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Determination of jacking forces based on highly weathered non-linear ‘soft rock’ strength parameters considering arching

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ABSTRACT

As microtunnelling by pipe-jacking continues to remain an efficient method of constructing buried infrastructure in densely populated urban areas, it is paramount to understand the effects of geology on pipe-jacking forces. There continues to be a knowledge gap when understanding the accrual of frictional jacking forces for drives negotiating geological rock formations, particularly highly erratic and highly weathered geology. This paper presents a methodology for understanding the effects of highly weathered geology on pipe-jacking forces. This method was developed during the construction of a 7.7 km long trunk sewer network at depths of up to 30 m below the central business district of Kuching city, Sarawak, Malaysia. At such depths, the encountered lithologies from the Tuang Formation predominantly presented RQD values of 0%, which created difficulties when extracting rock samples for strength characterization. Therefore, excavated tunnelling rock spoils were instead collected and subjected to direct shear testing. The reconstituted tunnelling rock spoils demonstrated behaviour, characteristic of the nonlinear power law. For application to assessment of jacking forces, the developed peak tangential strength parameters, $c'_{t,p}$ and $\phi'_{t,p}$ were found to have been closely related to the mineralogy of the respective lithological units, which subsequently affected the lubrication and accrual of jacking forces. This was explained through back-analysed values of pipe-rock frictional coefficient, μ_{avg} and vertical stresses at the pipe crown, σ_{EV}. These back-analyzed parameters provided insight into the effectiveness of lubrication efforts and the development of arching, which were closely related to the traversed lithologies. It was found that the highly weathered geology was able to arch, suggesting that the highly weathered and discontinuous ‘soft rock’ masses demonstrated soil-like behaviour.

Keywords: trenchless technology, pipe-jacking, friction, arching theory, soft rock

1 INTRODUCTION

With the advent of pipe-jacking in Sarawak, Malaysia, there was a need to understand how jacking forces were affected by the local geology. The introduction of pipe-jacking was through the construction of 7.7 km of trunk sewer lines for the Kuching Wastewater Management System (Phase 1) in Kuching city, Sarawak, Malaysia. Much of this buried pipeline would be installed at depths of up to 30 m below the busy central business district, which meant that the trunk sewer lines would be fully embedded within the various lithologies from the highly weathered Tuang Formation during microtunnelling by pipe-jacking (Tan, 1993). From soil investigation, the vast majority of the extracted rocks presented RQD values of zero.

Previous studies on assessing jacking forces have been based on pipe-jacking drives traversing soil (Chapman and Ichioka, 1999; Osumi, 2000; Staheli, 2006). Recent studies continue to be focused on pipe-jacking drives traversing soil (Cheng et al., 2018; Namli and Guler, 2017; Sheil et al., 2016; Zhang et al., 2018).

Therefore, there remains a gap in the knowledge when estimating jacking forces in rocks, particularly where rock masses were highly weathered, such as those found in the Tuang Formation. This paper presents the methodology which has been used successfully across multiple drives traversing various highly weathered lithologies (Choo and Ong, 2015a, 2015b, 2017, 2018; Ong and Choo, 2016, 2018). The findings from two of these drives will be presented, particularly those related to lithologies of phyllite and shale.

2 NON-LINEAR BEHAVIOUR OF RECONSTITUTED TUNNELLING ROCK SPOILS

Challenges arose from the characterization of the behaviour rock due to difficulties in extracting intact rock cores for conventional rock strength tests. Fig. 1 shows the highly weathered extracted rock cores from the Kuching Wastewater Management System (Phase 1), exhibiting lithologies of phyllite and shale.

