Geotechnical Aspects of Underground Construction in Soft Ground – Ng, Huang & Liu (eds)
© 2009 Taylor & Francis Group, London, ISBN 978-0-415-48475-6

3D FEM analysis on ground displacement induced by curved pipe-jacking construction

G.M. You
Shanghai Municipal Engineering Design General Institute, Shanghai, P.R. China

ABSTRACT: The power tunnel of Tibet road in Shanghai is the most difficult pipe-jacking project in China with long distance and large diameter. The tunnel crosses through Suzhou river, underground pipelines and area of dense buildings, especially the underground passage of subway and the existing subway line 2, so it's vital important to protect the surrounding environment when the pipe-jacking is constructed. The deformation of ground surface and the existing tunnels during the construction of curved pipe-jacking is studied with 3D finite element methods. First, the calculated results are analyzed and compared with the measured data in site to verify the correctness of the 3D FEM model. Second, there are many factors which can affect ground displacement when curved pipe-jacking is constructed. Among these factors, slurry sleeves' qualities, soil pressure on the face of pipe-jacking, slurry injection pressure and earth resistance are discussed on the basis of finite element simulation. Then, the deformation of existing tunnels of subway line 2 is studied. Finally, the ground displacement formula of curved pipe-jacking is discussed.The results show that the continuity of slurry sleeves and the pressure of the face are very important factors to ground surface deformation during the construction of curved pipe-jacking. The ground displacements induced by curved pipe-jacking are not larger than those of linear pipe-jacking if the slurry sleeves around pipe are good and continual. Because of additional earth resistance, the maximum of the ground surface deformation perpendicular to pipe axis is at the side of the center of the pipe-jacking curve, and the distance of deviation depends on the radius of pipe-jacking curve.

1 INTRODUCTION

Curved pipe-jacking technology was applied in Japan, Europe and America many years ago, and some successful experiences were also acquired. Nomura et al. (1985) developed a pipe jacking method (D301) to facilitate long-span, curved and high-speed capabilities in the construction of small diameter (300 mm) tunnels. Nanno (1996) proposed a new curving method called "the unit curving method" in which four joint-adjusters are installed between pipes. The joint angle is controlled by the adjusters and the thrust is also distributed uniformly in the four adjusters. The new method solved most of the technical problems in curved drives and performed many jobs successfully in actual construction sites. Vogler & Georg (2002) studied the stresses on the curved pipe. The prediction equation for a curved jacking area was analyzed in order to explain the characteristics of thrust and the friction resistance (Shimada et al. 2004). The thrusts in slurry pipe-jacking can be predicted accurately by using the resistance between the mud slurry and the concrete pipes and the resistance between the soil and the pipes in the curved jacking area.

In China, pipe-jacking technology has been developed rapidly in recent years and many successful constructions were obtained, such as the sewerage outfall project in Shenzhen (Mao, 2001), the secondary project of improving combined sewerage system in Shanghai (Ge, 2002), the project of Hefang street with sewage pipe and rainwater pipe in Hangzhou (Jin et al. 2002), the project of main trunk sewer pipe of Yangli wastewater treatment plant in Fuzhou (Liu, 2003). However, only single curve (horizontal curve or vertical curve) was used in these projects. Ding et al. (2001) calculated and analyzed the jacking force, joint stretching value, pipe internal force, stability of soil and earth resistance of curved pipe-jacking by means of pipe-joint mechanical model and beam on elastic foundation method.

Fang & Wang (1998) analyzed the ground settlement due to pipe jacking in soft soils and developed a method to predict the settlement profile of straight pipe-jacking. Wei et al. (2003) analyzed the mechanism and reason of ground deformation caused by pipe jacking construction. Wei et al. (2005) derived the computing formulas of ground deformation induced by bulkhead additive thrust, force of friction between shield and soil, and force of friction between follow-up pipes and soil by using the Mindlin solution in elastic mechanics. Furthermore, the formula of total ground deformation induced by pipe jacking construction was obtained by combining the formula of ground deformation induced by ground loss with the previous one. However, there is no study on the formula of ground deformation of curved pipe-jacking.

