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A new model to predict soil pressure acting on deep burial jacked pipes

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ABSTRACT

Soil pressure is a critical factor to pipe jacking projects both during and after the jacking. Current practices are based on modifications of one of Terzaghi arching model, e.g. Japan Microtunnelling Association, German standard ATV A 161, UK 'Pipe Jacking Association', ASCE 27, and Chinese standard GB 50332. In these practices, it is assumed that shearing bands arise from the outside of tunnel cross sections and extend to the ground surface. However, the shearing bands may desist below the ground surface (This scenario is called deep burial). If these practices are still applied, the calculations will result in underestimations. In this paper, a new calculation model, modified from the other Terzaghi arching model was proposed to specifically predict the soil pressure acting on the deep burial jacked pipes. Values of crucial parameters of the height of the shearing bands, friction angle, friction coefficient, soil pressure ratio, silo width and soil cohesion were analyzed based on published tunnel research results and trap-door experiments. The correctness of the new model was verified by in-situ measured soil pressure in Gongbei Tunnel project in Zhuhai city. In comparison to the in-situ measured soil pressure, the new model provided more logical estimations, while the current practices were found to underestimate the soil pressure.

1. Introduction

Pipe Jacking has been widely used for new pipeline installations. Application areas involve oil & gas, water supply, sewage, communication and electricity pipelines, and pipe-roof projects (Ma and Najafi, 2008). Usually jacked pipes are glass Fibre Reinforced plastic Mortar Pipes (FRMP), concrete pipes, clay pipes, cast ductile iron pipes, and steel pipes.

For shallow burial jacked pipes, the jacking load will control the cross-sectional design of the pipe, and the soil pressure may be insignificant. However, for deep burial projects, high soil pressure may lead to the buckling of pipes (Zhen et al., 2014), then the soil pressure becomes a crucial factor. Soil pressure on jacked pipes was also invoked to estimate the jacking force (Pellet-Beaucour and Kastner, 2002).

In current practices, the soil pressure on jacked pipes is estimated upon soil pressure models in Japan Microtunnelling Association (JMA), German standard ATV A 161 (ATV A 161), UK 'Pipe Jacking Association' (PJA), ASCE 27, and Chinese standard GB 50332 (GB 50332) (Japan Microtunnelling Association, 2013; German ATV rules and standards, 1990; Pipe Jacking Association, 1995; ASCE, 2001; The Ministry of Construction of China, 2002). These soil pressure models are modified from one of Terzaghi arching models **(termed Arching model I)** (Terzaghi, 1943).

Similar modifications are used in ASTM F 1962 and British standard BS EN 1594 for pipes installed by horizontal directional drilling (HDD) (ASTM, 2011; British standards, 2009). A similar model, Marston soil pressure model, is used for pipes in open cuts, (Marston and Anderson, 1913). Although the equations of the Arching model I and Marston soil pressure model are similar, the kinematics of the shearing bands involved are different. The former is mobilized by unloading, while the latter is induced by differential settlement of upper soils.

In the Arching model I, it is supposed that the shearing bands arise from the outside of tunnel cross sections and extend to the ground surface. This assumption is proper for shallow burial pipe jacking projects, which are usually accompanied by the ground surface settlement. However, for some scenarios, the ground loss may be balanced by volume dilation of the upper soils. Thereupon, the shearing bands desist below the ground surface, and the ground surface is intact. Active trap-door experiments have revealed that the shearing bands progress as the trap-door falls (Ladanyi and Hoyaux, 1969; Costa et al., 2009; Iglesia et al., 2013). Therefore, the general assumption of fully developed shearing bands is improper. A more logical model should consider partially developed shearing bands.

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Nomenclature

List of notations

σ_z	soil pressure (kN/m^2)
q	surcharge load (kN/m^2)
σ_{Vh}	normal stress at the shearing bands (kN/m^2)
τ_V	shear stress at the shearing bands (kN/m^2)
c	soil cohesion (kN/m^2)
γ	soil unit weight (kN/m^3)
K	soil pressure ratio
K_0	soil pressure ratio at rest
K_a	active soil pressure ratio
ϕ	soil internal friction angle (°)
ϕ_c	critical friction angle (°)
ψ	dilation angle (°)
ΔV	unit soil volume increment (m^3)
V_0	unit soil volume (m^3)
Z	burial depth of a jacked pipe's crown (m)
Z_1	height of soil prism above the shearing bands (m)
Z_2	height of the shearing bands (m)
$H_1 \sim H_n$	soil stratum thickness from the top down (m)
D_b	tunnel borehole diameter (m)
D	shield diameter (m)
d	pipe diameter (m)
B_1	silo width (m)
B_n	silo width of the bottom soil stratum (m)
ω	ground loss caused by workmanship (m)
β	average soil volume bulking factor
$N_{63.5}$	values of Standard Penetration Test

The scenarios of the shearing bands desisting below the ground surface are defined as deep burial jacked pipes. Here, the "deep burial" is a relative conception. It does not mean the absolute burial depth is very larger, but means the height of the shearing bands is smaller than the burial depth. Larger absolute burial depth promotes the arising of the deep burial scenarios. Whether a jacked pipe is a deep burial depends on the ground loss, soil volume dilation, and the burial depth. This conception will be discussed further in the latter content.

