trajectory has an impact on the posture of pipes which shows they have the same trend of variability. However, the variations have distance differences ranging from 3~10m. For instance, the jacking machine in Figure 7(a) has a deviation correction from 30~40m while the corresponding variation of pipe happens at 20~30m. The corresponding deviation ratios between pipes and machines are listed in Figure 8. According to the statistical histogram, 68% of the deviation ratios ranges from 0.5 to 1, namely the deviation values of pipes will be 50% to 100% of the machines’ deviation.
**Figure 6.** Deviation distribution of machine and pipe

(a) Deviation distribution of machine  
(b) Deviation distribution of pipe

**Figure 7.** The comparison of trajectory curves of machine and pipe

(a)  
(b)  
(c)  
(d)
3.2. Stiffness effect of pipeline

Because the steel pipes are connected with rigid pipe joints, the entire pipeline stiffness is very large which make the posture of pipe is difficulty to be rectified during the stages of pipe starting and receiving. As Figure 9(a) shows, the deviation of first section (14m) of pipe is directly caused by the deviation of jacking machine at starting point. Moreover, the deviation value of pipe keeps increasing from -2mm to -21mm, despite the machine trying to rectify its deviation from -10mm to 0mm. Due to the large stiffness of first section of pipe, there must be a sharp adjustment of machine posture for correcting the deviation of pipe. In Figure 9(b), the behavior of machine’s deviation correction from -5mm to 10mm has no effect on the pipe’s posture at starting stage. Then during the jacking distance between 10m and 40m, a dramatic correction from -20mm to 30mm compels the pipe’s posture changing from -15mm to 25mm. Therefore, in order to ensure the precision of first section of pipe and lower the difficulty of subsequent operation, the starting precision of jacking machine should be improved. Similarly, the deviation of the last section of pipe (12m) should be corrected in advance, otherwise the pipe will deviate unidirectionally and affect the precision of pipe receiving (Figure 9).

(a)  
(b)

Figure 8. Histogram of deviation ratio between pipe and machine

Figure 9. Stiffness effect of pipeline during starting and receiving
In addition, the stiffness effect of pipeline also reflects in adjacent two pipes. Because of the large stiffness of the existing prior pipe, there is an obvious positive correlation between the posture of latter pipe and prior pipe. As shown in Figure 10, the Pearson correlation coefficient of horizontal pipes and vertical pipes can be 0.46 and 0.68 respectively.

**Figure 10. Stiffness effect between latter pipe and prior pipe**

4. **Posture control of box culvert**

The posture of box culvert jacking is directly affected by the interspace between pipe roof and box culvert. Once the jacking deviation of box culvert exceeds the clearance limit, the structural collision is inevitable and resulting in difficult of jacking, even causing the excessive ground disturbance. Therefore, the posture control of box culvert should be of prime importance.

Generally, the interspace between pipe roof and box culvert will be influenced by these three factors: (1) Deviation of pipe jacking. (2) Pipe deformation induced by box culvert jacking. (3) Deviation of box culvert jacking. Considering that the interspace is only 10cm and the max previous deviation of pipe is 1.8cm, the sum of factor (2) and (3) should be controlled in 8.2cm. In this section, a numerical model (Figure 11(a)) is set up to predict the deformation of top pipes and proposed the control criterion for construction guidance.

**Figure 11. Numerical model and deformation of top pipes after box culvert excavation**
After the excavation of box culvert, the deformation of top pipes is showed in Figure 11(b). The maximum deformation can reach 3.2cm, so the control criterion of vertical deviation of box culvert is recommended as 5cm.

5. Conclusions

As an effective way for tackling the problems induced by “dead end roads”, the pipe roof-culvert box method is recommended in soft ground. Based on the typical underpass project in Shanghai, the precision of pipe roof jacking is analyzed and a control criterion of box culvert posture is proposed. Some conclusions are summarized as follows:

(1) In this project, more than 70 percent of the deflection values of jacking machines and pipes are controlled within 20mm.

(2) During the process of pipe jacking, the deflections of pipes tend to lag behind the machines’ about 3~10m. 68 percent of the rangeability of pipes’ deflection are 50%~100% of the corresponding machines’ deflection.

(3) Due to Stiffness effect of pipeline, posture of pipe is difficulty to be rectified during the stages of pipe starting and receiving. A compelling rectification will result in overlarge deviation and increase the difficulty of subsequent operation.

(4) For two adjacent pipes, the posture of latter pipe is positively related by the stiffness of prior pipe. The Pearson correlation coefficient of horizontal pipes and vertical pipes can be 0.46 and 0.68 respectively.

(5) Considering the interspace between top pipes and box culvert, the control criterion of vertical deviation of box culvert is recommended as 5cm.

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