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NUMERICAL ANALYSIS OF THE IMPACT OF OVERCUT ON THE SOIL-PIPE INTERACTION IN PIPEJACKING

Keh-Jian Shou [1*] and Chi-Yuan Su [2]

ABSTRACT

Overcut is a critical issue in pipejacking, especially for the cases with difficult geology conditions or with a curved alignment. For those cases, lubricants are frequently applied to fill the gap or to reduce the friction between soil and pipes. However, it is very difficult to quantitatively determine the real contact condition between the soil and pipe. New technology for soil-pipe interaction measurement is still scarce and requires further development. There are only indirect methods practically available for soil-pipe interaction, and engineering judgment is required for those measurements. In this study, the finite element software ABAQUS is used for the numerical analysis of the pipejacking, including the influence of lubricant property and the overcut on the soil-pipe interaction. The results show that lubrication can significantly reduce the stress concentration surrounding the pipe, the disturbing of the pipejacking on the surrounding soil was increased as the overcut increasing, the soil stress was decreased but the disturbance on the excavation face will be increased.

Key words: Overcut, pipe-jacking, numerical analysis, lubricantion, backfill.

1. INTRODUCTION

For a pipejacking process, the jacking force is one of the critical factors which determines the location of intermediate jacking station and the requirement of lubricantion (Khazaei *et al.* 2004; Staheli 2006; Shou and Jiang 2010; Yen and Shou 2015). By the reduction of jacking force, the risk of pipe damage can be minimized which in turn contributes to the reduction of construction cost. Especially for pipejacking with a comparatively long alignment or in difficult geologic conditions, application of lubricant is essential to reduce the requirement of jacking force (Staheli 2006; Sterling 2010; Shou and Yen 2010). Lubrication reduces the jacking force by reducing the frictional stress around the pipe. The lubricants are generally designed to form a layer surrounding the pipe string, be pressurized to overcome groundwater pressure and stabilize the over-cutting area.

Although over-cutting is a common phenomenon in shield excavation, comparisons of the over-cutting and the performance of lubricants are not feasible because the conditions and specifications of cases are rarely exactly the same. Beside the difference in geomaterial and groundwater conditions, the pipe diameter, depth, penetration rate, over-cutting ratio, *etc*. are hardly all the same for two pipejacking cases. Although overcutting obviously affects the soil-pipe interaction and the requirement of jacking force, there is no technology available to quantify the amount of overcutting and its influence. Therefore, the estimation of jacking force and the application of lubricants are still based on empirical rules (Staheli 2006; Yen and Shou 2015).

About the behavior of overcut, Asanprakit *et al*. (2011) applied numerical analysis to study on the influence of overcut length on jacking force. Hasanpour *et al*. (2015) studied the impact of overcut on interaction between shield and ground in the tunneling, however, it is a tunneling case by a double-shield TBM. In this study, a numerical method was applied to analyze the impact of overcutting on the soil-pipe interaction, with different overcutting considerations in straight line pipejacking and curved pipejacking. In this study, the pipejacking cases in Taichung area of Taiwan are adopted as examples, and suggestions are given based on the analysis results.

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[1] Professor (corresponding author), National Chung Hsing University, 250 Kuo-Kuang Road, Taichung, Taiwan (e-mail: kjshou@dragon.nchu.edu.tw).
[2] Graduate Student, National Chung Hsing University, 250 Kuo-Kuang Road, Taichung, Taiwan.

2. GEOMATERIALS AND LUBRICANTS

Due to the adopted cases in Taichung Science Park, this study focuses on the gravel formations in the central area of Taiwan. The gravel formations are composite geomaterials, which consist mainly of gravels and soils. As the diameters of the gravels, with a large volumetric percentage, are 5 ~ 20 cm in diameter, it is difficult to obtain the mechanical properties accurately due to the size effect. The gravels in this area are originally from quarzite with hardness more than 6.0 in the Mohr's scale and the uniaxial compressive strength of more than 1000 ~ 2000 kg/cm^2, which causes the difficulties in the excavation work. In general, the gravel formations in Taichung area possess high (see Fig. 1) internal friction angle (37 ~ 49°) and low cohesion (SINOTECH 1993; CECI 1994; Wu *el al*. 1995; Chen *et al*. 1995; Ren *et al*. 1998).

