Journal of GeoEngineering, Vol. 5, No. 3, pp. 77-85, December 2010

ON THE BEHAVIOR OF A STUCK CURVED PIPE JACKING

Keh-Jian Shou [1] and Jung-Hsing Yen [2]

ABSTRACT

The influences of coefficient of friction (COF) and contact condition on the soil-pipe interaction have been analyzed and discussed by different related studies, including the one performed by the authors (Liu 2010, Shou *et al.* 2010). It was done by simple experiment and by incorporating it into the set contact property after establishing a curved pipejacking numerical analysis model. However, the assessments of various jacking forces in literatures rarely explore the impact of changes in the COF caused by alterations in the geological conditions or construction situations.

In this paper, we first investigated common construction problems in two curved pipejacking cases from Chiayi and Kaohsiung, and one case of straight, long-distance pipejacking in Taichung. We discovered that the actual jacking force often exceeded the pre-construction calculations, revealing the possible causes or difficulties for the increase in jacking force. To examine the impact of a stuck pipe on the jacking force, we set different contact properties between the soil and the pipe within the area of the stuck pipe. In addition to a horizontal curved pipejacking simulation, this study also simulated vertical curved pipejacking. In the stuck pipe simulation, we found that because of the intense interactions between the pipe and the solum, the distribution of stress increased, and the jacking force also increased along with an increase in the area of stuck pipe. In the vertical simulation, where building elements were added, we found that the stuck pipe simulation also had some impact on the displacement of the structure.

Key words: Horizontal curved pipejacking, vertical curved pipejacking, numerical analysis, stuck pipe, coefficient of friction, jacking force.

1. INTRODUCTION

In this paper, we investigated the construction problems in two cases of curved pipejacking from Chiayi and Kaohsiung, and found that the pre-construction calculations of jacking force were often less than the level of actual jacking force. Whenever the jacking force suddenly increased, it could cause insufficient jacking force and halt pipejacking if workers were not prepared. Additionally, we included one case of long-distance, straight pipejacking from Taichung to investigate difficulties with stuck pipes. In this case, fine particles from the soil were found already filling the parameters of the ream overbreak outside the injecting holes of lubricant. The effect of contracting and sticking on the pipes also induces the increasing in resistance and raising in jacking force. Therefore, understanding the impact of change to the coefficient of friction (COF) during the construction process is extremely important.

Generally, previous studies obtained a single (COF) through lubricant experiments in curved pipejacking simulations, and have set the contact property between the soil and the pipe at a single value in numerical simulations. However, the COF for soil and pipe in actual pipejacking is likely to encounter the same situations as the above cases, and change due to variance in geological conditions. Within most empirical formulas and theoretical formulas, there is no formula that recommends solutions for pipejacking in the case of COF changes, causing pre-construction assessments of jacking force to often fail to meet construction needs. To understand the situations of stuck pipes, this paper investigated different contact properties in numerical simulations for both horizontal and vertical curved pipejacking. This paper also explored changes in the local coefficient to investigate its impact on jacking force and the distribution of stress.

2. REVIEW OF JACKING FORCE ESTIMATION AND PIPEJACKING CASES

2.1 Review of Pipejacking Force Estimation

Evaluating pipejacking force is necessary before the pipejacking construction. Theoretical formulas for pipejacking force assessment are normally directly calculated with the overburden pressure and geological materials as the parameters. This generally results in too great a jacking force. Theoretical formulas do not usually consider the impact of the ream overbreak around the pipe or the lubricant material. For this reason, few pipejacking assessments for normal projects use theoretical formulas; usually empirical formulas are applied instead.

Most empirical formulas directly ignore the impact of the overburden depth. In theory, if the parameters of the overbreak around the pipe can be completely preserved, the overburden pressure will not directly transfer to the tube body and therefore can be ignored. The calculated values for the jacking force of construction projects are nearer to the real jacking force data. This paper adopted the empirical formulas previously used (JMTA 2000, Osumi 2000) to calculate the jacking force for each numerical simulation.

Empirical formulas often gather on-site case studies to assist in the statistical processing of relevant on-site conditions. Chapman and Ichioka (1999) collected parameter values for various soil types and different pipejacking equipment established in numerous cases to estimate jacking force. Barla *et al.* (2006) investigated the impact of geological material factors on the accuracy of pipejacking force assessments by analyzing field data

---

Manuscript received November 15, 2010; revised December 6, 2010; accepted December 13, 2010.

[1] Professor (corresponding author), Department of Civil Engineering, National Chung-Hsing University, Taichung 402, Taiwan, R.O.C.

[2] Ph.D. student, Department of Civil Engineering, National Chung-Hsing University, Taiwan, R.O.C.

and numerical simulations for pipejacking cases which encountered difficulties. Using numerical analysis software to investigate the cause of difficulties, the results showed that the increase in jacking force was caused by volatility of rock mass. Shimada (2004) and Khazaei *et al*. (2006) believed that slurry balanced pipejacking machines could effectively stabilize and isolate the overburden pressure exerted directly by the soil outside the pipe barriers by taking advantage of the permeability of slurry and lubrication materials, and effectively reduce friction resistance and pipejacking force. The numerical analysis showed the characteristics among these elements. In a laboratory experiment, Zhou *et al*. (2009) proposed that using a dense slurry as lubricant during the pipejacking process was effective in reducing the COF between soil and pipe and in reducing surface subsidence. Each of these studies revealed that, to ensure an effective decrease in pipejacking force, we must reduce the impact of the friction resistance by fully taking advantage of lubricant properties and by maintaining the space in the ream overbreak. However, it is exceedingly difficult to completely maintain an ideal state in actual cases, so it is necessary to fully understand the impact of an increase in local friction resistance.

