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A simple approach for characterising tunnel bore conditions based upon pipe-jacking data

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ABSTRACT

There are several well-established jacking force models available for determining the jacking loads. However, their ability to characterise the tunnel bore conditions is limited. A simple approach to characterise the tunnel bore conditions is proposed and applied to a case study where four sewer pipelines of the Shulin district sewer network in Taipei County, Taiwan were constructed to verify its validity. In this paper, four jacking force models are reviewed. Based upon the given soil properties and pipe dimensions as well as the pipe buried depth, the normal contact pressure (σ') in each jacking force model and the measured frictional stress (τ) in each baseline section are utilised for back-analysis of the frictional coefficient (μ_{avg}). The μ_{avg} values outside the range of 0.1–0.3 recommended for lubricated drives can be attributed to the increasing pipe friction resulting from excessive pipe deviation or ground closure or due to the gravel formation not being long enough to establish lower face resistance or total jacking load. JMTA (Japan Microtunnelling Association) has indicated a further potential use in assessment of the interface performance during pipe-jacking works.

1. Introduction

Jacking force prediction highly correlates with the design and selection of a pipe-jacking system (Chapman and Ichioka, 1999; Sofianos et al., 2004; Khazaei et al., 2004; Staheli, 2006; Barla et al., 2006; Shou et al., 2010; Rahjoo et al., 2012; Choo and Ong, 2015; Cui et al., 2015; Yen and Shou, 2015; Shen et al., 2016; Wham et al., 2016; Cheng et al., 2017a,b). There are many well-established jacking force models available for guiding to the provision of jacking capacity (Rogers and Yonan, 1992; Kastner et al., 1996; Pellet-Beacour and Kastner, 2002; Rahjoo et al., 2012). However, their ability to characterise the tunnel bore conditions is limited. As tunnelling through the permeable ground, ground closure can be regarded as one of the main factors to lead to some difficulties in estimating the jacking loads. Jet-grouting technology may be used to enhance the shear strength and watertightness of ground prior to tunnel excavation (Ni and Cheng, 2011a, 2014; Shen et al., 2017). Additionally, misalignment stands for the angular deviation between the central axes of successive pipes, and severe misalignment can lead to a significant increase in the friction resistance causing an increment of the jacking loads (Norris, 1992; Ni and Cheng, 2011b, 2012a; Kou et al., 2015; Namli and Guler, 2017).

In this study, a pipe-jacking data from four sewer pipelines of the Shulin district sewer network in Taipei County, Taiwan was analysed using the baseline technique. The specific objectives of this study are (i) to review four well-established jacking force models, (ii) to propose a simple approach that is capable of characterising the tunnel bore conditions, and (iii) to determine the tunnel bore conditions by comparing the back-analysed frictional coefficients to the recommended values.

2. Jacking force models

The four well-established jacking force models that were studied are: (i) Japan Microtunnelling Association (JMTA, 2000), hereinafter, referred to as JMTA, (ii) Ma Baosong (Ma, 2008), (iii) Shimada and Matsui (Shimada and Matsui, 1998), and (iv) Pellet-Beaucour and Kastner (Pellet-Beacour and Kastner, 2002). In the JMTA model, the resistance at the cutting wheel, F_0, is theoretically between active and passive earth pressure and can be empirically correlated to the blow count N-value (JMTA, 2000). The resistance along the pipe string, F_s, considers two components; one from the friction at the pipe-soil interface and the other from the pipe self-weight induced contact pressure. In the Ma Baosong model, the face resistance, F_0, has been assumed to be equal to the K_0 earth pressure against the cutting wheel, while the friction resistance, F_s, takes the earth pressure acting upon the

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Table 1
Review of jacking force models.