An arching model involving the height of the shearing bands was also proposed by Terzaghi **(termed Arching model II)** (Terzaghi, 1943). However, how to calculate the height of the shearing bands is unknown in the Arching model II. Maybe, this is the reason why this has not been widely utilized.

In this paper, firstly, the deficiencies of the Arching model I and the current practices were highlighted in comparison with the Arching model II. Then a new calculating model modified from the **Arching model II** was proposed. Critical parameters of silo width, the height of the shearing bands, friction angle, friction coefficient, soil pressure ratio, and soil cohesion were determined. The in-situ soil pressure measured in Gongbei Tunnel Project in Zhuhai city was compared with the new model and the current practices. By comparison, the new model provided more logical estimations, while current practices were found to underestimate the soil pressure.

2. Terzaghi arching models and the current practices

2.1. Arching model I

The Arching model I is founded on active trap-door experiments (Terzaghi, 1936), and it has been widely used in tunnels. In this model, the shearing bands yield from two bottom corners of a tunnel's cross section along oblique lines. Then they turn to vertical lines after passing the level of tunnel's crown, and ultimately arrive at the ground surface as depicted in Fig. 1(a). The acute angle of the oblique lines to the horizontal is supposed to be $45^\circ + \phi/2$ based on the Mohr-Coulomb failure criteria. The soil prism weight acting upon the tunnel partially transfers to adjacent soils through mobilized shearing force. The mathematical equation of this model was derived from the limit equilibrium of a horizontal slice (Terzaghi, 1943):

$$\gamma B_1 dz - B_1 d\sigma_z - 2cdz - (2K\sigma_z \cdot \tan\phi)dz = 0 \tag{1}$$

Transforming this equation as:

$$\frac{d\sigma_z}{dz} = \gamma - \frac{2c}{B_1} - 2K\sigma_z \cdot \frac{\tan\phi}{B_1} \tag{2}$$

Eq. (2) is a single order ordinary differential equation. Integrating and using boundary condition at the ground surface ($\sigma_{z=0} = q$), soil pressure at any level is deduced as:

$$\sigma_z = \frac{1 - e^{-2K\tan\phi\frac{Z}{B_1}}}{2K\tan\phi\frac{Z}{B_1}} \cdot \left(\gamma - \frac{2c}{B_1}\right)Z + qe^{-2K\tan\phi\frac{Z}{B_1}} \tag{3}$$

Dividing Eq. (3) with the soil prism weight, and ignoring the soil cohesion as well as the surcharge load, then the soil arching coefficient is deduced, as shown in Eq. (4). The soil arching coefficient is unrelated to the soil prism weight.

$$\frac{\sigma_z}{\gamma Z} = \frac{1 - e^{-2K\tan\phi\frac{Z}{B_1}}}{2K\tan\phi\frac{Z}{B_1}} \tag{4}$$

2.2. Arching model II

As observed in active trap-door experiments, the shearing bands extend upward as the trap-door subsides. Before the shearing bands arrive at the ground surface, the soil prism above the shearing bands acts like a surcharge load, as depicted in Fig. 1(b). Thereupon, the surcharge load (q) in Eq. (3) is substituted by the upper soil prism weight. Ignoring the surcharge load and the soil cohesion, Eq. (3) was transformed to Eq. (5) (Terzaghi, 1943):

$$\sigma_z = \frac{1 - e^{-2K\tan\phi\frac{Z_2}{B_1}}}{2K\tan\phi\frac{Z_2}{B_1}}\gamma Z_2 + \gamma Z_1 e^{-2K\tan\phi\frac{Z_2}{B_1}} \tag{5}$$

Dividing Eq. (5) by the soil prism weight, one can deduce the soil arching coefficient:

$$\frac{\sigma_z}{\gamma Z} = \frac{1 - e^{-2K\tan\phi\frac{Z_2}{B_1}}}{2K\tan\phi\frac{Z_2}{B_1}}\frac{Z_2}{Z_1 + Z_2} + \frac{Z_1}{Z_1 + Z_2}e^{-2K\tan\phi\frac{Z_2}{B_1}} \tag{6}$$

Values of parameters (B_1, ϕ, K and c) are identical to those used in Eq. (3). However, the height of the shearing bands (Z_2) is unknown according to the Arching model II.

2.3. The current practices

As the Arching model I was applied by JMA, ATV A 161, PJA, ASCE 27 and GB 50332, values of parameters (B_1, ϕ, K and c) were re-calculated based on different understanding, as listed in Table 1.