The power tunnel of Tibet road in Shanghai is the most difficult pipe-jacking project in China which is 3.033 kilometers long. This paper discusses the deformation of ground surface and the existing tunnels by means of the numerical analysis. Some important parameters during the construction and the ground displacement formula of curved pipe-jacking are also discussed.

2 3D NUMERICAL ANALYSIS OF CURVED PIPE-JACKING

2.1 *Mechanical model*

The radius of pipe-jacking plane curve is 600 m. The distance along the pipe axis range form 0 to 70 m. The distance perpendicular to pipe axis is 66 m and the height of the model is 40 m. The tunnel is located at a depth of 7.5 m (from the top of pipe to ground surface). The outer- and inner-diameter of the concrete pipe are 3,200 mm and 2,700 mm, respectively. In this analysis, we use the following assumptions:

1. The pressure on the excavation face is uniformly distributed with circular shape. The value is equal to the actual measurement pressure of soil and water cabin (face pressure). According to the actual observation record, the face pressure is 0.18 MPa.
2. During the construction of pipe-jacking, time dependent behavior of soil is not considered.
3. The frictional resistance between soil and pipe-ring is uniformly distributed along pipe axis. According to the actual observation record, the frictional resistance is about 2.0 kPa (You et al. 2006).
4. To distinguish with straight pipe-jacking, earth resistance should be accounted which induced by curved pipe-jacking. The relationship between earth resistance and radius of pipe-jacking curvature is approximately inversely-proportional linear (Ding et al. 2001). The earth resistance is 12.0 kPa at a radius of 600 m.

2.2 *Boundary conditions*

Displacement boundary conditions are applied to this model. The top side of the model is free boundary. Vertical displacements of the bottom side and normal displacements of the vertical sides are fixed, respectively.

2.3 *Compute parameters*

According to the geological report, the materials and their parameters that are used for this simulation are listed in table 1.

Table 1. Physical and mechanical parameters of the materials.

Materials	Unit weight (kN/m^3)	Young's modulus (MPa)	Poisson's ratio	Cohesion (kPa)	Friction angle (deg)
Brown clay	18.6	26.7	0.35	21.6	14.5
Silty clay	17.3	14.2	0.37	14.4	13.0
Muddy clay	16.9	11.8	0.39	14.0	10.5
Gray clay	17.3	16.1	0.36	15.7	11.5
Silty clay	17.8	27.2	0.35	18.5	17.5

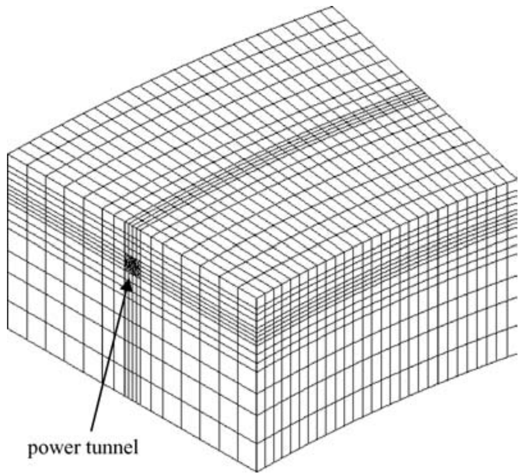

Figure 1. 3D-FEM mesh model.

The breaking criterion used in the model is Drucker-Prager criterion.

2.4 *Initial stress state*

Initial stress state is obtained by the FEM software directly. Only self-weight stress of soil is considered without tectonic stress.

2.5 *Finite element mesh*

The mesh, consisting of 11120 nodes and of 10696 elements, is subdivided into 6 regions, having different material properties. Eight node, solid element and four node, shell element are used to simulate soil and pipe-jacking ring, respectively. In order to simulate the support effect of slurry sleeves, contact surface element is engaged between pipe-jacking ring and outer soil. Figure 1 shows the 3D FEM model used in this study.