2.2 Background of the Cases

The two cases of curved pipejacking were collected from the cities of Chiayi and Kaohsiung in Taiwan. Details of each case are provided in Table 1. The geological drilling data for the Chiayi case showed that the soil at the entry shaft site between ground level and 7.9 meters below ground was silty sand with an SPT-N value between 5 and 16; from the depth of 7.9 meters to 15.8 meters the soil was silty medium sand with an SPT-N value between 23 and 38; from 15.8 meters to 20 meters the soil was silty sand with an SPT-N value between 42 and 48. The water table was located approximately 6.4 meters below ground. The soil at the arrival shaft down to 1.8 meters below ground was backfill layer; from 1.8 meters to 8.3 meters was silty medium sand with an SPT-N value between 13 and 21; from 8.3 meters to 14.8 meters was the gravel layer with an SPT-N value greater than 100; from 14.8 meters to 20.0 meters was silty sand with an SPT-N value between 38 and 52. The water table was located approximately 3.7 meters below ground (see Fig. 1 for the pipejacking route). The empirical formula used before construction estimated that the jacking force would be approximately 400 T, but the actual greatest jacking force measured after construction surpassed 800 T. Figure 2 below shows the distribution of jacking force.

Table 1 Comparison of the two curved pipejacking cases

Location	Method	RC Pipe internal diameter (m)	Jacking length (m)	Length of curve CL (m)	Radius of curve (m)	Depth (m)
Chiayi	Slurry type	1.8	276	61.5	41	9
Kaohsiung	Slurry type	2.0	232	21.5; 29.8; 32.6	120; 250; 250	7

Fig. 1 The alignment of curved pipejacking case in Chiayi

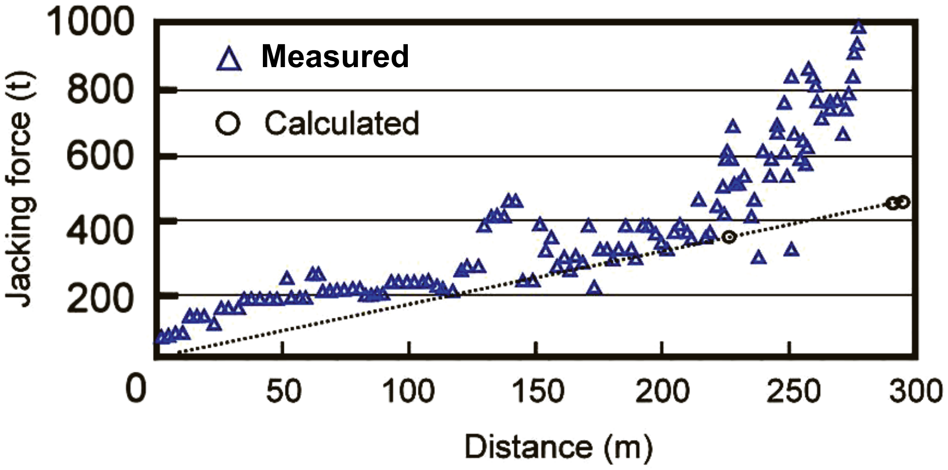


Fig. 2 The history of jacking force of the curved pipejacking case in Chiayi (Sun *et al*. 2007)

