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# On the frictional property of lubricants and its impact on jacking force and soil–pipe interaction of pipe-jacking

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ABSTRACT

Lubricants are frequently applied in pipe-jacking, especially under difficult geological conditions or in cases of a longer alignment. The main purpose of lubricant application is to reduce the friction between pipe and soil. However, it is very difficult to quantitatively determine the real contact conditions between the two. New technology for soil–pipe interaction measurement is still scarce and requires further development. Only indirect methods are available for practical measurement of soil–pipe interaction, and engineering judgment is required for the application of those measurements. In this study, a simple test method was applied to obtain the frictional properties of the most popular lubricants in the Taiwan area. Those frictional properties were used for jacking force estimation and numerical analysis of soil–pipe interaction for linear and curved pipe-jacking. The analyses of jacking force show that reduction in jacking force is closely related to reduction in friction coefficients, and the effect of lubrication is slightly more significant in the case of curved alignment than the case of linear alignment. In addition, a study of a 400-m linear pipe-jacking case in the Taichung Science Park shows overestimation of the jacking force by an empirical formula. It reveals the reduction in pipe-soil contact area induced by over-cutting is significant for pipe-jacking in gravel formations.



## 1. Introduction

In pipe-jacking, the jacking force is a critical factor that determines the pipe wall thickness, location of intermediate jacking stations, and lubricant requirements. By reducing the jacking force, the risk of pipe damage can be minimized, which also helps reduce the construction cost. In particular, for pipe-jacking with a comparatively long alignment or in difficult geological conditions, application of lubricant is essential to reduce the required jacking force. Lubrication reduces the jacking force by reducing the frictional stress around the pipe. Lubricants are generally designed to form a layer in the surrounding soil and to be pressurised to overcome groundwater pressure and stabilize the over cut area.

However, comparison of lubricant performance is not feasible because the conditions and specifications of cases are rarely exactly the same. In addition to the difference in geomaterial and groundwater conditions, the pipe diameter, depth, penetration rate, over-cutting ratio, etc. are seldom the same for two pipe-jacking cases. Although those factors obviously affect the required jacking force, no technology is available to quantify their influence. The estimation of jacking force and application of lubricants are still based on empirical rules.

Taichung Science Park is being developed in the western suburbs of Taichung City, which is located on lateritic gravel formations. The construction of a sewage system, including wastewater treatment plants and pipelines, started in early 2005. More than 20,898 m of underground pipelines are the major components of the system, and 68% of the underground pipelines were or will be installed by no-dig methods.

Focusing on these no-dig projects, a simple testing method was applied to measure the frictional properties of lubricants. The impact of lubrication on jacking force as well as soil–pipe behaviour was analysed and discussed. The jacking force record of a 400 m linear pipe-jacking case in the Taichung Science Park was also analysed and discussed. Soil–pipe behaviour was numerically studied for cases with linear alignment and curved alignment.

## 2. Geomaterials and lubricants

To provide suggestions for the development of Taichung Science Park, this study focuses on no-dig construction in the gravel formations in central Taiwan. These formations are composite geomaterials consisting mainly of gravels and soils. As the diameters of the gravels, with a large volumetric percentage, are 5–20 cm, it is difficult to obtain the mechanical properties accurately due to the size effect in experiments. The gravels in this area are originally from

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quartzite, with a hardness of more than 6.0 in the Moh's scale of hardness and an uniaxial compressive strength of more than 1000–2000 kg/cm$^2$, which causes difficulties in excavation work. In general, gravel formations in the Taichung area possess a high internal friction angle (37–49°) and low cohesion (Wu et al., 1995; Ren et al., 1998).

As a drilling fluid, mud is commonly applied in oil exploration, to stabilize the boreholes and remove cutting debris. For shield excavation and pipe-jacking, drilling fluids provide mainly soil conditioning and lubrication. In many cases, their functions include supporting the excavated face, reducing friction by generating pore water pressure and conditioning the excavated soil into a dischargeable mixture (Norris and Milligan, 1992; Milligan, 2000; Mair et al., 2003; Merrit et al., 2003; Chapman et al., 2007).

In general, besides water, a drilling fluid consists of bentonite, polymers, and soluble chemicals (Darley and Gray, 1988; ASME Shale Shaker Committee, 2004; Aberson, 2007; Carey, 2009). Through the development of pipe-jacking technology, new chemical additives have been developed and applied. Their main purposes include creating a protective layer and repelling surrounding water (Darley and Gray, 1988; Milligan, 2001; Baumert et al., 2005).

## 3. Testing frictional properties

Like other no-dig methods, pipe-jacking is a complex process. The soil–pipe interaction is greatly affected by excavation conditions, such as over cut, stoppage, pipe misalignment and lubrication. Although many studies have investigated the interface frictional strength between soil and ground reinforcements (piles, geosynthetics, etc.), few have examined the frictional resistance between soil and pipe (Uesugi and Kishida, 1986; Dove and Frost, 1999; Pellet and Kastner, 2002).

In this study, considering the size effect of the gravelly soil in the study area, a simple large-scale testing method was applied to determine the frictional properties of lubricant between concrete pipes and soil. This method places lubricant between a concrete block and the soil and then measures the critical drag force to move the concrete block (see Fig. 1). Different dead loads were applied to change the normal stress on the concrete block. Different sets of normal stress and frictional force can be obtained to determine the frictional properties of the lubricants.

The geomaterial collected from Taichung Science Park was evenly placed in a 122 cm ∗ 76 cm ∗ 30 cm water proof wooden box for testing. A specially made 21.5 cm ∗ 21.5 cm ∗ 7 cm concrete block was applied to represent part of a concrete pipe. Steel plates were placed on the concrete block as an extra dead load. Then a digital load scale (with an accuracy of 0.1 kg) was used to measure the critical drag force when the concrete block starts to move.