2.6 *Analysis of numerical results*

Figures 2 and 3 show the comparison between ground surface deformation obtained from numerical analysis and form measured data. The predictions from the FEM compare reasonably well with the observed results.

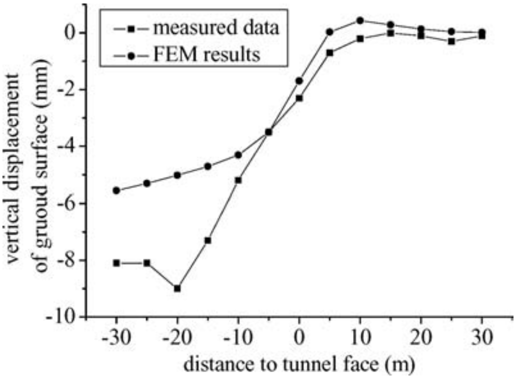

Figure 2. Displacements of ground surface along pipe axis.

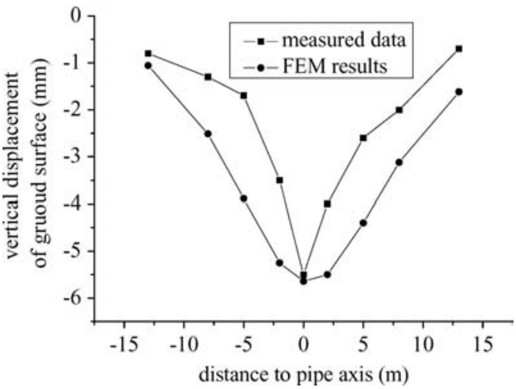

Figure 3. Displacements of ground surface perpendicular to pipe axis.

Because of the complex factors affecting the deformation of ground surface, it is impossible to consider every factor during the simulation of construction. Only several main factors are involved in this study. These factors are slurry sleeves, the pressure of the face and the earth resistance.

2.6.1 *Contribution of slurry sleeves*

The effect of slurry sleeves to reduce resistance between pipe and soil relates not only to the material and mixture ratio of slurry but also to the injection parameters such as the location of injection holes, injection pressure and slurry injection quantity. The location of injection holes and slurry injection quantity can be simulated by different locations of slurry sleeves around pipe. In this study, 5 cases are considered, as shown in Figure 4.

Figures 5 and 6 show the surface displacements with different locations of slurry sleeves. Figure 5 indicates that the continuity of slurry sleeves has vital important effect on the surface displacements. The surface displacements will be reduced sharply if good slurry sleeves can be formed around the pipe. This

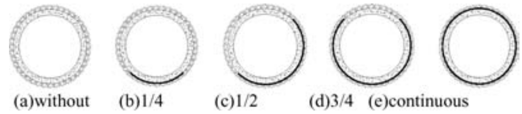

Figure 4. Different locations of slurry sleeves around pipe.

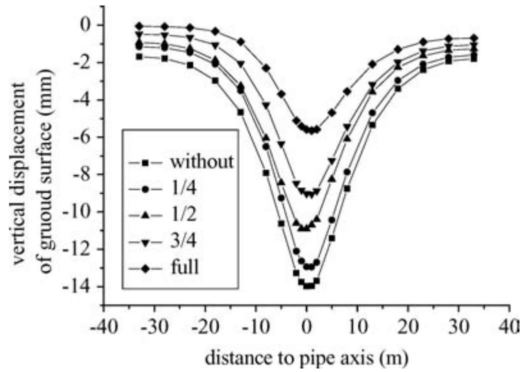

Figure 5. Displacements of ground surface perpendicular to pipe axis with different locations of slurry sleeves.