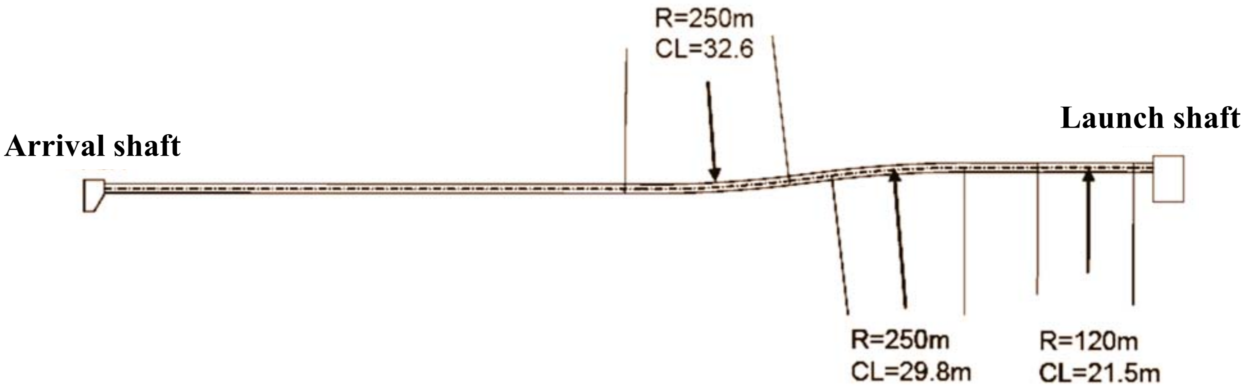


Fig. 3 **The alignment of curved pipejacking case in Kaohsiung**

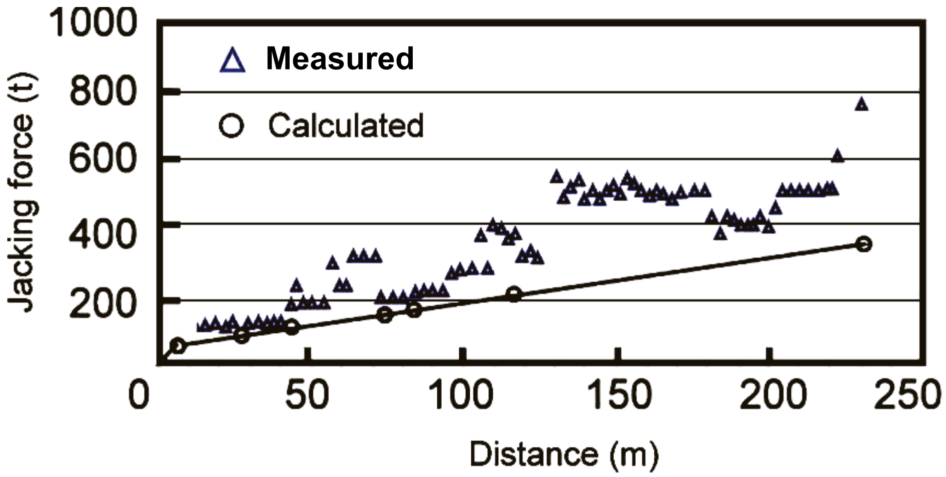


Fig. 4 **The history of jacking force of the curved pipejacking case in Kaohsiung (Sun *et al.* 2007)**

In the Kaohsiung case, the area primarily had an alluvial stratigraphy: Within 1 meter below ground was the backfill layer; from 1 meter to 6.1 meters of depth the soil was silty fine sand with a SPT-N value approximately between 9 and 16; from 6.1 meters to 7 meters the soil was silty clay with an SPT-N value approximately between 10 and 12; from 7 meters to 15 meters the soil was silty fine sand with a thin layer of clay in the middle with an SPT-N value between approximately 11and 15; and the water table was located approximately 4.0 meters below ground (see Fig. 3 for the pipejacking route). The pre-construction empirical formula estimated that the jacking force would be approximately 376 T, but the actual greatest jacking force measured after construction reached 545 T. Figure 4 below shows the distribution of jacking force.

In the case of long-distance straight pipejacking from Taichung, a sudden increase in resistance in the final stage of the project caused a stuck pipe (Chu 2008, Lan *et al.* 2009). In investigating the reasons for the increase in resistance, objects other than lubricant were discovered flowing out of the pipe lubricant hole, specifically gravel layer fill. It was determined that groundwater may have seeped toward the outside of the pipe in this section of pipejacking and brought the gravel layer fill into the ream overbreak space around the original pipe, resulting in fine material pressing against the pipe and halting further jacking. Fortunately, the workers were able to overcome this sudden increase in jacking force by using the security jack mounted during the original installation.

The empirical formula used to calculate the jacking force considers the initial geological and site conditions. However it usually fails to accurately estimate jacking force even during the construction process. This is because the ground layer conditions continually change with the construction process and the location of pipejacking, causing the jacking force for many projects to exceed original expectations. When the COF and resistance differ, the empirical formula cannot assess the needs of pipejacking. More cases need to be examined to understand the causes and results. Through numerical simulations, this study discussed the contact properties between the pipe and the solum both under normal circumstances and under a stuck pipe circumstance. We hoped to better understand the scope of increase in pipejacking force and the impact of stress strain in the solum when there is a stuck pipe during the process of pipejacking (Shou and Liu 2004; Wei *et al.* 2005; Broere 2007).

3. THE NUMERICAL MODEL

3.1 Material Parameters

In addition to horizontal curved pipejacking, this study also established a numerical model analysis for vertical curved pipejacking to explore its various effects. We also added new building elements to the vertical pipejacking model. Through various simulations, we hoped to understand the effect of surface structure. To discuss the impact of stuck pipes, different COF around the pipe were set to simulate a partial-collapsed stuck pipe. When the lubricant functions normally under normal conditions, the COF was set at 0.13 (Shou *et al*. 2010), while the COF within the area of the stuck pipe were set at 0.6, the value of COF without lubricant.

The simulation considered two cases of pipejacking: Horizontal curved pipejacking and vertical curved pipejacking. Each of the material parameters are described in Table 2. The elastic parameters were converted to plastic parameters by the Drucker-Prager Harding failure criterion (Abaqus, Inc., 2005). σ_c^0 was calculated as follows:

$$\sigma_c^0 = \frac{1}{1-\frac{1}{3}\tan\beta}\, d \tag{1}$$

$$d = \frac{3\sqrt{3}c}{\sqrt{9+12\tan^2\phi}} \tag{2}$$

$$\tan\beta = \frac{3\sqrt{3}\tan\phi}{\sqrt{9+12\tan^2\phi}} \tag{3}$$

where σ_c^0 is compressive yield strength; β is dilation angle; d is y-intercept in Drucker-Prager Harding failure criterion.

The linear Drucker-Prager parameters obtained after being converted by the formula were: The dilation angle of β was 46.94° and the σ_c^0 compressive yield strength was 55,462 kPa.

3.2 Numerical Analysis Model Grid

In the horizontal curved pipejacking model, the radius of the curvature was 20 m; the outer pipe diameter was 2.85 m; the inner pipe diameter was 2.4 m; the overburden depth for sharp curved pipejacking was 9.4 m; the number of nodes totaled 24,218 and the number of elements totaled 21,871, of which 906 were pipe elements and 20,965 were soil elements. For the established vertical curved pipejacking, the radius of curvature was 200 m; the outer pipe diameter was 2.85 m; the inner pipe diameter was 2.4 m; the overburden depth for vertical curved pipejacking was 8 m; and the model also added a 20 × 10 × 5 m building element to the surface. The number of nodes totaled 61,108 and the number of elements totaled 55,222, of which 850 were pipe elements, 36 were structure elements, and 54,336 were soil elements. The meshes for the two models are shown in Fig. 5.