In this study, we tested combinations of several of the most popular lubricants: bentonite, polymer (Super-PAA) and plasticizer (a combination of sodium silicate and polyacrylate). The five different types of lubrication are:

(1) a 4.5-cm layer of bentonite fluid (with Marsh funnel time 130 s. for 1.0 quart),
(2) a 1.5-cm layer of polymer above a 3-cm layer of bentonite fluid,
(3) a 3.0-cm layer of plasticizer above a 1.5-cm layer of bentonite fluid,
(4) a 3.0-cm layer of plasticizer above a 1.5-cm layer of polymer fluid, and
(5) a 4.5-cm layer of plasticizer.

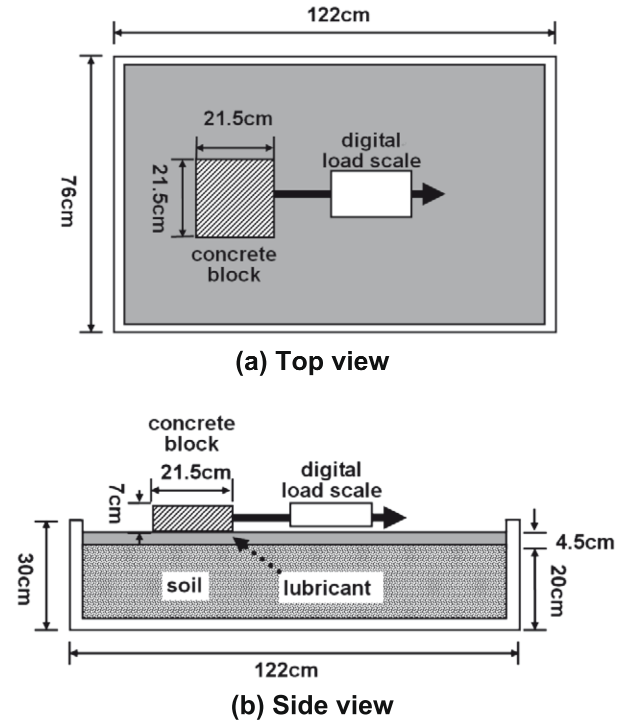


**Fig. 1.** The simple test for pipe-soil frictional property measurement.

The friction coefficients for those lubrication types were obtained by a simple large-scale test with different normal stresses (see Table 1). The results show that both bentonite and plasticizer can reduce the friction by about 20–25%; combining plasticizer with bentonite or polymer can reduce the friction by about 65–75%, which is comparable to the best friction reduction by lubrication found in other studies (Milligan and Norris, 1999; Borghi and Mair, 2006). However, a combination of polymer and bentonite is slightly less effective than bentonite alone.

During the simple friction testing, similar to real pipe–soil interaction in pipe-jacking, the lubricants were squeezed out from beneath the concrete plate. However, the relative effects of lubrication were quantified. It is worth noting that a thick layer of plasticizer can remain between the concrete plate and the soil, which can more significantly reduce the interface friction.

Because smaller loads result in higher inaccuracy, the results of a lower normal load and the cases with plasticizer (less friction) are less accurate. However, these test results were applied to estimation of jacking forces and numerical analyses in the following sections.

## 4. Estimation of jacking force

A number of researchers have conducted both laboratory and field studies to understand the development of jacking forces during pipe-jacking. Many of these studies evaluated jacking forces by considering of parameters, including the resistance at the cutting head, steering corrections, pipe joint deflection, and the effects of lubrication. Other studies involved statistical analyses of a large number of case histories and empirically proposed factors for jacking force predictive models (Chapman and Ichioka, 1999; Osumi, 2000; Pellet and Kastner, 2002; Sofianos et al., 2004; Staheli, 2006). In this study, both linear and curved alignments are investigated. Empirical formulas are briefly reviewed and applied for jacking force estimation.

**Table 1**
Test results of friction coefficients for different type lubrications.

| Normal pressure[a] | No lubricant | Bentonite | Bentonite + polymer | Plasticizer + bentonite | Plasticizer + polymer | Plasticizer |
|---|---|---|---|---|---|---|
| 4.3 kN/m$^2$ | 0.53 | 0.33 | 0.4 | 0.15 | 0.13 | 0.43 |
| 7.8 kN/m$^2$ | 0.54 | 0.46 | 0.45 | 0.20 | 0.11 | 0.40 |
| 11.2 kN/m$^2$ | 0.50 | 0.41 | 0.47 | 0.21 | 0.15 | 0.36 |
| Average | 0.52 | 0.40 | 0.44 | 0.19 | 0.13 | 0.40 |
| Reduction percentage (%) | 0 | 23.5 | 16 | 65 | 75 | 23.5 |

[a] Including the weight of concrete block.

### 4.1. Linear pipe-jacking

For typical pipe-jacking, the jacking force overcomes resistance from two major sources, i.e., the resistance at the cutting head ($F_o$) and that at the pipe string ($F_s$):

$$F = F_o + F_s \tag{1}$$

The resistance at the cutting head $F_o$ ($kN$) is theoretically between active and passive earth pressure, and can be empirically related to the SPT $N$-value (Japan Micro Tunneling Association, 2000)

$$F_o = 10.0 \times 1.32\pi \times D \times N \tag{2}$$

where $D$ (m) is the outer diameter of the pipe and $N$ is the SPT $N$-value. However, based on empirical data this was modified to:

$$F_o = 10.0 \times 1.32\pi \times D_s \times N' \tag{3}$$

where $D_s$ (m) is the outer diameter of the shield machine and $N'$ is an empirically based factor (set to 1.0 for clayey soil, 2.5 for sandy soil and 3.0 for gravelly soil).