As a drilling fluid, mud was commonly applied in oil exploration, in order to stabilize the boreholes and take out the cutting debris. For shield excavation and pipejacking, the function for mud can be different, since it is not necessary to transport cutting debris, lower field stress, *etc*. In general, beside water, a drilling fluid comprises three components bentonite, polymers, and soluble chemicals (ASME 2004; Darley & Gray 1988). Through the development of pipejacking technology, new chemical additives were developed and applied, their main purposes include creating a protecting layer and repelling surrounding water (Darley & Gray 1988; Baumert *et al*. 2005).

3. NUMERICAL SIMULATION OF SOIL-PIPE BEHAVIOR

3.1 Meshes and Boundary Conditions

The boundary conditions and element type are considered as described below: (A) the bottom face is confined by hinges and the surrounding vertical faces are framed by rollers, (B) three-dimensional solid elements (C3D8R) are used to simulate the soil and the pipe, and (C) interface elements are applied to simulate the soil-pipe frictional behavior. Numerically, we simulate the pipe jacking process by repeating three numerical steps: Remove the soil element in the pipe and at the pipe location, equilibrate the domain to obtain and accumulate the influences, and drive the pipe elements forward. The three-dimensional functions of the finite element software ABAQUS (Abaqus Inc., 2005) were applied in this study.

To simulate the pipejacking cases, the pipe is assumed 10 m below surface, and a 40 m × 40 m × 25 m block of soil was considered. The jacking pipes are 2 m long, 2 m in diameter and 0.2 m in thickness. The pipejacking machine is also considered as 2 m long and 2 m in diameter. However, for the case of the curved pipejacking, 20 m in the radius of curvature was considered. In total, 25464 elements were used for the straight line pipejacking case (see Fig. 2(a)) and 29130 elements were used for the curved pipejacking case (see Fig. 2(b)).

3.2 Material Properties

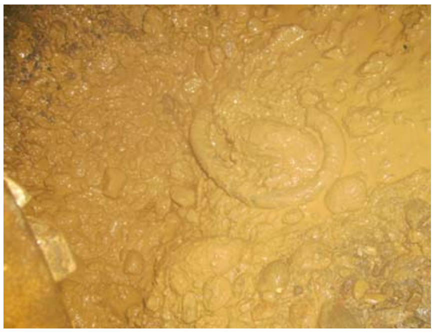
Based on the experimental results for the geomaterials in Taichung area, the extended Drucker-Prager model is adopted as the constitutive law. The failure criterion is deduced by in situ triaxial testing results, the Young's modulus is considered increasing with depth. The required parameters for the Drucker-Prager model were obtained by the least square fitting of the triaxial test results. However, for simplicity, the material properties of the pipes and shield machine were considered as linear elastic.

According to the related references mentioned in section 2, mechanical properties of the gravelly soil of Taichung were adopted as: Cohesion (c) equals 15 kPa, friction angle (φ) equals 37°, the Young's modulus (E) equals 300 MPa, the Poisson's ratio (ν) equals 0.3, and density (γ) equals 21 kN/m^3 as shown in Table 1. The additional parameters a, b, and β in Table 1 are the parameters of the Drucker-Prager model obtained by experiment. In addition, we considered the Young's modulus as 30 GPa, the Poisson's ratio as 0.3, the density as 24 kN/m^3 for the pipes, and the Young's modulus as 200 GPa, the Poisson's ratio as 0.3, the density as 78.5 kN/m^3 for the pipejacking machine.

For the properties of interface element, we applied the hard contact option in the normal direction and the penalty function option in the tangential direction, in which only the friction coefficient is required for the analysis (Abaqus Inc. 2005). The frictional coefficient 0.13, obtained from testing of the lubricated interface between concrete pipe and gravelly soil (Shou *et al.* 2010), was adopted in the analysis.