In the simulation of the horizontal curved pipejacking cases, the stuck pipe was located in the upper left side of the boring cross-section, shown by the red position in Fig. 6. The area of the stuck pipe was 5.25 m long and 2.2 m wide. In the simulation of the vertical curved pipejacking, the stuck pipe was also located in the upper left side of the boring cross-section. The locations of the two different cases of stuck pipe are shown by the red positions in Figs. 7 and 8. The stuck pipes for both cases were 5.5 m long, and 1.1 m and 2.2 m wide, respectively. The COF in between the soil and the tube at the stuck pipe was defined as 0.6, and the contact position was set at 0.13.

Table 2 Parameters for the analysis

Soil (gravel)	
Internal friction angle ϕ (°)	41.41
Cohesion c (kPa)	29.40
Elastic modulus E (kPa)	382,200
Density (kg/m^3)	2,100
Poisson's ratio (ν)	0.3
Dilation angle β (°)	46.94
Yielding strength σ_c^0 (kPa)	55,462
Concrete pipe and building	
Density (kg/m^3)	2400
Elastic modulus (kPa)	47,000,000
Poisson's ratio (ν)	0.3

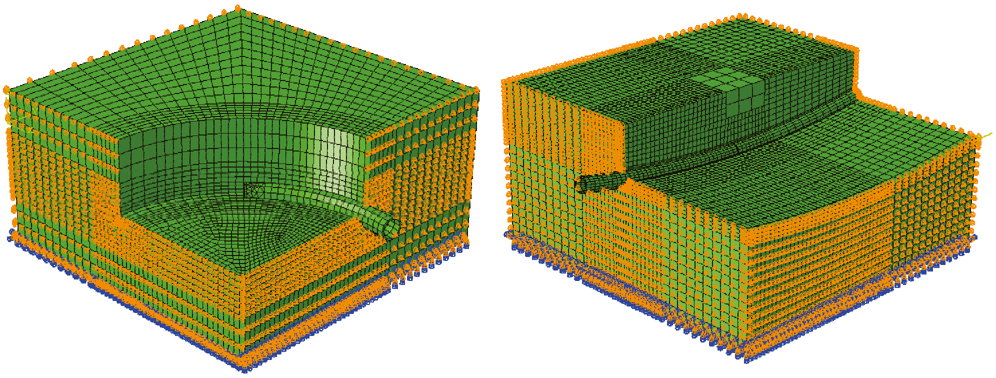
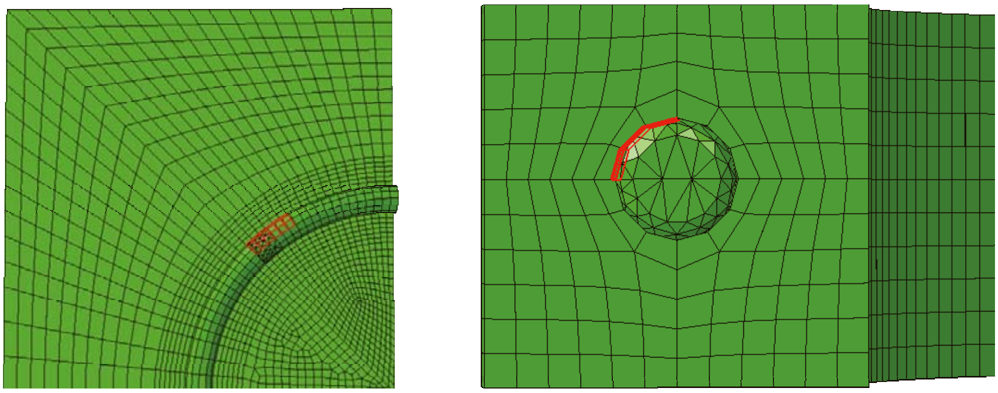
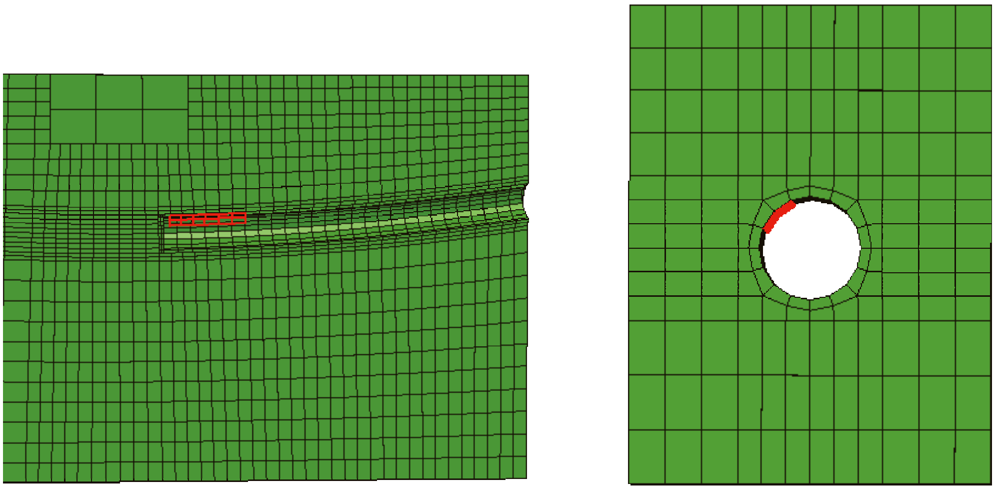