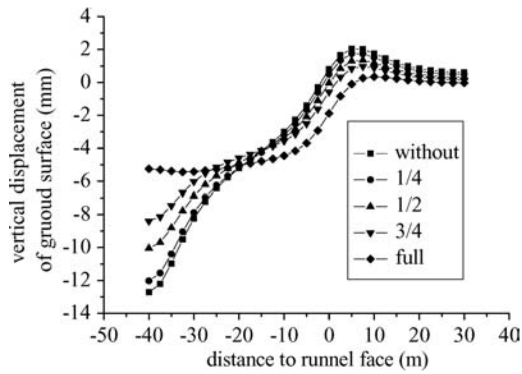

Figure 6. Displacements of ground surface along pipe axis with different locations of slurry sleeves.

phenomenon is more obvious at the top center of pipe. The range of deformation is wider if the slurry sleeves are less continuous. Figure 6 indicates that the less continuous the slurry sleeves, the lager is the ground surface uplift movement ahead the tunnel face and the less are the ground surface settlements above the tunnel face. The less continuous the slurry sleeves, the less are the ground surface settlements behind the tunnel face (in the range 0~ -15 m). The settlements are invariant after 15 m behind the tunnel face if the slurry sleeves are continuous. Moreover, the settlements will develop fast if the slurry sleeves are not continuous.

2.6.2 *Contribution of face pressure*

Figures 7 and 8 show the surface displacements with different face pressures. Figure 7 indicates that face

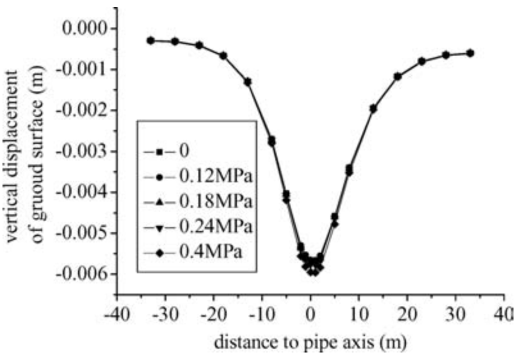

Figure 7. Displacements of ground surface perpendicular to pipe axis with different face pressures.

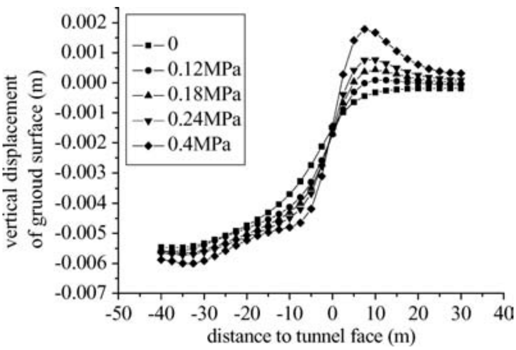

Figure 8. Displacements of ground surface along pipe axis with different face pressures.

pressure has important effect on the surface displacements at the top center of pipe. Figure 8 indicates that the larger the face pressure, the more obvious is the uplift movement of surface ground. The point with maximum uplift movement is closer to the tunnel face with increase of face pressure. The deformations ahead and behind the tunnel face will be increased with increase of face pressure. The settlement at the top of the tunnel face is invariant with different face pressure.

2.6.3 *Contribution of earth resistance*

Figures 9 and 10 show the surface displacements with different earth resistances. The alteration of earth resistance does not change much the displacements perpendicular to pipe axis. The displacements are almost the same with different earth resistance. From this result, it means that if good and continual slurry sleeves can be obtained, the displacements of ground surface of curved pipe-jacking are almost the same as straight one. Moreover, because of additional earth resistance, the deformation profile perpendicular to pipe axis is not symmetric. The larger the earth resistance, the more obvious is the difference. Furthermore,

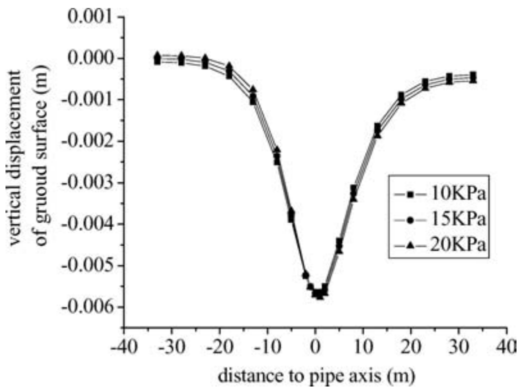

Figure 9. Displacements of ground surface perpendicular to pipe axis with different earth resistances.