Although the resistance at the pipe string is mainly due to friction between pipe and soil, determining the resistance is quite difficult. This is because the complex process of pipe-jacking is greatly affected by excavation conditions (over cut, stoppage, pipe misalignment, lubrication, etc.). The resistance at the pipe string $F_s$ can be expressed empirically as

$$F_s = \pi \times D \times \tau \times L + \omega \times f \times L \tag{4}$$

$$\tau = \sigma \times f + c' \tag{5}$$

where $L$ is the length of the pipe string, $\omega$ is the pipe weight per unit length, $\sigma$ is the normal stress on the pipe surface, and $f$ and $c'$ are the friction coefficient and adhesion between pipe and soil, respectively. Since Terzaghi's arching theory (Terzaghi, 1943) is the most widely accepted theory for soil stress acting on pipelines, Terzaghi's

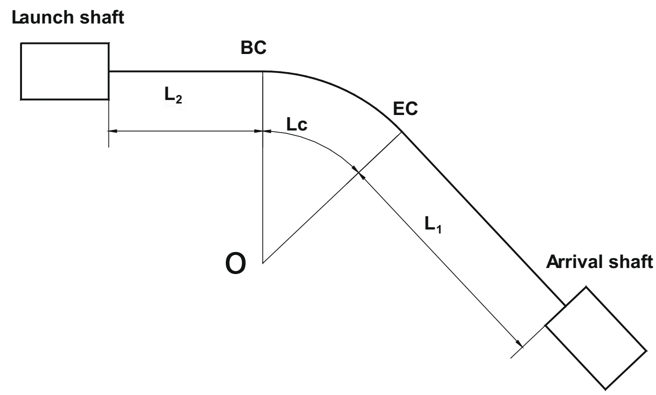


**Fig. 2.** The alignment of a generalized pipe-jacking case.

**Table 2**
Parameters for jacking force estimations.

| Parameters for linear pipe-jacking | | Parameters for curved pipe-jacking | |
|---|---|---|---|
| $F_o$ | Eq. (3) | $F_o$ | Eq. (9) |
| $N'$ | 3 | $\lambda$ | 1.129 |
| $D$ (m) | 2.85 | $D$ (m) | 2.85 |
| $\varphi$ (°) | 37 | $\varphi$(°) | 37 |
| $\omega$ (kN/m) | 44.5 | $\alpha$(°) | 1.15 |
| Length (m) | 8 | $n$ | 20 |
| c' (kN/m2) | 0. | $L_c$ (m) | 0.4 * 20 |

**Table 3**
The jacking force requirement for a 8-m linear pipe-jacking.

| Type of lubricant | Friction coefficient $k$ | Resistance at cutting head $F_0$ (kN) | Resistance at pipe string $F$ (kN) | Total jacking force $F_{total}$ (kN) |
|---|---|---|---|---|
| No lubricant | 0.52 | 354.56 | 1805.36 | 2159.92 |
| Bentonite | 0.40 | 354.56 | 1388.74 | 1743.30 |
| Bentonite + polymer | 0.44 | 354.56 | 1527.61 | 1882.17 |
| Plasticizer + bentonite | 0.19 | 354.56 | 659.65 | 1014.21 |
| Plasticizer + polymer | 0.13 | 354.56 | 451.34 | 805.90 |
| Plasticizer | 0.40 | 354.56 | 1388.74 | 1743.30 |

**Table 4**
The jacking force requirement for a 8-m curved pipe-jacking.

| Type of lubricant | Friction coefficient $k$ | Resistance at cutting head $F_0$ (kN) | Resistance at pipe string $F$ (kN) | Total jacking force $F_{total}$ (kN) |
|---|---|---|---|---|
| No lubricant | 0.52 | 377.18 | 1872.08 | 2249.25 |
| Bentonite | 0.40 | 377.18 | 1392.08 | 1769.26 |
| Bentonite + polymer | 0.44 | 377.18 | 1545.43 | 1922.60 |
| Plasticizer + bentonite | 0.19 | 377.18 | 611.02 | 988.20 |
| Plasticizer + polymer | 0.13 | 377.18 | 419.00 | 796.18 |
| Plasticizer | 0.40 | 377.18 | 1392.08 | 1769.26 |

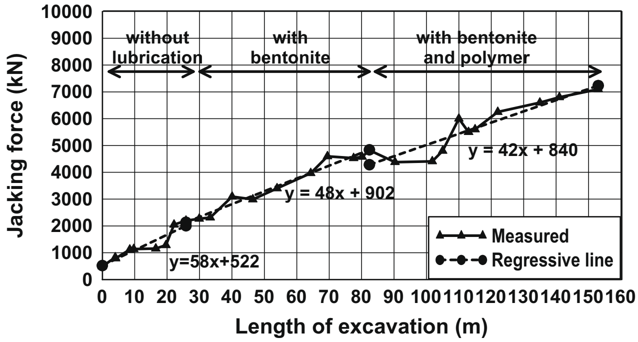


**Fig. 3.** Comparison of jacking forces for a 100-m linear pipe-jacking case in Taichung Science Park.

trap door formula is applied in this study to obtain the normal stress $\sigma$,

$$\sigma = \gamma(D/2)/\tan\varphi \tag{6}$$

where $\gamma$ is the unit weight of the soil, and $\varphi$ is the internal friction angle of the soil. Noting that the friction coefficient $f$ is determined by the friction angle $\delta$ between pipe and soil;

$$f = \tan\delta \tag{7}$$

$\delta$ can be empirically taken as half of the internal friction angle of the soil, or $\varphi/2$ (Japan Micro Tunneling Association, 2000; Pellet and Kastner, 2002; Sofianos et al., 2004; Staheli, 2006).