Table 1 Mechanical properties of the gravelly soil

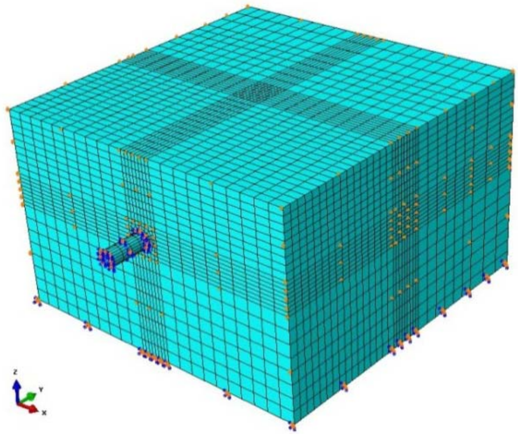
Cohesion	Friction angle	Young's modulus	Poission's ratio	Parameters of the Drucker-Prager model obtained by experiement			Density
c (kPa)	φ (°)	E (MPa)	ν	a	b	β (°)	γ (kN/m^3)
15	37	300	0.3	0.69309	1.0004	46.18	21



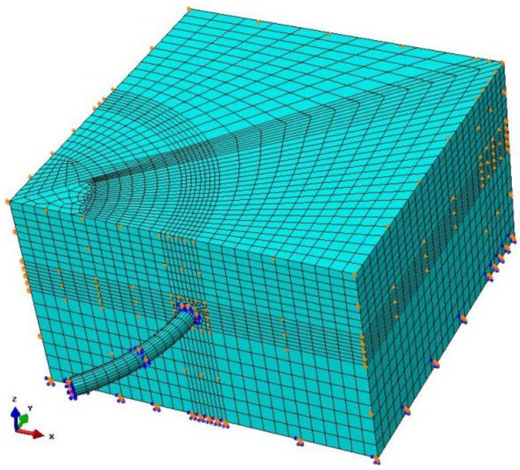
(a) Formation at the mining face

(b) ϕ 95 cm large cobble

Fig. 1 The gravel formation encountered in Taichung



(a) Straight line pipejacking



(b) Curved pipejacking

Fig. 2 The FE meshes for the pipejacking analyses

3.3 Consideration of Overcutting

Overcutting is a common phenomenon in pipejacking as the size of the cutter head is generally designed larger than the size of the shield and the pipes behind it. It is helpful for the advancing, only if the amount of overcutting is reasonable. Otherwise, a negative effect will be encountered which might cause the stoppage of advancing or the subsidence on the surface. To numerically analyze the effect of overcutting, we must consider to remove one more layer of soil outside of the shield machine. However, due to the gravity, the removal of an extra layer of soil should be restricted at the upper half of the periphery. In this study, the overcutting was considered by removing a layer of soil at the upper half of the periphery for the straight line pipejacking. However, due to the asymmetrical deformation in the inner side and outer side, two different overcutting conditions, *i.e.*, 144 degree case and 180 degree case, were considered as shown in Fig. 3.

4. RESULTS AND DISCUSSION

4.1 The Influence of Backfill Lubricant

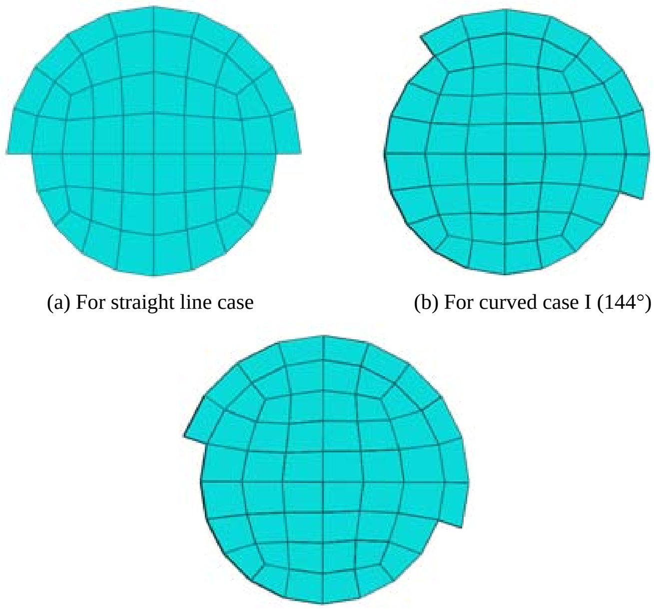
In the pipejacking practices, the overcutting is generally controlled by the application of backfill lubricant. The lubricant can reduce the friction between the soil and pipe, and reduce the deformation due to the overcutting. Therefore, the application of backfill lubricant is critical for both the overcutting control and the advancing rate. In this study, the soil elements simulating the overcut area were considered with different Young's modulus (E = 3, 30, and 300 MPa; E = 3 MPa is for the extreme case that almost no lubricant is present in the overcut area), to understand the influence lubricant of the overcutting.