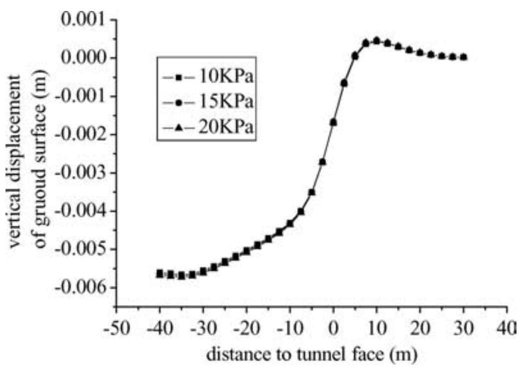

Figure 10. Displacements of ground surface along pipe axis with different earth resistance.

the point with maximum ground surface displacement perpendicular to pipe axis is not on the projection line of pipe axis but at the side of the center of the pipe-jacking curve.

3 NUMERICAL ANALYSIS OF SUBWAY LINE 2'S DEFORMATION

The power tunnel passed over the existing subway line 2, and the minimum clear distance between power tunnel and existing subway line 2 is 1.5 m. The total projected length of crossover zone is about 25 m long. The acute angle between power tunnel and subway line 2 is about 75 degree.

Figure 12 shows the relationship between vertical displacement of subway line 2 and jacking distance. Figure 13 shows the relationship between horizontal displacement of subway line 2 and jacking distance. In Figures 12 and 13 origin of jacking distance is 40 m away from the cross point. For the total projected length of crossover zone is about 25 m long, the jacking

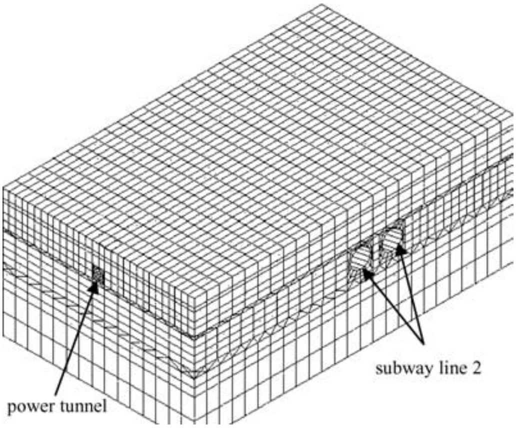

Figure 11. Mesh of power tunnel and subway line 2.

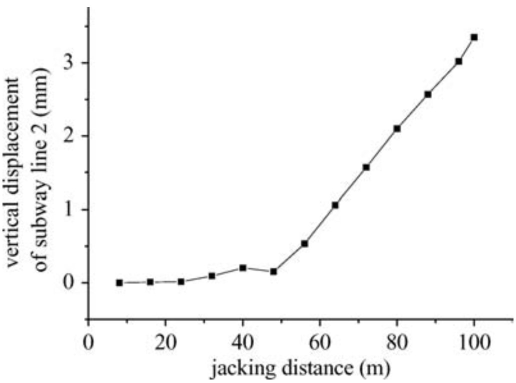

Figure 12. Relationship between vertical displacement of subway line 2 and jacking distance.

distance ranged from 40 to 65 m when the power tunnel passed through subway line 2.

Figure 11 shows the 3D finite element mesh of the power tunnel and subway line 2. The region of the model is: 100 m (along pipe axis) × 60 m (perpendicular to pipe axis) × 40 m (depth). Eight node, solid element and four node, shell element are used to simulate soil and pipe-jacking ring, respectively. Displacement boundary conditions are applied to this model. The top side of the model is free boundary. Vertical displacements of the bottom side and normal displacements of the vertical sides are fixed, respectively. The parameters that are used for this simulation are listed in table 1.