(a) Horizontal case (b) Vertical case

Fig. 5 Meshes for curved pipejacking



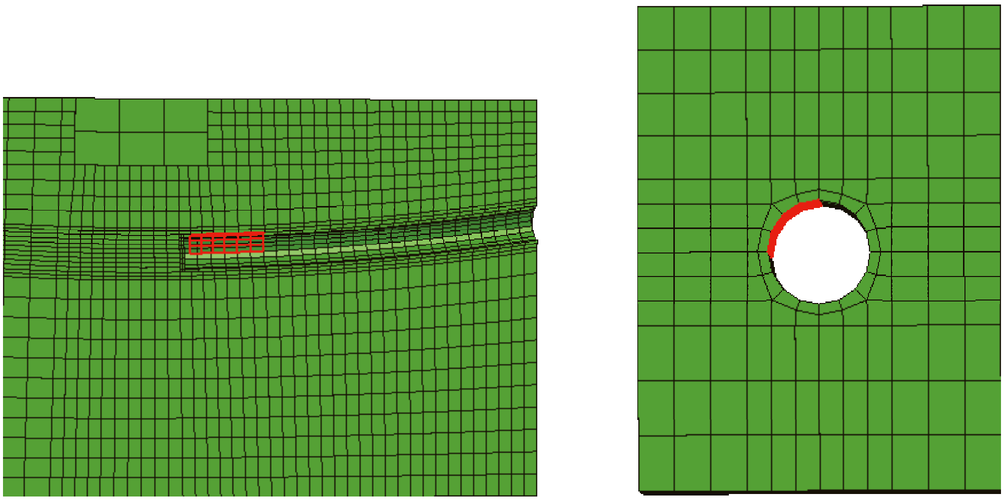
(a) Top view (b) Cross section

Fig. 6 Simulation of stuck horizontal curved pipejacking



(a) Front view (b) Cross section

Fig. 7 Simulation of stuck vertical curved pipejacking – case 1



(a) Front view (b) Cross section

Fig. 8 Simulation of stuck vertical curved pipejacking – case 2

4. NUMERICAL ANALYSIS RESULTS

4.1 Horizontal Curved Pipejacking

In the simulation of the horizontal curved pipejacking, each excavation path was 2.6 m long and the jacking force, calculated by the empirical formula, was approximately 6.5 × 106 Pa. However, the jacking force could not successfully pipejack the entire pipe string. After multiple attempts, the jacking force ultimately had to be slightly strengthened to around 1.15 times the original, approximately 7.5 × 106 Pa to 8.0 × 106 Pa, before it moved smoothly. The pipejacking forces differed in the two different simulations. The simulation without a stuck pipe required 7.5 × 106 Pa to push 2.6 m. The simulation with a stuck pipe 2.2 m wide, 5.26 m long, and a total area of 11.57 m^2 required a jacking force of 8 × 106 Pa to push 2.6 m. The total area of the pipe string was approximately 140 m^2. Thus, the total area of the stuck pipe constituted 8%, and it increased jacking force by a total of 6.67%.

The stuck pipe also created different distributions of solum stress in the two simulations. The paths of soil stress distribution for both models are shown by the dotted line in Fig. 9(a), and the stress values are shown in Fig. 9(b). These figures show that in the cases with a stuck pipe, both the pipejacking force and the soil stress increased.

4.2 Vertical Curved Pipejacking

In the simulation of the vertical curved pipejacking, each excavation path was 2.88 m long, and the jacking force, calculated by the empirical formula, was 1.56 × 106 Pa. However, this jacking force was unable to successfully push the pipe string. After an attempt, the jacking force had to be slightly strengthened to 2.53 times the original before it moved smoothly. The pipejacking forces differed in the different simulations. The simulation without a stuck pipe required 3.95 × 106 Pa to push 2.85 m. In the simulation for the first case of stuck pipe, the stuck pipe parameters were 1.1 m wide, 5.58 m long, and 6.138 m^2 in area, requiring a jacking force of 4.0 × 106 Pa to push 2.85 m. The total area of the pipe string was approximately 268 m^2. Thus, the total area of the stuck pipe constituted 2.3%, and it increased jacking force by a total of 1.26%. In the simulation of the second case of stuck pipe, the parameters of the stuck pipe were 2.2 m wide, 5.58 m long, and 12.276 m^2 in area, requiring a jacking force of 4.05 × 106 Pa to push 2.85 m. The total area of the pipe string was approximately 268 m^2. Thus, the total area of the stuck pipe constituted 4.6%, and it increased jacking force by a total of 2.53%.

Using the same 3.95 × 106 Pa of jacking force, the case without a stuck pipe could push forward 2.88 m, while the first and second cases of stuck pipe could only reach 2.857 m and 2.814 m, respectively. Under 4.0 × 106 Pa of jacking force, the first case could pipejack 2.88 m, but the second case could only pipejack 2.85 m, an approximate 1% decrease in pipejacking distance. A jacking force of 4.05 × 106 Pa was required in the second case to pipejack 2.88 m. Looking at the relationship between the jacking force and the pipejacking distance, for the model without a stuck pipe, 3.95 × 106 Pa of jacking force was sufficient to complete one path, while it reduced the pipejacking distance by 0.8% in the first and and 2.3% in the second case of stuck pipe.