### 4.2. Curved pipe-jacking

Curved pipe-jacking was initiated about two decades ago, and was theoretically studied by Nanno (1996). However, theoretical estimation of the jacking force is difficult due to the instability of the force systems (Nanno, 1996; Wei et al., 2005; Broere et al., 2007). The Japan Micro Tunneling Association (2000) presents an empirical formula to estimate the jacking force for a general curved pipe-jacking (Fig. 2):

$$F = (F_o + f_1 \cdot L_1) \cdot K^n + \lambda \cdot f_1 \cdot L_c + f_1 \cdot L_2 \tag{8}$$

where $n$ is the number of pipes, $L_1$ is the distance from point EC to the arrival shaft, $L_c$ is the length of the curved segment, and $L_2$ is the distance from the launch shaft to point BC. The resistance at the cutting head $F_o$ can be expressed as

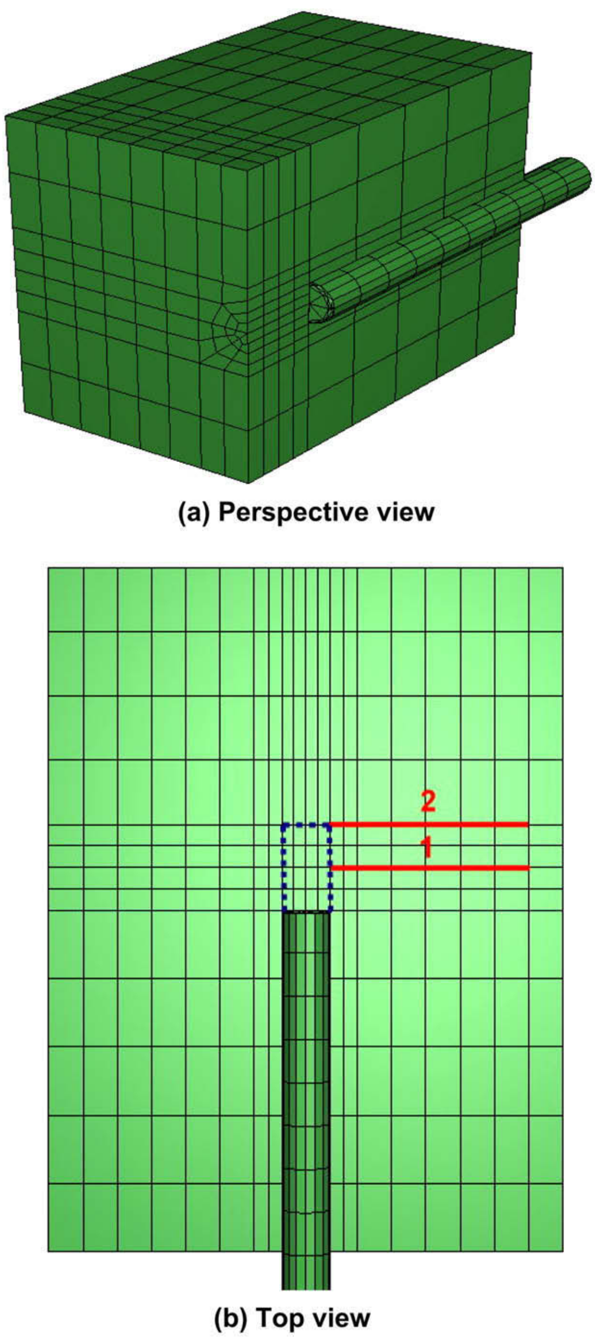


**Fig. 4.** The three-dimensional mesh for the analyses of linear pipe-jacking.

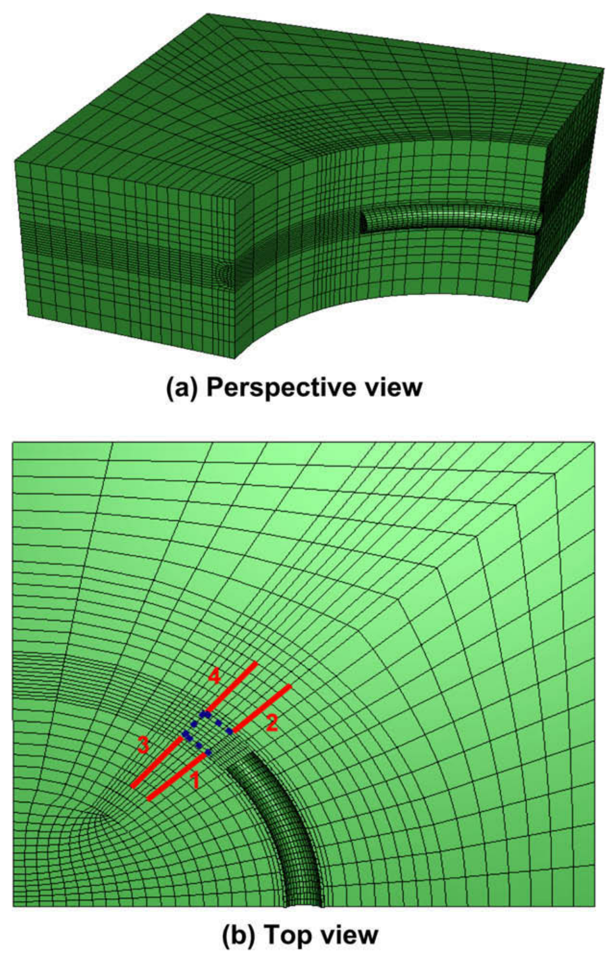


**Fig. 5.** The three-dimensional mesh for the analyses of curved pipe-jacking.

$$F_o = \frac{Q_1 + Q_2}{2} \times Acs \quad (9)$$

where $Q_1$ and $Q_2$ are the earth pressure at the top and bottom of the pipe, respectively, and *Acs* is the cross-sectional area of the cutting head. The resistance of the pipe–soil interface friction $f_1$ is a function of the frictional stress $P$ (=$\sigma \times f$) and diameter $D$

$$f_1 = P \times \pi \times D \quad (10)$$

The correction factor for the curved segment $K$ can be defined as

$$K = \frac{1}{\cos\alpha - k \cdot \sin\alpha} \quad (11)$$

in which $\alpha$ is the deflection angle and $k$ is the friction coefficient in the curved segment. Although $k$ is set the same as $f$ in this study, they can be different due to different lubrication condition in the curved segment. However, $k$ can be empirically set to $tan(\varphi/2)$, where $\varphi$ is the internal friction angle of the soil. In addition, the resistance ratio of the curved and straight line segments $\lambda$ is defined as

$$\lambda = \frac{K^{n+1} - K}{n \cdot (K - 1)} \quad (12)$$

In this study, Eqs. (1), (3), and (4) were applied to jacking force estimation of linear pipe-jacking, and Eq. (8) was applied to jacking force estimation of curved pipe-jacking.