In Figure 12 positive displacement indicates heaving movement. It can be seen that vertical displacement of subway line 2 increased sharply after the jacking face passed through the subway. There was almost no displacement of subway line 2 before the pipe began to traverse the subway. Because the pipelines traversed above the subway line 2, only uplift displacements

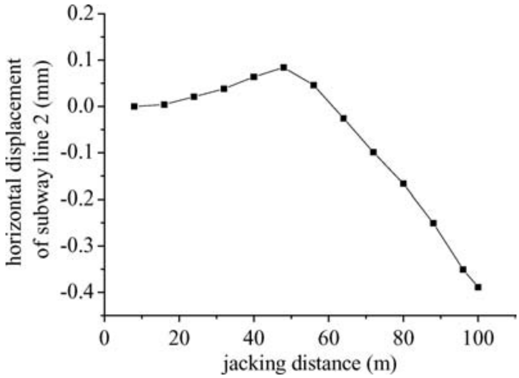

Figure 13. Relationship between horizontal displacement of subway line 2 and jacking distance.

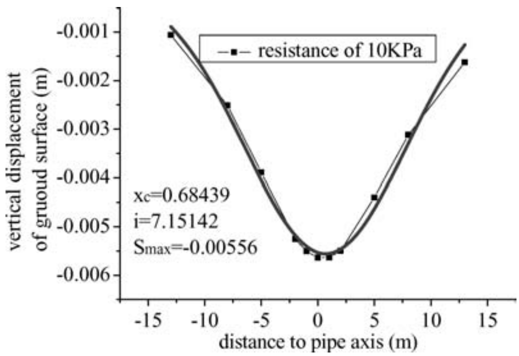

Figure 14. Regression curve of ground surface displacements with 10 kPa earth resistance.

occurred during the construction. Figure 13 indicates that the direction of horizontal displacement pointed to the tunnel face.

The FEM results show that the maximum of vertical and horizontal displacements were 3.3 mm and 0.39 mm, respectively. The values meet the demand of the normal operation of existing subway line 2.

4 GROUND DISPLACEMENT EQUATION OF CURVED PIPE-JACKING

Because of earth resistance, the deformation profile perpendicular to pipe axis of curved pipe-jacking is not symmetric to the normal line of pipe axis. According to numerical results as well as measured data, the ground displacement formula of curved pipe-jacking is obtained by means of regression analysis (Fig. 14). The vertical displacements perpendicular to pipe axis are:

$$S_V = S_{\max} \exp\left(\frac{-(x - x_c)^2}{2i^2} \right) \quad (1)$$

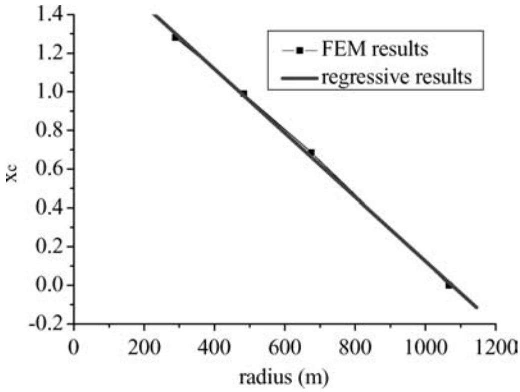

Figure 15. Relationship between curvature radius r and regressive coefficient x_c.

Where x_c is the regression coefficient related to the radius of pipe-jacking, S_{max} and i are the maximum settlement of ground surface (when $x = x_c$) and standard deviation of the settlement curve, respectively.

Based on the research consequence (Ding et al. 2001), we can get the curvature radiuses correspondence to the earth resistances mentioned above (10 kPa, 15 kPa and 20 kPa). Then, according to the previous fitting result, the relationship between curvature radius r and regressive coefficient x_c is obtained (Fig. 15). The fitted linear regression line can be expressed as follows:

$$x_c = -0.00165r + 1.7789 \quad (2)$$

It should be noted that the equations (1) and (2) are obtained with the special geological conditions of this project. The equations' suitability for other areas and geological conditions need more practical verifications.