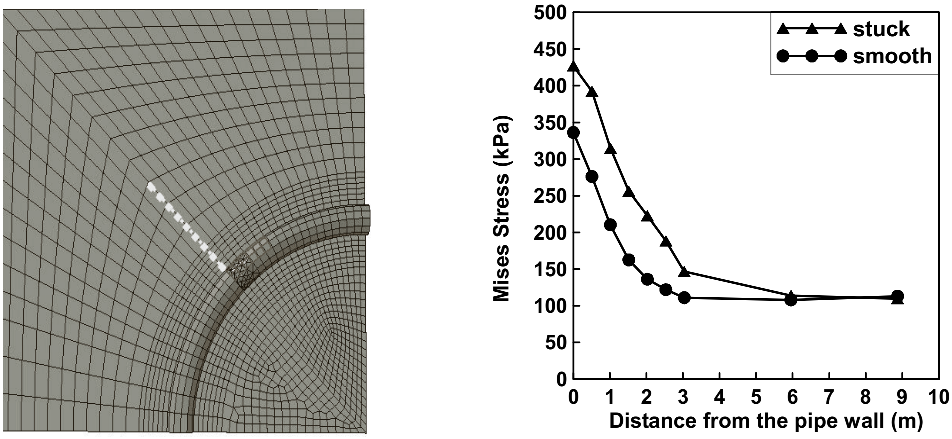
Combining the above three cases of vertical curved pipejacking, we can estimate that each additional 6 m^2 (0 to 6 to 12 m^2) of stuck pipe will increase the jacking force by 1.26% and reduce the pipejacking distance by approximately 0.8 to 1.0%. In the second case of stuck pipe, each increase of approximately 1.25% to 1.26% (3.95 to 4.00 to 4.05) of jacking force can increase the pipejacking distance by 1.27 to 1.05%. The jacking force value and pipejacking distance reduction rate are shown in Table 3.

Table 3 Jacking force reduction for vertical curved pipejacking with different stuck conditions

Jacking force	Smooth (stuck area 0 m^2)		Stuck - case I (stuck area 6.138 m^2)		Stuck - case II (stuck area 12.276 m^2)	
	distance (m)	reduction (%)	distance (m)	reduction (%)	distance (m)	reduction (%)
748 ton	2.88	0.0	2.86	0.8	2.81	2.3
758 ton			2.88	0.0	2.85	1.0
767 ton					2.88	0.0

Due to the symmetrical geometric conditions of vertical curved pipejacking, only the vertical sides of the pipejacking pipe were considered in investigating the distribution of soil stress. The selected location is shown by the dotted line in Fig. 10(a), and the distributions of stress in the soil above and below the pipe are shown in Figs. 10(b) and (c). This shows that for the vertical curved pipejacking case, the upper part of the pipeline is the pressure releasing side, similar to the inner pipe for horizontal curved pipejacking, then the scope of the stuck pipe will influence the stress distribution: The greater the scope, the greater the influence on the stress in the soil. The lower part of the pipeline is the pressure side, similar to the outer pipe for horizontal curved pipejacking, the value of the stress in the lower soil will be greater than in the upper soil. However, since it is further from the location of the stuck pipe, the scope of the stuck pipe will have relatively no influence on the value, meaning the values of the three cases will only differ negligibly.

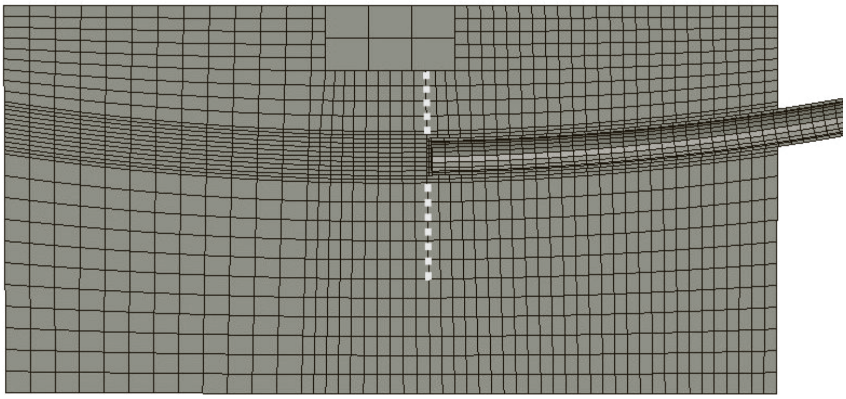
In the cases of vertical change curves, the pipejacking all arrived at the next excavation face intact. Also, for the slight pressure behavior on the excavation face, the cross-section node of the bottom structure was selected to investigate vertical displacement. The selected location is shown by the dotted line in Figs. 11(a) and 11(b). The U_3 displacement is shown in Fig. 11(c).