## 4.3. Results and discussion

Since this study focused on application in Taichung Science Park, pipe-jacking in gravel formations was considered and analysed. For comparison, we consider a case of 8-m linear alignment and a case of 8-m curved alignment (20 m in radius). The depth of the pipes is 9.65 m below the ground surface in both cases, and the five different types of lubrication are considered to estimate the required jacking forces with the input data shown in Table 2.

As expected, the results in Tables 3 and 4 show a similar trend in lubricant performance. The reduction ratio of jacking force for plasticizer plus polymer is about 63–64%, which is slightly lower than but comparable to the reduction in the friction coefficients. The discrepancy is expected to be smaller for longer pipe strings, because the jacking force will be balanced mainly by the resistance from the pipe–soil interface friction of pipe strings. Moreover, the effect of lubricants is more significant for curved alignment cases.

The adopted 400-m linear pipe-jacking case was excavated by an MTS Perforator pipe-jacking machine, with a 2.85-m external diameter. To avoid a larger jacking force at the launch shaft, eight intermediate jacking stations were designed along the alignment. The groundwater level is below the excavation surface. For this case, no lubricant was applied in the first 23 m of driving, and bentonite was then applied due to an abrupt increase in resistance. A new formula, i.e., bentonite plus polymer, was applied after 82 m of driving. The intermediate jacking stations were not in operation until after 150 m of driving. Therefore, only the first 150 m of monitoring results of the jacking force were adopted and analysed (see Fig. 3).

Fig. 3 appears to show points of gradient change right after the changes in lubrication condition. It reasonably reveals the impacts of lubrication, although the reduction of jacking force does not quantitatively match the estimated jacking force, from either theoretical or empirical formulas. The friction coefficients can be obtained by back-calculating the slopes of the regressive lines. This approach obtains friction coefficients for those three interface conditions of 0.15, 0.09 and 0.06, which are only about 1/3–1/6 of the experimentally obtained values of 0.52, 0.40 and 0.44.

Since pipe-jacking is a complex procedure, there are many possible reasons for the discrepancies between the measured and estimated jacking forces. In Taichung Science Park, the main reason for

**Table 5**
The input data for ABAQUS analyses.

| | | |
|---|---|---|
| Soil property (gravelly soil in Taichung) | $\varphi$ (°) | 37 |
| | $c$ (kPa) | 29.4 |
| | $E$ (kPa) | 1E + 006 |
| | $\nu$ | 0.3 |
| | $\gamma$ (kN/m$^3$) | 23.00 |
| Concrete property | $E$ (kPa) | 2.17E + 007 |
| | $\nu$ | 0.3 |
| | $\gamma$ (kN/m$^3$) | 23.52 |
| Interface property | Normal behaviour | Hard contact |
| | Tangential behaviour (friction/penalty) | Use different friction coefficients |