1. Straight Line Pipejacking

For the straight line pipejacking, the cross sections near the cutter head were investigated (see Fig. 4). The results in Fig. 5 show that the stress in the backfill lubricant, *i.e.*, the layer outside of the shield, increases as the Young's modulus increases, especially at the top of the shield. It also reveals that the soil at the top of the periphery will be squeezed more during the pipejacking. Similarly, the stress distributions in the longitudinal cross section and the lateral cross section behind the cutter head also increase as the Young's modulus increases (see Figs. 6 and 7). The results suggest a softer backfill lubricant can help to reduce the stress concentration, and the differential deformation to better control the advancing alignment. In addition, the dragging effect diminishes above 3 m (1.5D) in the lateral direction, but slower in the longitudinal direction.

2. Curved Pipejacking

For the curved pipejacking, the cross sections near the cutter head were investigated (see Fig. 8). The results in Figs. 9 and 10 show that the displacement and stress at the inner side of the curved pipejacking significantly reduces as the Young's modulus increases. The differences in displacement and stress decrease and diminish at a distance above 3 m (1.5D). The comparison of the results at the inner side and outer side in Figs. 10 and 11 show that the influence of the Young's modulus of the backfill is similar, however, it is more significant in the inner side than that in the outer side. The results suggest a harder backfill lubricant can help to reduce the stress concentration and the differential deformation to better control the advancing alignment in curved pipejacking.



(a) For straight line case (b) For curved case I (144°)

(c) For curved case II (180°)

Fig. 3 The meshes for the simulations of overcut

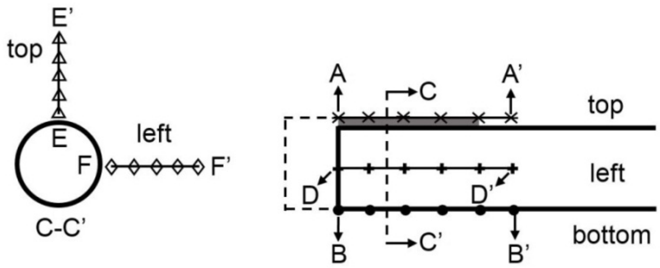


Fig. 4 The lateral and longitudinal cross sections for the straight line pipejacking

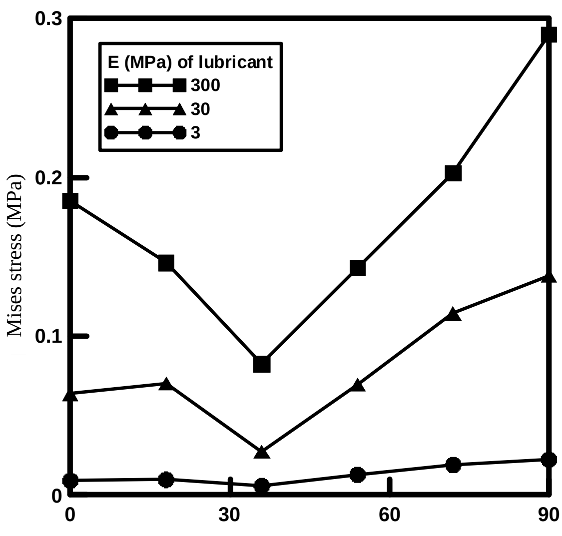


Fig. 5 The stress distribution along the periphery of lubricant, straight line case (The periphery is defined as 0° at the sidewall and 90° at the top of the shield).

