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Back-analysis and finite element modeling of jacking forces in weathered rocks

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ABSTRACT

Prediction of jacking forces has been well-established for pipe-jacking drives traversing soils. However, the accrual of jacking forces for drives negotiating weathered rock formations has not been well understood. Three pipe-jacking drives in Kuching City, Malaysia spanning weathered lithological units of sandstone, phyllite and shale were studied. In the absence of in-situ pressuremeter testing during the investigation stage, tunneling rock spoils were collected and characterized through direct shear testing. The "generalized tangential" technique was applied to the nonlinear direct shear test results to obtain linear Mohr–Coulomb parameters, c'_p and ϕ'_p. This allowed for back-analysis of frictional coefficient, μ_{avg} through the use of a well-established predictive jacking force model. The reliability of using c'_p, ϕ'_p and μ_{avg} was assessed through 3D finite element modeling of the studied pipe-jacking drives. Based on these parameters, the results obtained from the numerical analyses of the studied pipe-jacking drives show good agreement with the jacking forces measured in-situ. The outcome of this research demonstrates that the derived strength parameters from direct shear testing of tunneling rock spoils has the potential to be used as reliable input parameters in finite element modeling to predict pipe-jacking forces in highly weathered geological formations.

1. Introduction

The understanding of pipe-jacking forces is critical in project planning and cost estimation of underground infrastructure projects. Such was the case in the installation of 7.7 km trunk sewerage pipelines within the central business district of Kuching City, Malaysia. The microtunneling works traversed the young pre-upper carboniferous Tuang formation, characterized by tightly folded, highly fractured lithological units of shale, phyllite, and sandstone (Tan, 1993).

As a result of the highly fractured geology, the extracted rock cores were scarcely intact. The majority of recovered cores from the studied pipe-jacking drives had Rock Quality Designation (RQD) values of zero. Intact rock core lengths are necessary for common rock strength tests, such as uniaxial compression strength (UCS), and point load. The lack of intact rock cores created challenges in assessing the in-situ strength parameters of the highly fractured weathered rock lithological units. The situation was made worse as in-situ pressuremeter tests were not locally available and were not budgeted during the investigation stage of the project. As rock strength parameters were essential in the prediction of jacking forces, the lack of any reliable rock strength values impeded further efforts in assessing jacking loads accrued during pipe-jacking works.

The work described in this paper was motivated by the need to characterize rock mass strength of the various highly fractured lithological units found within the Tuang Formation in Kuching City. Hence, a novel approach by reconstituting tunneling rock spoils obtained during the construction stage of the project was proposed to characterize the rock strengths for subsequent use in the back-analysis and prediction of jacking forces. The use of tunneling rock spoils for the purpose of back-analyzing jacking forces was explored (Choo and Ong, 2012, 2014, 2015), where rock spoils from tunneling works were reconstituted and scalped for direct shear testing. Based on field measured jacking forces, the direct shear test results of c' and ϕ' were applied to a well-established empirical jacking force predictive model (Pellet-Beaucour and Kastner, 2002) to reliably back-analyze soil–pipe frictional coefficients.

In this paper, finite element analysis was used as a tool to assess the reliability of applying the strength parameters obtained from direct shear testing to predict jacking forces and compare against corresponding field measured values.

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1.1. Direct shear testing

Iscimen (2004) developed an apparatus capable of measuring soil–pipe interface shear stresses for curved surfaces, such as that on the outer peripheral of jacked pipes. The apparatus was outfitted with interchangeable inner walls to allow for testing at different pipe curvatures. Various sands were tested against pipes made from different materials. The soil–pipe interface strength was found to increase with surface roughness, up to an upper limit "critical roughness", beyond which the influence of surface roughness on shear strength value was negligible. This value corresponded with the internal shear strength of the soil. This observation was similar to that made by Kishida and Uesugi (1987). The study found that particle shape greatly affected the soil–pipe interface shear strength, with angular particles exhibiting stronger interlocking than sub-rounded particles, and this is an important observation for the work presented in this paper as both argillaceous and arenaceous materials are tested.

Staheli (2006) conducted interface direct shear testing on various commonly available pipe materials, using sands. Interface friction values were developed from the tests and applied to field case studies for comparison. From analyses of the measured jacking forces for unlubricated sections of the case studies, a frictional pipe-jacking force model was developed to estimate normal stresses acting along the pipeline. The pipe-jacking force model was based on Terzaghi's arching theory. However, usage of the model is restricted to unlubricated pipe-jacking drives. The work showed that the direct shear test is capable of obtaining useful strength parameters for the assessment of jacking forces in unlubricated pipe-jacking drives.