Fig. 1. Rock cores demonstrating very low RQD upon retrieval from highly weathered Tuang Formation for lithological units of (a) phyllite; and (b) shale. (Ong and Choo, 2018)

Therefore, excavated rock spoils of phyllite and shale were collected from decantation chambers (desanders) from the studied drives. The excavated rock spoils were transported via pressurized slurry from the tunnelling face to the decantation chambers, and subsequently segregated from the slurry through a series of sieves. The collected spoils were then reconstituted and subjected to direct shear testing (ASTM, 2003). Details of these tests can be found in Choo and Ong (2015b, 2017). The reconstituted tunnelling rock spoils exhibited nonlinear stress-strain behaviour, thus were characterized using the nonlinear power law (De Mello, 1977), given by

$$\tau = A \cdot (\sigma')^{B} \tag{1}$$

where A is a dimensionless coefficient governing the magnitude of the power law, and B is a dimensionless coefficient governing the curvature of the power law. This stress-dependent behaviour was observed in both peak and residual states, with the peak parameters denoted by A_p and B_p, while the residual parameters were denoted by A_r and B_r. The interpreted power law parameters are presented in Table 1. However, the majority of frictional jacking force models were developed primarily for soils, which were primarily functions of classical Mohr-Coulomb (MC) strength parameters. In this study, the Pellet-Beaucour and Kastner (2002) jacking force model was used, with the equations given as

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

$$\sigma_{EV} = \frac{b\left(\gamma - \frac{2C}{b}\right)}{2K\tan\phi}\left(1 - e^{2K\frac{h}{b}\tan\phi}\right) \tag{3}$$

where F is the total frictional jacking force; L is the pipe span; D_e is the outer pipe diameter; γ is the soil unit weight; h is the soil cover from the ground level to the pipe crown; K is the lateral earth pressure coefficient; 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); C is the soil cohesion; and ϕ is the soil internal friction angle. This model considers the redistribution of soil stresses acting normally onto the pipe due to soil arching phenomenon. This is considered through the vertical stresses acting on the pipe crown, σ_{EV} as given in Eq. (3). Therefore, it was necessary to develop equivalent MC strength parameters while accounting for stress-dependency of the reconstituted tunnelling rock spoils. This was achieved through the differentiation of Eq. (1) with respect to σ', resulting in the following equations.

$$\phi'_t = \tan^{-1}(AB\sigma'^{B-1}) \tag{4}$$

$$c'_t = A\sigma'^{B}(1-B) \tag{5}$$

where ϕ_t is the tangential friction angle; c_t is the tangential apparent cohesion; and σ' is the effective overburden pressure at the pipe crown. The resulting peak tangential MC parameters for both drives have been tabulated in Table 1. These parameters allowed for the back-analysis of frictional jacking forces for the studied pipe-jacking drives, hereinafter.

Table 1. Strength parameters of excavated tunnelling rock spoils subjected to direct shear testing

Drive			A	B
Lithology			Phyllite	Shale
Peak power law parameters	A_p	[-]	3.86	1.92
	B_p	[-]	0.79	0.87
Residual power law parameters	A_r	[-]	3.37	1.07
	B_r	[-]	0.78	0.96
Effective overburden pressure	σ'_v	[kPa]	162	158
Peak tangential friction angle	$\phi_{t,p}$	[°]	46.2	40.2
Peak tangential apparent cohesion	$c_{t,p}$	[kPa]	45.1	20.6

3 BACK-ANALYSIS OF JACKING FORCES

The two studied pipe-jacking drives will demonstrate how the earlier developed peak tangential MC parameters, $\phi_{t,p}$ and $c_{t,p}$ are to be used for the back-analysis of jacking forces. From the strength parameters of the reconstituted tunnelling rock spoils, back-analysed values of the coefficient of pipe-rock friction, μ_{avg} and vertical stress at the pipe crown, σ_{EV} were developed. These back-analysed values were then compared against μ values reported by Stein (2005), where a value between 0.1 and 0.3 would indicate efficient lubrication, while a value exceeding 0.3 would indicate a condition of poor lubrication. Values of σ_{EV} were used to indicate the degree of vertical arching above the tunnels. The back-analysed values were subsequently used to provide insight into pipe-jacking activities, particularly the volume of injected lubrication, jacking speed and measured jacking forces. The results from back-analysis and field measurements from pipe-jacking activities are presented in Table 2. The studied drives traversed lithologies of similar RQD values. The diameters of both drives were also identical. Thus, the effects of the traversed lithologies on jacking forces will be demonstrated through the following case studies. Of particular interest is the ability of the traversed lithologies to arch, possibly suggesting the ability of the 'soft rocks' to exhibit soil-like arching behaviour.