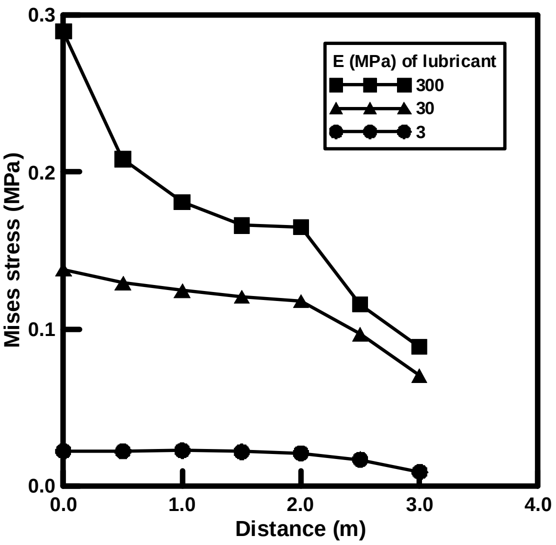


Fig. 6 The stress distribution along the longitudinal cross section of lubricant, straight line case

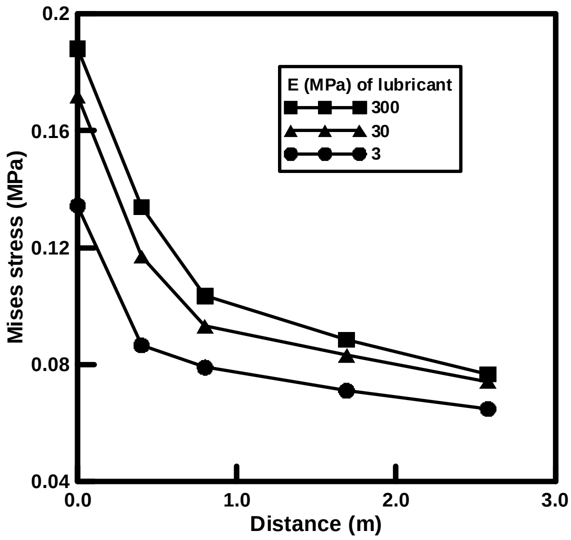


Fig. 7 The stress distribution at the lateral cross section C-C', straight line case