Shou et al. (2010) conducted a simple large scale frictional experiment to test the frictional properties of various lubricants. A discrete lubricating layer was introduced between a concrete block and a soil mass. This would simulate the soil–pipe interaction in pipe-jacking at the pipe invert. It was found that the combination of plasticizer with polymer was most effective in reducing jacking forces due to frictional resistance. The findings from the large scale frictional test were applied to two sections (one linear and one curved) of a pipe-jacking case study in Taiwan. The analyses of jacking forces using frictional coefficients from the experiment resulted in overestimation of the jacking forces when compared against site measurements. This discrepancy was attributed to overestimation of the soil–pipe contact area. Shou et al. (2010) showed that the direct shear test can be used to assess jacking forces for lubricated drives.

Choo and Ong (2015) evaluated pipe-jacking forces accrued through drives in highly fractured and weathered rock. Equivalent strength parameters based on nonlinear power law functions were obtained from direct shear testing of reconstituted tunneling rock spoils. These strength parameters were subsequently applied to a well-established jacking force model by Pellet-Beaucour and Kastner (2002). Interpreted values of frictional coefficient, μ_{avg} for various weathered lithological units were analyzed against jacking forces, lubrication patterns and stoppages for consistency. The authors found that the use of reconstituted tunneling rock spoils was reliable in the analyses of jacking loads for drives traversing weathered rock formations. Hence, the use of finite element modeling in the current paper is a natural extension of the established work by Choo and Ong (2015).

The various studies presented above that involve interface friction and soil-structure interaction have clearly indicated that direct shear testing can be used to study jacking forces. The applicability of direct shear testing allows for the characterization of rock strength during the construction stage, and subsequent back-analyses of measured jacking forces. This is significant in light of the unavailability of in-situ testing methods (such as the pressuremeter test) during the early investigative stage of the project. The suitability of using direct shear test results from reconstituted tunneling rock spoils for the back-analyses of jacking forces can be validated through 3D finite element analysis.

1.2. Jacking force models

Jacking force models are typically dependent on the geology traversed during pipe-jacking (Chapman and Ichioka, 1999; Osumi, 2000; Staheli, 2006). The majority of these models are well-developed for predicting pipe-jacking forces when traversing soils. Such models usually rely on the shear strengths of the traversed geomaterials, which are typically characterized by the Mohr–Coulomb model. Frictional coefficients for different combinations of soil–pipe materials are often developed empirically. There are very limited provisions made for strength characterization and values of frictional coefficients for pipe-jacking involving rock-structure interaction. This study proposes a novel method for obtaining equivalent rock strength properties for use in the analysis of jacking forces using a well-established jacking force equation developed by Pellet-Beaucour and Kastner (2002).

Pellet-Beaucour and Kastner (2002) developed a predictive jacking force equation based on nine microtunneling operations in France. The model postulated that normal stresses acting on the outer periphery of the pipe resulted from ground overburden pressure. As a pipeline is buried at depth, the phenomenon of soil arching becomes relevant in understanding the contact stresses acting on the pipe. The phenomenon of soil arching was observed by Terzaghi (1936) by the downward deflection of a trap door underlying a sand mass. The opening of the trap door is analogous to the excavation of a tunnel. This disturbance to the geostatic conditions induces a redistribution of soil stresses, principally oriented to the tunnel perimeter. The soil stresses acting normal to the trap door (or tunnel in this case) are relaxed, thus reducing the contact stresses on the outer surface of any installed structure, i.e. jacked pipes in a microtunneling operation. The model developed by Pellet-Beaucour and Kastner (2002) was preferred for use in this paper due to its consideration of arching effect. This predictive jacking force model is shown in Eq. (1),

$$F = \mu L D_e \frac{\pi}{2}\left[\left(\sigma_{EV} + \frac{\gamma D_e}{2}\right) + K_2\left(\sigma_{EV} + \frac{\gamma D_e}{2}\right)\right] \tag{1}$$

in which F is the total frictional jacking force; L is the pipe span; D_e is the outer pipe diameter; σ_{EV} is the vertical soil stress at the pipe crown; γ is the soil unit weight; and K_2 is the thrust coefficient of soil acting on the pipe, with a suggested value of 0.3 (French Society for Trenchless Technology, 2006). μ is the coefficient of soil–pipe friction, given in Eq. (2) as

$$\mu = \tan\delta \tag{2}$$

where δ is the soil–pipe friction angle. Previous studies have empirically assumed δ to be half the internal soil friction angle, ϕ (Sofianos et al., 2004; Staheli, 2006). More realistically, Stein et al. (1989) recommended values of μ for various states of friction encountered during pipe-jacking. In lubricated drives, μ was recommended to be between 0.1 and 0.3. Various studies have used these values of μ as a basis for identifying lubricated drives through soil and rock (Barla et al., 2006; French Society for Trenchless Technology, 2006; Pellet-Beaucour and Kastner, 2002).

The vertical soil stress at the pipe crown, σ_{EV} is determined by the soil cohesion, C; the soil internal friction angle, ϕ; the lateral earth pressure coefficient, K; h is the soil cover from the ground level to the pipe crown; and the influencing soil width above the pipe, b;