Jacking force model	Japan Microtunnelling Association (JMTA) (JMTA, 2000)	Ma Baosong (Ma, 2008)	Shimada and Matsui (Shimada and Matsui, 1998)	Pellet-Beaucour and Kastner (Pellet-Beacour and Kastner, 2002)
Face resistance (F_0)	$F_0 = 10 \times 1.32\pi \times D_e \times N$ where D_e = outer pipe diameter, N = blow count N value of soil	$F_0 = 1/4 \times \pi \times D_e^2 \times [K_0\Sigma(\gamma_i{}'h_i) + \gamma_w h_w]$ where K_0 = coefficient of static soil pressure, h_i = thickness of the soil in ith layer, $\gamma_i{}'$ = density of the soil in ith layer, h_w = distance of the groundwater table to the pipe axis, and γ_w = density of water	$F_0 = P_w \times A$ where P_w = slurry pressure, A = area of the tunnel face	F_0= initial jacking or first load
Friction resistance (F_s)	$F_s = \pi \times D_e \times \tau \times L + \omega \times \mu \times L$ where $\tau = c' + \sigma'\tan\delta$, $\sigma' = \gamma' \times (D_e/2)/\tan\phi'$, c' = soil cohesion, σ' = normal contact pressure acting upon the pipe, δ = angle of wall friction in plane of sliding, γ' = soil density, L = pipe string length, ω = pipe self-weight, and μ = frictional coefficient	$F_s = K \times [\mu \times (2P_V + 2P_H + P_B)]$ where $P_V = K_p \times \gamma' \times h \times D_e \times L$, $P_H = \gamma' \times (h + D_e/2) \times D_e \times L \times \tan^2(45° - \phi'/2)$, P_B = w× L, K = factor of safety (normally 1.2 is used), P_V = vertical pressure of soil above the top of the pipe, P_H = lateral earth pressure, P_B = total weight of planned jacking pipeline, and K_p = vertical earth pressure coefficient	$F_s = [p \times b \times \mu_1 + P_w \times \mu_2 \times (\pi D_2 - b)] \times L$ where b (contact width between the pipe and bore) = $1.6\times$ $(P_u \times k_d \times C_e)$ for which $P_u = (D_1^2 - D_2^2) \times \gamma_c \times 0.25 \times \pi$ where D_1 = diameter of bore, D_2 = outer diameter of pipe, γ_c = concrete density, $k_d = (D_1 \times D_2)/(D_1 - D_2)$, $C_e = (1-n_1^2)/E_1 + (1-n_2^2)/E_2$ where n_1 = poisson's ratio of soil, n_2 = poisson's ratio of concrete pipe, p (contact stress acting on the pipe bottom) = $2P_u \times [1-(x^2/a^2)]^{0.5}/(\pi \times a)$ for which a = b/2 and x = distance to either side of centerline of the area of contact	$F_s = \mu \times L \times D_e \times (\pi/2) \times [(\sigma_{EV} + \gamma D_e/2) + K_2(\sigma_{EV} + \gamma D_e/2)]$ where K_2 = thrust coefficient of soil arching acting on the pipe, with a suggested value of 0.3 (French Society for Trenchless Technology, 2006)
Normal contact pressure (σ')	$\sigma' = \gamma' \times (D_e/2)/\tan\phi' + \omega/(\pi D_e)$	$\sigma' = K_p \times \gamma' \times h + \gamma' \times \left(h + \frac{D_e}{2}\right) \times \tan^2(45° - \frac{\phi'}{2}) + \frac{\omega}{2 \times D_e}$	$\sigma' = 2P_u \times [1-(x^2/a^2)]^{0.5}/(\pi \times a)$	$\sigma_{EV} = \frac{b \times \left(\gamma - \frac{2 \times C}{b}\right)}{2 \times K \times \tan\delta} \times \left(1 - e^{-2 \times K \times \tan\delta \times \left(\frac{h}{b}\right)}\right)$ where b (influencing silo width) = $D_e \times \left[1 + 2\tan\left(\frac{\pi}{4} - \frac{\phi}{2}\right)\right]$