5 CONCLUSIONS

1. Because of additional earth resistance, the maximum value of the ground surface displacement perpendicular to pipe axis is at the side of the center of the pipe-jacking curve, and the distance of deviation depends on the radius of pipe-jacking curve. The larger the radius of pipe-jacking plane curve, the less is the deviation.
2. The deformation profile perpendicular to pipe axis of curved pipe-jacking is not symmetric about the normal line of pipe axis.
3. Slurry sleeves have vital effect on ground displacements. If good and continual slurry sleeves can be obtained, the displacements of ground surface of curved pipe-jacking are almost the same as straight one. The key to control the displacements of ground surface is to control the quality of slurry sleeves.
4. The face pressure is an important factor to ground surface displacements. During the construction of curved pipe-jacking, the pressure of soil and water cabin should be controlled strictly.
5. Only uplift displacements of subway line 2 occurred during the construction of pipe-jacking. The direction of horizontal displacements of subway line 2 pointed to the tunnel face.

REFERENCES

Ding, W.Q. & Zhu, H.H. et al. 2001. Beam on elastic foundation method considering pipe-joint and analysis of pipe packing construction. *Journal of Tongji University* 29(5): 616–620.(in Chinese)

Fang, C.Q. & Wang, C.D. 1998. An analysis and prediction of ground settlement due to pipe jacking. *Journal of Jiangsu University of Science and Technology* 19(4): 106–110.(in Chinese)

Ge, J.K. & Zhang, Y. 2002. Application of jacking technology to sharply curved pile. *Chinese Journal of Geotechnical Engineering* 24(2): 247–250.(in Chinese)

Jin, W.H. & Gong, F.X. et al. 2002. Application of long distance curve pipe-jacking to Hangzhou project. *Special Structures* 19(4): 62–65.(in Chinese)

Liu, P.R. 2003. The Application of long-distance curved pipe jacking technology. *Fujian Construction Science and Technology* (2): 38–39.(in Chinese)

Mao, B.Q. 2001. Technology of curved pipe-jacking with long-distance and large-diameter in sea area. *Special Structures* 18(3): 48–53.(in Chinese)

Nanno, T. 1996. A method for driving curved pipe-jacked tunnels. *Tunnelling and Underground Space Technology* 11(2): 3–25.

Nomura, Y. & Hoshina, H. et al. 1985a. Pipe jacking method for long curve construction. *Journal of Construction Engineering and Management* 111(2): 138–148.

Nomura, Y. & Hoshina, H. et al. 1985b. Design and characteristics of D301 pipe jacking machine. *Denki Tsushin Kenkyusho Kenkyu Jitsuyoka Hokoku* 34(12): 1789–1799.

Shimada, H. & Khazaei, S. et al. 2004. Small diameter tunnel excavation method using slurry pipe-jacking. *Geotechnical and Geological Engineering* 22(2): 161–186.

Vogler & Georg. 2002. Stresses on jacking pipes when driving curved alignments. *Betonwerk und Fertigteil Technik/Concrete Precasting Plant and Technology* 68(7): 50–61.

Wei, G. & Huang, Z.Y. et al. 2005. Study on calculation methods of ground deformation induced by pipe jacking construction. *Chinese Journal of Rock Mechanics and Engineering* 24(Suppl. 2): 5808–5815.(in Chinese)

Wei, G. & Xu, R.Q. et al. 2003. Analysis of ground deformation caused by pipe jacking construction. *Trenchless Technology* 20(6): 24–27.(in Chinese)

You, G.M. & Ge, J.K. et al. 2006. Study on environmental protection and control techniques of 3-D curved pipe-jacking construction. *Rock and Soil Mechanics* 27(Suppl.): 398–401.(in Chinese)