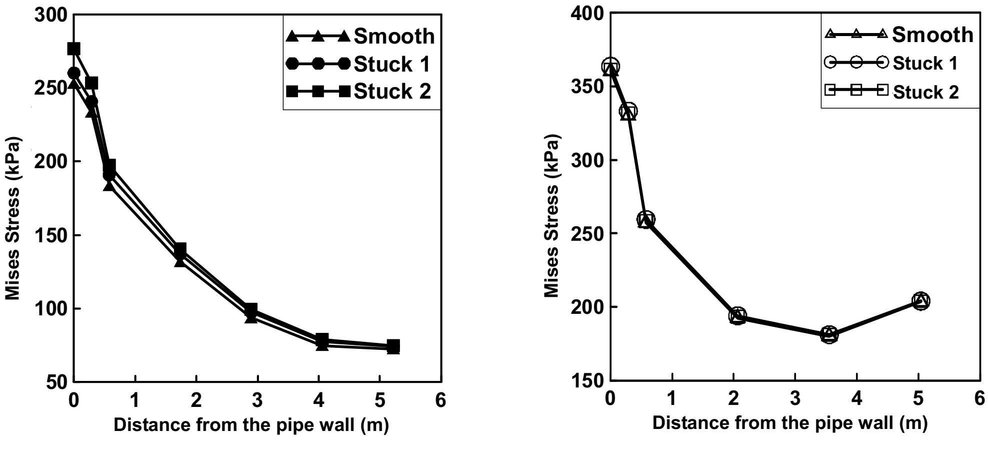
(a) Cross section for comparison

(b) Stress distribution

Fig. 9 Comparison of stress distributions for horizontal curved pipejacking with and without stuck condition



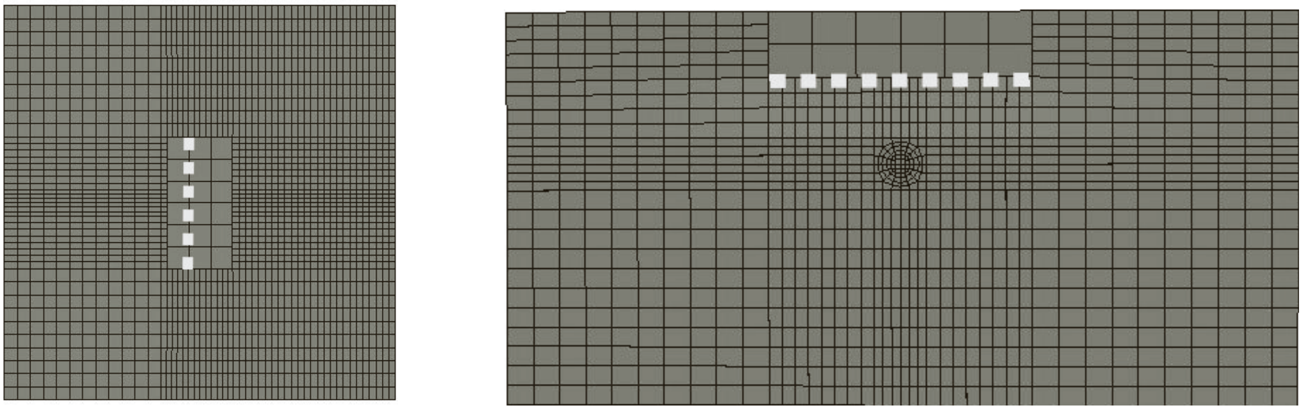
(a) Cross section for comparison



(b) Stress above pipe

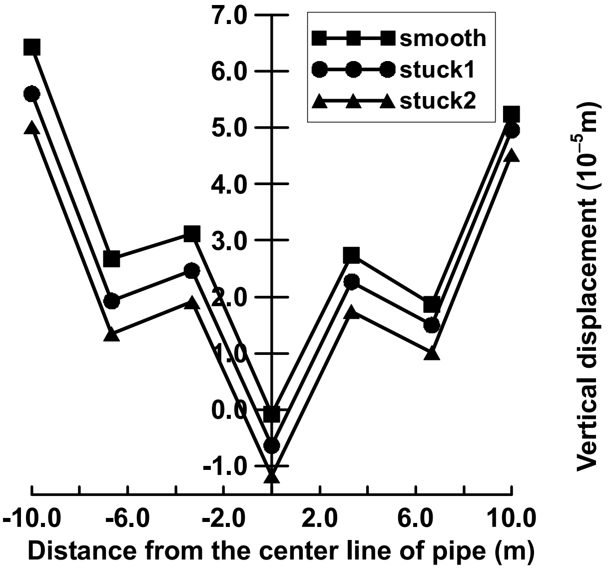
(c) Stress below pipe

Fig. 10 Comparison of stress distributions for vertical curved pipejacking with and without stuck condition



(a) Top view

(b) Cross section



(c) Deformation below building

Fig. 11 Comparison of deformation distributions below building for vertical curved pipejacking with and without sticking condition

The U_3 displacement figure shows that the bottom of the structure had a tendency to raise slightly. After the pipejacking was complete, the nose on the pipejacking machines pressured the excavation face slightly, causing bulging above. As the scope of the stuck pipe expanded, the bulging became more obvious. In addition, it is also clear that this figure is not completely symmetrical. One of the differences is that the negative side of the position is the stuck pipe. Also, because a larger scope of the stuck pipe corresponds to a more obvious interaction between the pipe and the solum, the impact on the bulging at the ground level structure during the process of pressuring the excavation face is more apparent.

5. CONCLUSIONS AND SUGGESTIONS

Due to the sharp curves (R = 20 m) of horizontal curved pipejacking, the corresponding impact of a stuck pipe on jacking force was relatively high: An 8% increase in the area of the stuck pipe increased jacking force by 6.67%, making the percentage increase of jacking force approximately 83% of the percentage increase of the stuck pipe area. Due to the moderate curvature (R = 200 m) of vertical curved pipejacking, a 2.3% increase in the area of the stuck pipe increased the jacking force by 1.26%, and a 4.6% increase in area increased jacking force by 2.53%, making the percentage increase of jacking force approximately 50% of the percentage increase of area of the stuck pipe. The cases of R = 20 m and R = 200 m show that the sharper the pipejacking curvature, the more obvious the impact of a stuck pipe on jacking force will be.