Table 2. Information from field measurements of pipe-jacking activities, and outcomes from back-analysis using Pellet-Beaucour and Kastner (2002) jacking force model

Drive			A	B
Lithology			Phyllite	Shale
RQD		[%]	17.5	14.0
Volume of injected lubricant		[L/m]	181	729
Volume of overcut		[L/m]	113	113
Jacking speed		[mm/min]	44	34
Cutter face diameter		[m]	1.82	1.82
Measured jacking forces	JF	[kN/m]	4.8	81.1
Vertical stress at pipe crown	σ_{EV}	[kN/m^2]	-14.4	12.4
Coefficient of pipe-rock friction	μ_{avg}	[-]	0.080	0.783

Note: Quantities reported above are typically average values across the respective pipe-jacking drive spans.

3.1 Drive A (Phyllite)

The encountered lithology at Drive A was metamorphic phyllite, exhibiting an average RQD of 17.5% across the 15.1 m of extracted cores. The pipe-jacking drive spanned 120 m through the highly weathered phyllite. The average measured jacking forces across the drive accrued at a rate of 4.8 kN/m. During typical tunnelling operations, decisions on jacking speed and lubrication are made in response to the jacking forces. As reported in Table 2, the average volume of injected lubricant was 181 L/m, into a theoretical overcut annulus of 113 L/m. There were also no significant stoppages in tunnelling works, and jacking progressed steadily at a speed of 44 mm/min. The 120 m drive was completed over 23 days. The injected lubrication and jacking speeds were expected responses to the steady increase in the jacking forces.

From the earlier developed values of $\phi_{t,p} = 46.2°$ and $c_{t,p} = 45.1$ kPa through testing on reconstituted phyllite spoils collected from Drive A, the resulting back-analysed values were $\sigma_{EV} = -14.4$ kN/m^2 and $\mu_{avg} = 0.080$. The back-analysed μ_{avg} was well below the μ values recommended by Stein (2005) for well-lubricated drives Fig. 2. This indicated that the lubrication for Drive A in phyllite was efficient. This was corroborated by the injected lubrication, which was only slightly in excess of the theoretical overcut volume. The back-analysed $\sigma_{EV} = -14.4$ kN/m^2 also indicated that there was significant arching over the tunnel, thus reducing the normal stresses on the outer periphery of the pipes. This was the case despite the poor RQD values. This suggests that the surrounding lithology had substantial contributions to the combined effects of the efficient lubrication and the significant arching, resulting in the low jacking forces measured at Drive A (Choo and Ong, 2015b, 2017; Ong and Choo, 2018).

3.2 Drive B (Shale)

Drive B traversed an initial 135 m section of stiff clay, followed by a latter 93 m section traversing shale. The current study is only focused on this latter shale section of Drive B. The traversed shale at Drive B exhibited an average RQD of 14.0% across the 6 m of extracted cores. The average measured jacking forces increased at a rate of 81.1 kN/m (Fig. 3), which was significantly larger than those measured from Drive A. The jacking forces also fluctuated significantly. The average volume of injected lubricant was 729 L/m which was 545% in excess of the theoretical overcut annulus of 113 L/m, suggesting there was significant loss of lubricant into the surrounding shale. There were no significant stoppages in tunnelling works.