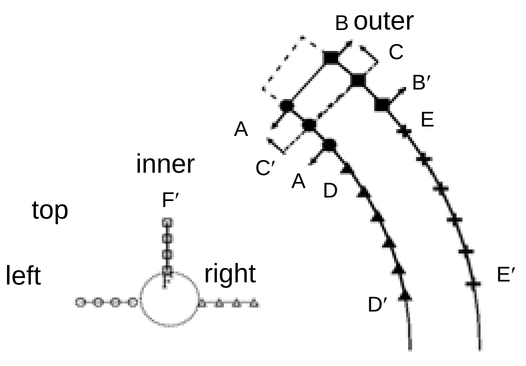


Fig. 8 The lateral and longitudinal cross sections for the curved pipejacking

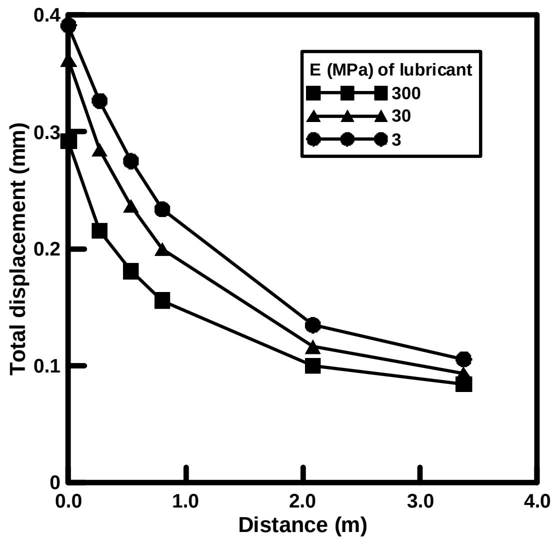


Fig. 9 The displacement distribution at the inner side of the curved pipejacking

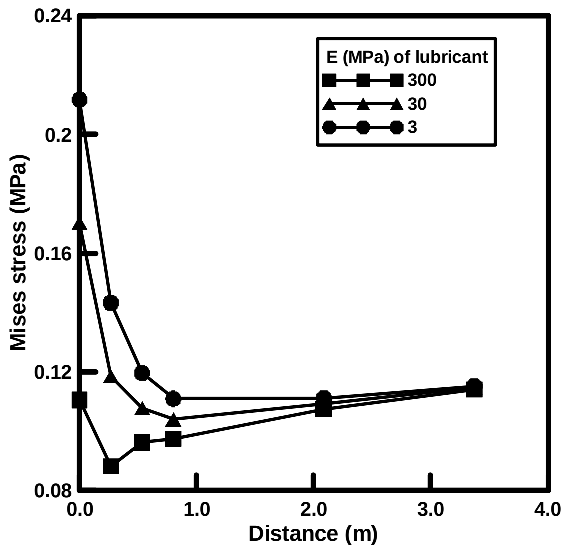


Fig. 10 The stress distribution at the inner side of the curved pipejacking

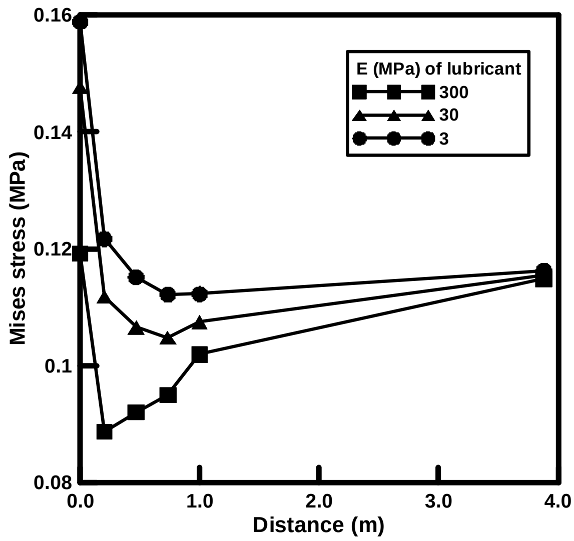


Fig. 11 The stress distribution at the outer side of the curved pipejacking

4.2 The Influence of Overcuting Condition on Curved Pipejacking

To investigate the influence of overcutting condition on the curved pipejacking, two different conditions, i.e., the cases of 144° and 180° as shown in Fig. 3, were considered and analyzed. The results in Figs. 12 and 13 show that the larger overcut results in a smaller displacement at the inner side, but conversely a larger displacement at the outer side. On the other hand, the results in the longitudinal direction reveal that the larger overcut results in a larger stress at the inner side but, more significantly the smaller stress at the outer side (see Figs. 14 and 15). And the differences gradually diminish at a distance above 3 m (1.5*D*). It is worth noting that the longitudinal displacement distribution at the inner side shows a transition of the influence of overcutting. The finding also suggests that the overcutting can affect the (see Fig. 16) deformation far behind and influence the advancing alignment more significantly than previously thought.

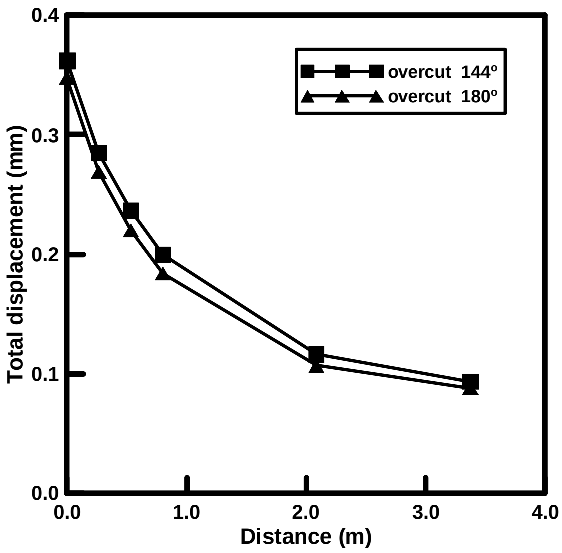


Fig. 12 The displacement distribution at the inner side of the curved pipejacking for different overcutting conditions

