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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.

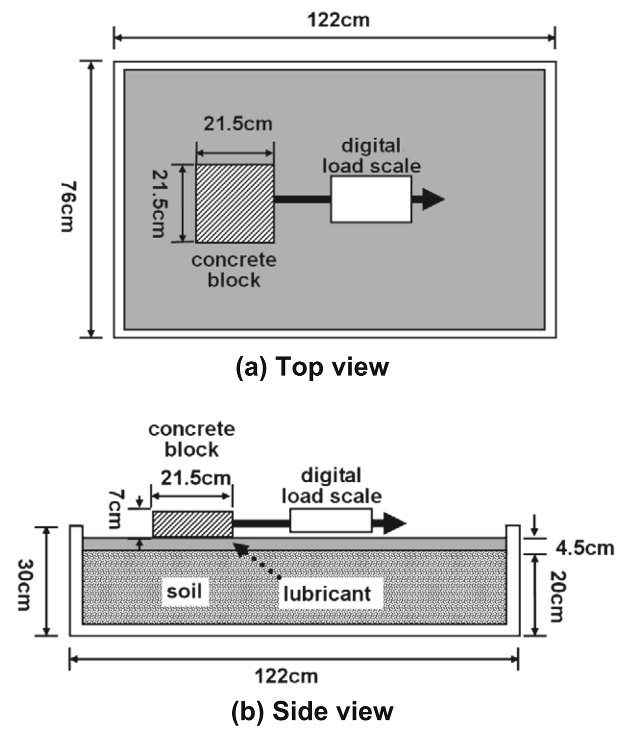

Fig. 1. The simple test for pipe-soil frictional property measurement.

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.