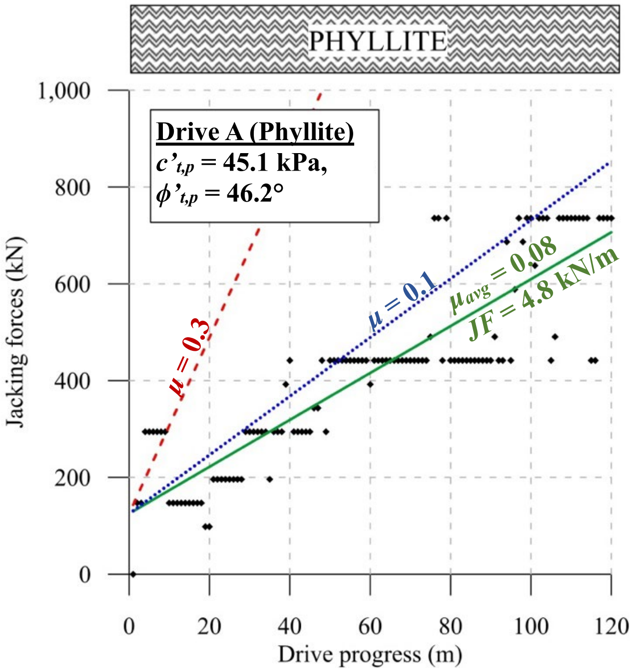

Fig. 2. Results from back-analysis of jacking forces for Drive A, showing back-analysed μ_{avg} against μ_{avg} values of 0.1 and 0.3

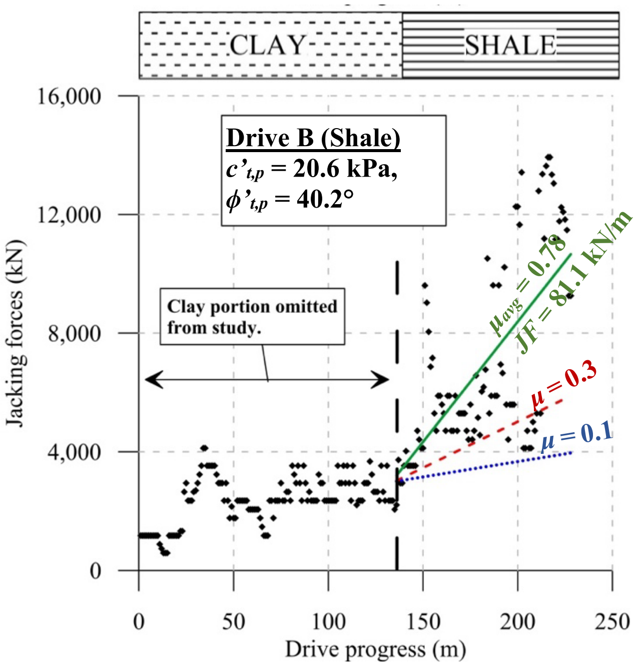

Fig. 3. Results from back-analysis of jacking forces for Drive B, showing back-analysed μ_{avg} against μ_{avg} values of 0.1 and 0.3

Jacking progressed steadily at an average jacking speed of 34 mm/min, which was slower than those measured in Drive A traversing phyllite. From earlier testing on reconstituted shale spoils retrieved from Drive B, the developed tangential MC parameters were $\phi_{t,p}$ = 40.2° and $c_{t,p}$ = 20.6 kPa. The resulting back-analysed vertical stress at the pipe crown was σ_{EV} = 12.4 kN/m^2. This suggests that there was some stress acting normally onto the outer periphery of the pipeline, indicating reduced arching as compared to phyllite from Drive A. The back-analysed pipe-rock frictional coefficient was $\mu_{avg} = 0.783$, which was significantly larger than $\mu = 0.3$ for well-lubricated drives. This indicated that the lubrication for Drive B in shale was significantly inadequate.

4 CONCLUSION

The absence of any reliable methods for assessing jacking forces in highly weathered lithologies necessitates the development of the methodology described in the current study. This paper has described how the methodology developed by Choo and Ong (2015b, 2017) and Ong and Choo (2018) have been used to successfully assess the jacking forces at two pipe-jacking drives traversing lithologies of highly weathered phyllite and shale, both of which exhibited low RQD values. The low RQD values prevented the extraction of intact rock cores. Therefore, tunnelling rock spoils were collected and subjected to direct shear testing. The nonlinear behaviour of the tested spoils have been used to develop tangential MC strength parameters, $\phi_{t,p}$ and $c_{t,p}$ which have been subsequently used for understanding the effectiveness of lubrication and arching in the studied drives. This paper concludes that equivalent MC parameters can be developed from reconstituted tunnelling rock spoils for the assessment of pipe-jacking forces. Furthermore, lithologies have substantial effects on the construction activities, particularly jacking speeds, lubrication usage, and ultimately jacking forces when pipe-jacking is performed through highly weathered rocks. This was due to the ability of the highly weathered lithologies to behave as ‘soft rocks’, which demonstrated the soil-like phenomenon of arching.

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