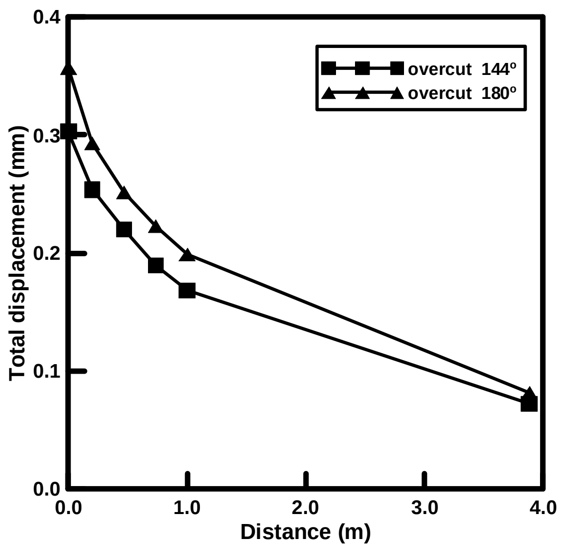


Fig. 13 The displacement distribution at the outer side of the curved pipejacking for different overcutting conditions

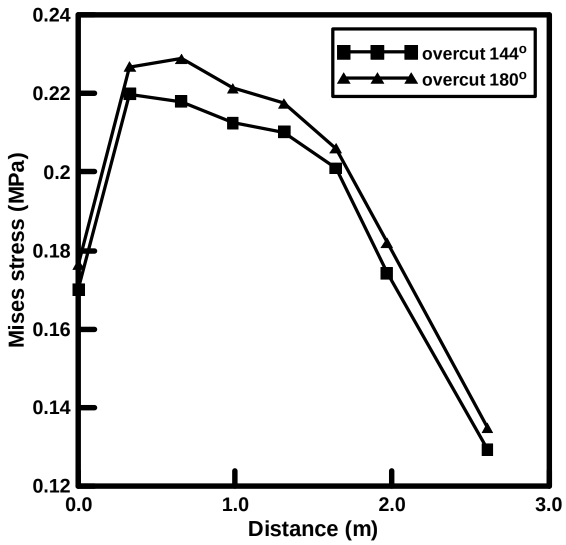


Fig. 14 The longitudinal distribution of stress at the inner side of the curved pipejacking

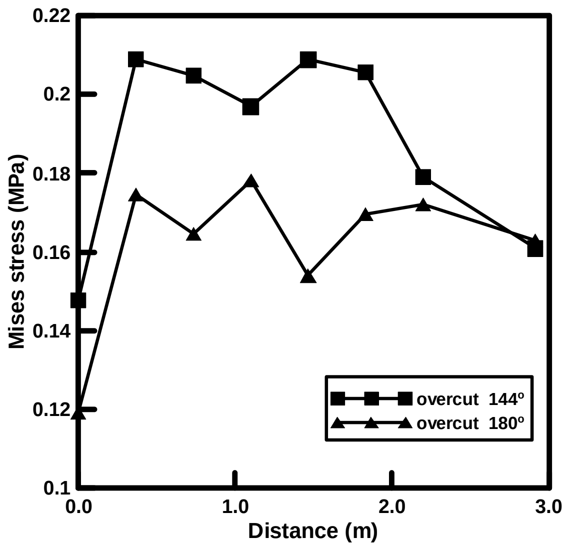


Fig. 15 The longitudinal distribution of stress at the outer side of the curved pipejacking

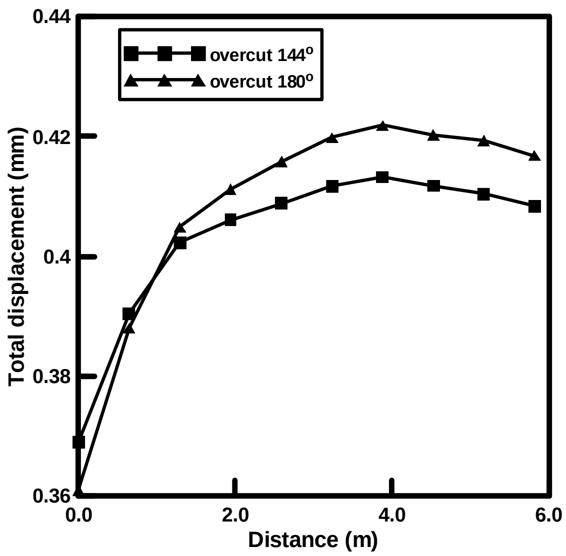


Fig. 16 The longitudinal distribution of displacement at the inner side of the curved pipejacking

5. CONCLUSIONS

In this study, the finite element software ABAQUS has been used for the numerical analysis of the effect of overcutting and the application of backfill lubricant. The influence of overcutting was investigated for both the straight line pipejacking and curved pipejacking. And different overcutting conditions were considered in the analyses.