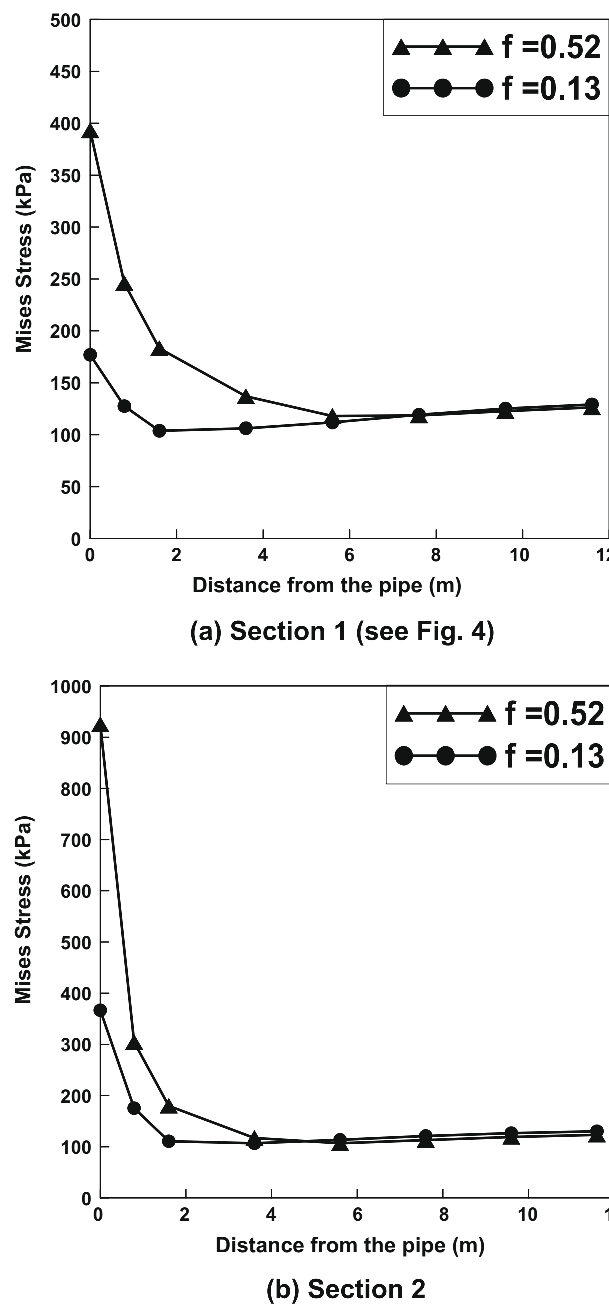


**Fig. 6.** Distribution of Mises stress outside the pipe- linear pipe-jacking with different friction coefficient.

the discrepancy could be overestimation of the contact area between pipe and soil. The gravel formations in the study area consist mainly of different-size gravels (more than 65%) and sandy soils. Destruction of the matrix of gravel and sandy soil is the major failure mechanism of cutting, which can easily generate over cut in the surrounding geomaterials. Therefore, subsidence due to over cut is a common problem for no-dig construction in this type of soil. When excavation takes place in loose soil, the excavating face and the over cut are generally unstable unless lubrication is applied (Marshall and Milligan, 1998a; Marshall and Milligan, 1998b; Camusso and Barla, 2007).

It is worth noting that the copy cutter in this project was set to enlarge the circular excavation from 2.85 m to 2.92 m in diameter. To summarize, it appears that over cut contributes significantly to the reduction in jacking force for pipe-jacking in gravel formations. Regarding the back-calculated friction coefficients, the reduction of friction in this practical case is slightly smaller than the reduction factor of 0.35–0.60 suggested by Osumi (2000).

The overestimation of jacking force may come from the smaller contact area or smaller contact stress induced by over cut. However, both factors are affected by the amount of over cut, the amount of lubricant within the over cut, and the stability of over cut around the pipe. With a fully effective lubrication system, the ground is held back from the pipe, and the pipes can float within the lubricant. Theoretically, jacking resistance can then be very small.

## 5. Numerical analysis of soil–pipe behaviour

Finite element analyses were conducted to investigate the soil–pipe behaviour affected by lubrication. The pipeline is assumed to