Horizontal curved and vertical curved pipejackings are identical in that the inner and outer pipes (or the upper and lower sides for the vertical case) differ in relation to their geometric shapes. The distribution of soil pressure for the simulations of the horizontal curved pipejacking with a stuck pipe was larger than the case without a stuck pipe. For the vertical curved pipejacking, the upper part of the pipejacking pipe was impacted by the stuck pipe, but because it released pressure, there was less soil stress. The lower part of the pipejacking pipe, though, had greater soil stress due to its pressure.

In the case of vertical curved pipejacking, when the scope of the stuck pipe was greater, the interaction between the pipe and the solum was more obvious, and when the nose of the pipejacking machine pressured the excavation face, the ground surface bulged even more. For the simulation of geometric symmetry, the U_3 displacement figure was not symmetrical primarily because the scope of the stuck pipe was only set on the negative side. Also, the impact of the side with a stuck pipe was only slightly larger than the side without a stuck pipe.

Various cases in both the literature review and this study have found that using lubricant can reduce jacking force and decrease interaction between the solum and the pipe (Pellet and Kastner 2002; Sofianos 2004; Staheli 2006). To avoid sharp increases in jacking force and to avert stuck pipe cases similar to the long-distance pipejacking in Taichung where overburden pressure applied to the pipe directly, lubricant filler must be used to maintain the overbreak space around the pipe.

Simulations for both horizontal and vertical curved pipejacking show a significant impact of a stuck pipe on pipejacking. It not only increased jacking force; but also increased the interaction between the pipe and the soil, including the stress increase on both. For this reason, for a stuck pipe, special attention needs to be paid to whether the pipe is damaged, especially in the case of sharp curved pipejacking.

REFERENCES

Abaqus, Inc. (2005). *ABAQUS Version 5.8 User's Manual*, Pawtucket, U.S.A.

Broere, W. (2007). "Modelling the boring of curves in (very) soft soils during microtunnelling." *Tunnelling and Underground Space Technology,* **22**(5-6), 600-609.

Chapman, D. N. and Ichioka, Y. (1999). "Prediction of jacking forces for microtunnelling operations." *Trenchless Technology Research*, ISTT, **14**(1), 31-41.

Shimada, H., Khazaei, S., and Matsui, K. (2004). "Small diameter tunnel excavation method using slurry pipe-jacking." *Geotechnical and Geological Engineering*, **22**(2), 161-186.

Japan Micro Tunnelling Association (2000). *Pipe-jacking Application*. JMTA, Tokyo.

Shou, K., Yen, J., and Liu, M. (2010). "On the frictional property of lubricants and its impact on jacking force and soil-pipe interaction of pipe-jacking." *Tunnelling and Underground Space Technology*, **25**(4), 469-477.

Liu, M. (2010). "Numerical analysis on the influence of vertically curved pipe-jacking to soil and neighboring building." Master thesis, National Chung Hsing University.

Lan, C., Yen, C., Li, Y., and Tang, C. (2009). "A case study of long span pipe jacking technique in Taichung gravel formation." *Sino-Geotechnics*, **115**, 71-80

Barla, M., Camusso, M., and Aiassa, S. (2006). "Analysis of jacking forces during microtunnelling in limestone." *Tunnelling and Underground Space Technology*, **21**(4), 668-683.

Chu, W. Y. (2008). *A Study on Design and Construction of Curved Pipe Jacking Method*, Master thesis, National Kaohsiung First University of Science and Technology.

Osumi, T. (2000). *Calculating Jacking Forces for Pipe Jacking Methods*, No-Dig International Research, 40-42.

Pellet, A. L. and Kastner, R. (2002). "Experimental and analytical study of friction forces during microtunnelling operations." *Tunnelling and Underground Space Technology*, **17**(1), 83-97.

Staheli, K. (2006). *Jacking Force Prediction: An Interface Friction Approach Based on Pipe Surface Roughness*, Ph.D. Dissertation, Georgia Institute of Technology.

Sun, H., Chung, R., Chen, W., Lee, T., and Chu, W. (2007). "Case studies of curved pipe jacking method in Taiwan area." *Cross Strait Seminar on Geotechnical Engineering*, 401-408.

Shou, K. J. and Liu, Y. C. (2004). "Modeling of soft rock tunnelling in Western Taiwan." *Tunnelling and Underground Space Technology*, **19**(4-5), 419.

Sofianos, A. I., Loukas, P., Chantzakos, Ch. (2004). "Pipe jacking a sewer under Athens." *Tunnelling and Underground Space Technology*, **19**(2), 83-97.

Khazaei, S., Shimada, H., Kawai, T., Yotsumoto, J., and Matsui, K. (2006). "Monitoring of over cutting area and lubrication distribution in a large slurry pipe jacking operation." *Geotechnical and Geological Engineering*, **24**(3), 735-755.

Khazaei, S., Shimada, H., Kawai, T., Yotsumoto, J., and Matsui, K. (2006). "Performance of mortar and chemical grout injection into surrounding soil when slurry pipe-jacking method is used." *Geotechnical and Geological Engineering*, **24**(1), 57-77.

Wei, G., Xu, R., and Huang, B. (2005). "Analysis of stability failure for pipeline during long distance pipe jacking." *Chinese Journal of Rock Mechanics and Engineering*, **24**(8), 1427-1432.

Zhou, S., Wang, Y., and Huang, X. (2009). "Experimental study on the effect of injecting slurry inside a jacking pipe tunnel in silt