The results of numerical simulation show that the backfill lubricant can effectively reduce the stress and strain of the soil surrounding the pipes. However, the influence of the deformability of the backfill lubricant might not be the same for different pipejacking cases and the lubricant material needs to be chosen carefully to have a better control on the advancing alignment. For the curved alignment case, the impact of overcutting might not be the same in the lateral direction and in the longitudinal direction. Also, the requirements of lubrication for the stability of soil and for the reduction of jacking force might not be the same. Therefore, the design of lubrication is still largely based on a case-by-case empirical practice. More soil-pipe interface simulations are suggested for the future research to gain additional insight into this issue.

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REFERENCES

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

Asanprakit, A., Sugimoto, M., and Chen, J. (2011). "Influence of overcut length on jack force and acting earth pressure during pipe jacking." *The Seventh International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground*, Rome, Italy, 16–18.

ASME Shale Shaker Committee (2004). *Drilling Fluids Processing Handbook*, New York.

Baumert, M.E., Allouche, E.N., and Moore, I. D. (2005). "Drilling fluid considerations in design of engineered horizontal directional drilling installations." *International Journal of Geomechanics*, **5**(4), 339–349.

CECI (1994). *The Geological Exploration of the Maoli-Taichung Sector—The Detailed Design of Taiwan High Speed Rail*, Report to Bureau of Taiwan High Speed Rail, Taiwan.

Chen, Y.C., Hsieh, Y.S., Lin, K.C., and Lu, W.D. (1995). "Numerical analysis of shallow tunnelling in gravel formations." *International Symposium of Underground Engineering in Gravel Formations*, 2-73–2-88.

Darley, H.C.H. and Gray, G. (1988). *Composition and Properties of Drilling and Completion Fluids*, New York, Elsevier.

Hasanpour, R., Jamal Rostami, J., and Özçelik, Y. (2015). "Impact of overcut on interaction between shield and ground in the tunneling with a double-shield TBM." *Rock Mechanics and Rock Engineering*, DOI 10.1007/s00603-015-0823-x.

Khazaei, S., Shimada, H., and Matsui, K. (2004). "Analysis and prediction of thrust in using slurry pipe jacking method." *Proceedings 30th ITA-AITES World Tunnel Congress*, Singapore, 22–27.

Ren, D., Huang, K., Lin, T., and Shou, K. (1998). "A study on the direct shear test at the driving pit of a pipejacking project." *1998 Taiwan Rock Engineering Symposium*, *Taiwan*, 119–128.

Shou, K.J. and Jiang, J.M. (2010). "A study of jacking force for a curved pipejacking." *Journal of Rock Mechanics and Geotechnical Engineering*, **2**(4), 298–304.

Shou, K.J. and Yen, J.H. (2010). "On the behavior of a stuck curved pipe jacking." *Journal of GeoEngineering*, **5**(3), 77–85.

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.

SINOTECH (1993). The Geological Explorations and Geotechnical Experiments in the Fourth Phase Development of Taichung Science Park, Report to NSC, Taiwan.

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

Sterling, R.M. (2010). "No-Dig techniques and challenges." *Journal of GeoEngineering*, **5**(3), 63–67.

Wu, W., Ho, T., and Lin, T. (1995). "The engineering properties of the gravel formations in Taiwan area." *International Symposium of Underground Engineering in Gravel Formations*, 1-61–1-72.

Yen, J. and Shou, K. (2015). "Numerical simulation for the estimation the jacking force of pipe jacking." *Tunnelling and Underground Space Technology*, **49**, 218–229.