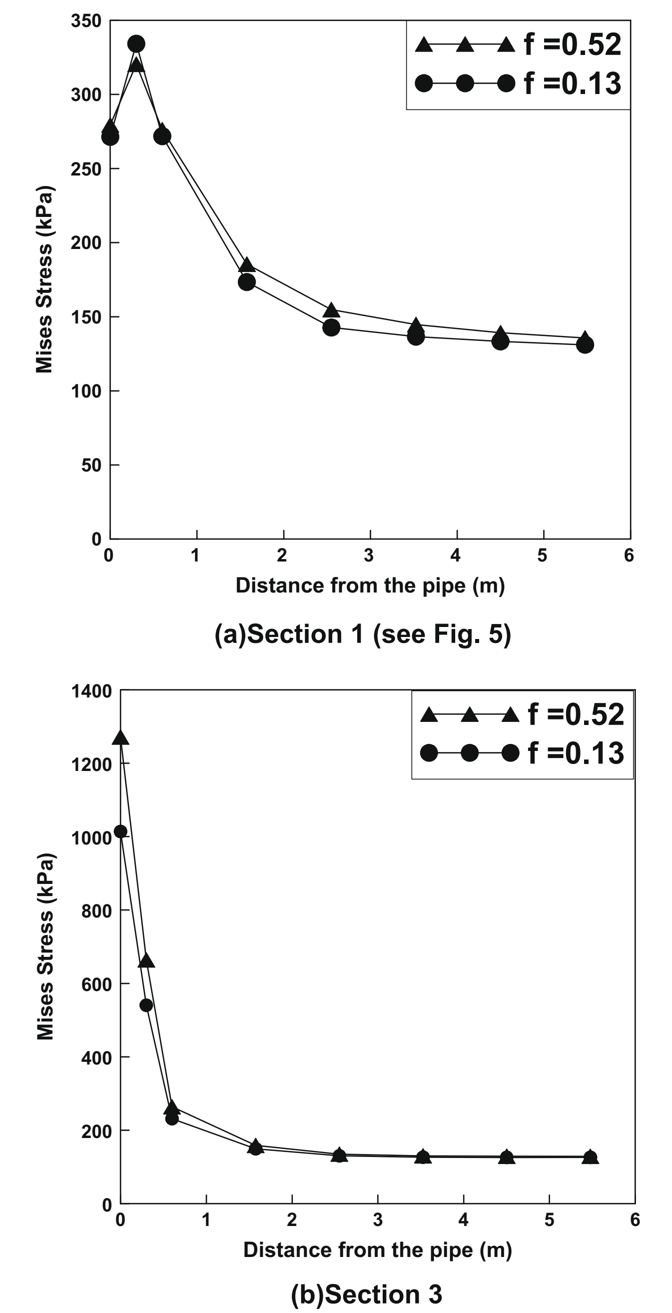


**Fig. 7.** Distribution of Mises stress at the inner side of the curved pipe with different friction coefficient.

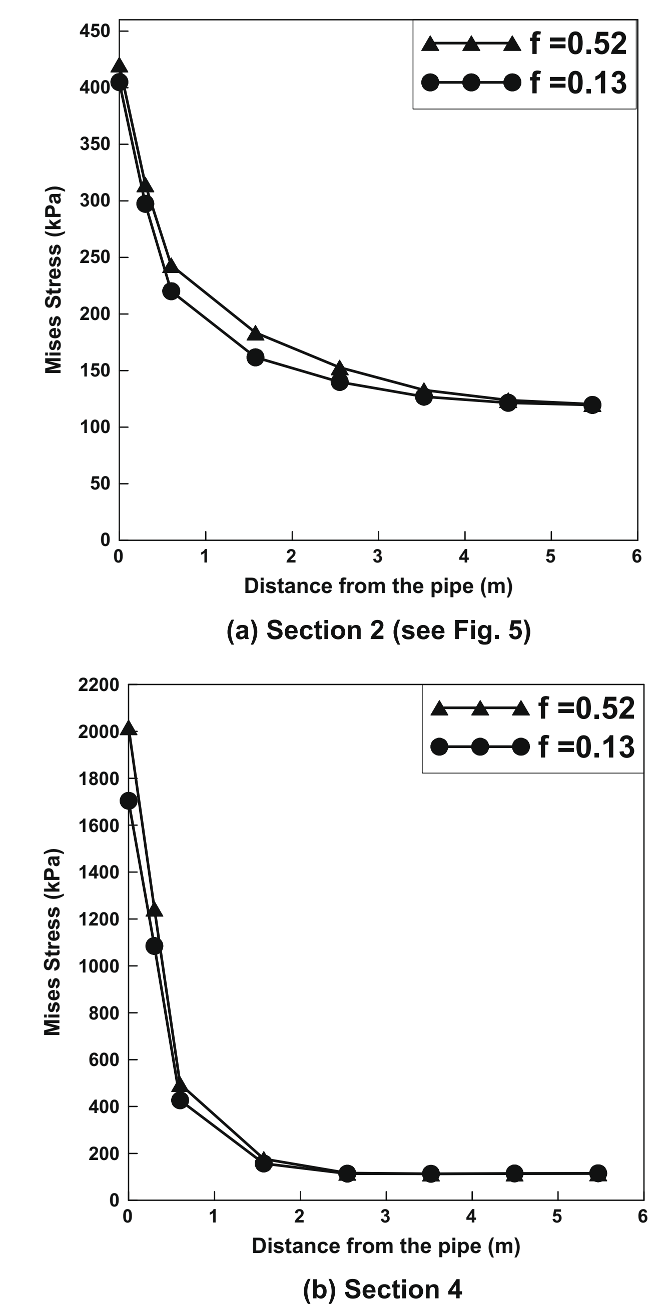


**Fig. 8.** Distribution of Mises stress at the outer side of the curved pipe with different friction coefficient.

be 2.85 m in diameter and 9.65 m below the ground surface. For comparison, we consider pipe-jacking cases with a 20-m linear alignment and a 20-m curved alignment (20 m in radius). The analyses were performed by the finite element software ABAQUS (Abaqus, Inc., 2005).

The boundary conditions and element type are as follows: (A) the bottom face is confined by hinges and the surrounding vertical faces are framed by rollers, (B) three-dimensional solid elements (C3D8I) are used to simulate the soil and the pipe, and (C) interface elements are applied to simulate the soil–pipe frictional behaviour. The three-dimensional meshes for the analyses of the linear and curved alignments are shown in Figs. 4 and 5, respectively. The pipe strings are jacked to the end of the dashed lines, and the stresses along the designated sections are illustrated and discussed.

Numerically, we simulate the pipe-jacking process by repeating three numerical steps: remove the soil element inside the pipe and at the pipe location, equilibrate the domain to obtain and accumulate the influences and finally drive the pipe elements forwards. The jacking force was estimated by the empirical formula and applied at the back of the pipe string. Based on experimental results for geomaterials in central Taiwan, the extended Drucker–Prager model is adopted as the constitutive law (Shou and Wu, 2002; Shou and Liu, 2004). The failure criterion is determined by the results of in situ triaxial testing, and Young's modulus is considered to increase with depth (see Table 5).

For comparison, two typical friction coefficients 0.13 and 0.52, are introduced as the properties of interface elements. The results for the linear case in Fig. 6 demonstrate that lubrication effectively reduces the stress of the soil surrounding the pipes. For the curved alignment case, the stress field near the cutting head is investigated. The stress release at the inner side can be observed from the stress distribution curve of Fig. 7a. Regarding the asymmetrical stress field around the curved pipe, Figs. 7 and 8, respectively, show the stress distributions at the inner and outer sides of the pipe. Similar to the linear case, lubrication reduces the stress concentration at the soil close to the pipes. The influence of lubrication is more significant near the cutting head and at the outer side of the pipe. The displacement profiles, obtained numerically, are illustrated in Fig. 9. It appears that the lubrication considerably re-

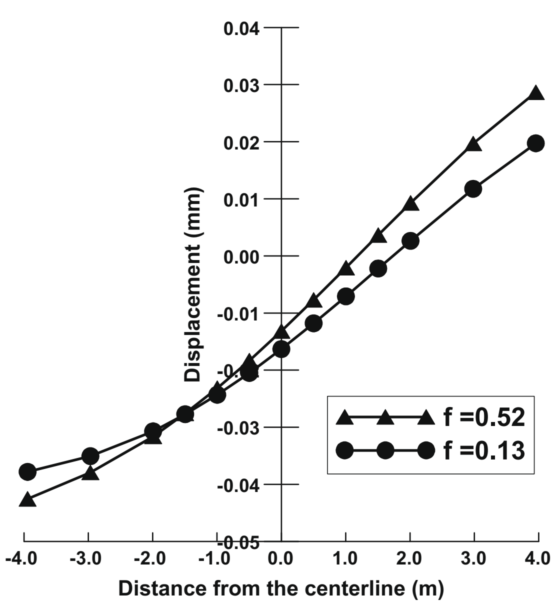


**Fig. 9.** Distribution of displacement for the curved pipe with different friction coefficient.

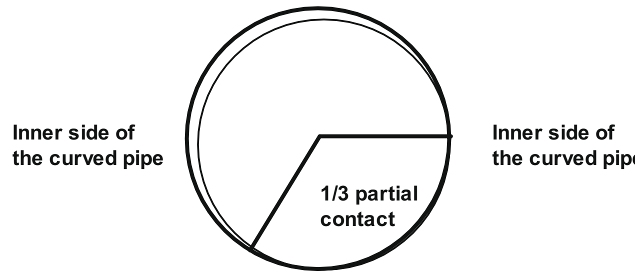


**Fig. 10.** The considerations of 1/3 partial contact between pipe and soil due to over cut.

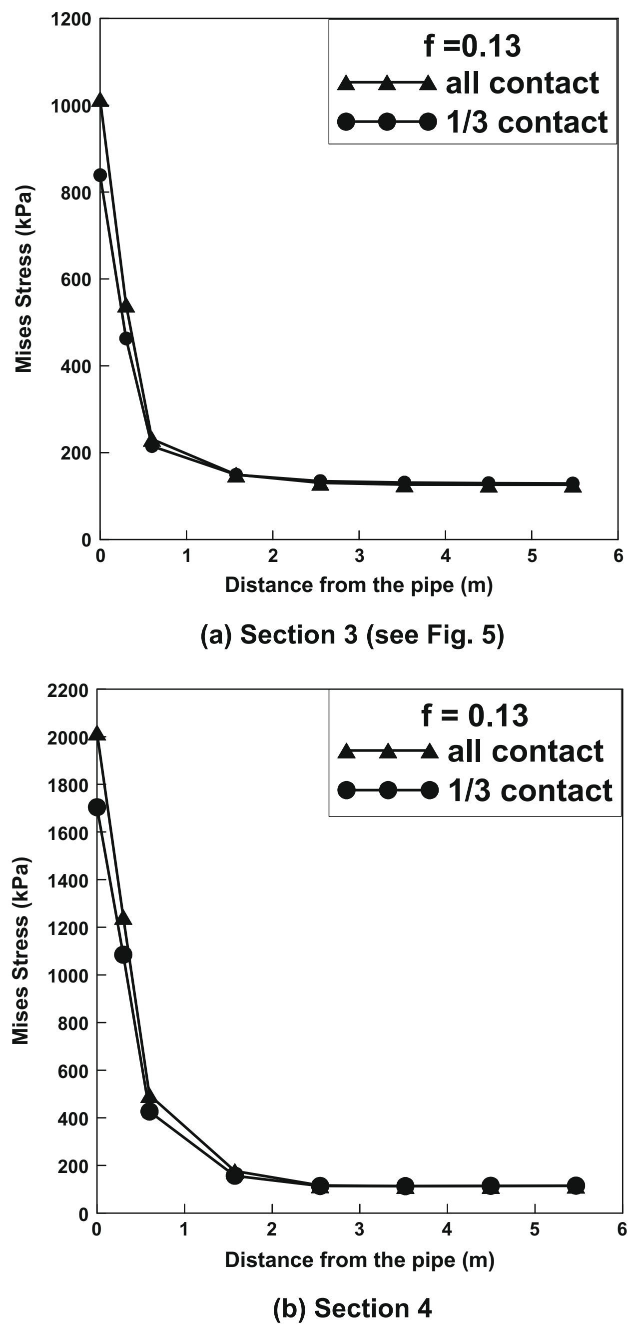


**Fig. 11.** Distribution of Mises stress outside the curved pipe with different pipe–soil contact area.

duces the displacement at the outer side but slightly increases the displacement at the inner side of the pipe.

Considering the effect of over cut, the pipe might slide only on a limited contact surface, which could be the main reason for the overestimation of jacking force by theoretical or empirical formulas. The case with only 1/3 partial pipe-soil contact (see Fig. 10) is also simulated to investigate the impact of over cut. Fig. 11 shows that the partial contact condition not only reduces contact area but also reduces the stress by about 15% (for friction coefficient of 0.13). This finding reveals that the effect of over cut is significant, and it is important in the control of jacking force (Marshall and Milligan, 1998b; Pellet and Kastner, 2002; Phelipot et al., 2003).

## 6. Conclusions and suggestions

Focusing on pipe-jacking in Taichung Science Park, the most popular lubricants were tested by a simple large-scale test. Test results show that bentonite and plasticizer can reduce the friction by about 20–25%, and combining plasticizer with bentonite or polymer can reduce the friction by about 65–75%, which is comparable to the best friction reduction found by other studies (Milligan and Norris, 1999; Borghi and Mair, 2006). However, in this study it was found that the performance of the combined polymer and bentonite lubricant was less effective than using the bentonite on its own.

The estimation of jacking forces shows that the ratio of reduction in jacking force is comparable to the reduction in friction coefficients at the pipe–soil interface. The effect of lubricants is more significant for cases of curved alignment than cases of linear alignment. For the case study in Taichung Science Park, we observed discrepancies between the monitored and estimated jacking forces that could be caused by overestimation of the contact area between pipe and soil. Since subsidence due to over cut is a common problem for no-dig construction in this area, the effect of over cut contributes considerably to the reduction in jacking force. In addition, the back-calculated friction coefficients are slightly smaller than those obtained by multiplying the reduction factor suggested by Osumi (2000).

Numerical analysis reveals that lubrication effectively reduces the stress and displacement of the soil surrounding the pipes. For a curved alignment, the influence of lubrication is more significant near the cutting head and at the outer side of the pipe. The over cut-induced partial contact condition not only reduces the contact area but also reduces the stress near the pipe. This finding reveals that over cut has a significant effect and is critical in the control of jacking force.

The jacking force is affected by not only the amount of over cut but also the over cut conditions, i.e., whether the lubricant is pressurised within the over cut, and whether the over cut around the pipe is maintained by the lubricant. With effective lubrication, the ground is held back from the pipe, and the pipe can float within the lubricant. The jacking resistance can theoretically be very small.

Since pipe-jacking is a complex procedure, the lubrication requirements for soil stability and for reduction in jacking force might not be the same. The design of lubrication is still a case-by-case empirical practice. More frictional property testing, soil–pipe interface simulation and jacking force prediction analysis are suggested as future studies.

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