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Earth pressure on shield excavation face for pipe jacking considering arching effect

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ABSTRACT

Pipe jacking is often used to install pipelines in congested urban areas or river crossings. The applied jacking force needs to be greater than the frictional resistance along the pipe and the face resistance. Lubricant slurries are usually employed to minimize the frictional resistance. Therefore, it is critical to estimate earth pressures acting on shield excavation face correctly. In this paper, the original Protodyakonov's arch model is modified to calculate the vertical pressure on deeply buried pipes. For shallow burial depth less than 5 m, the Terzaghi arching model is still applicable to estimate the vertical pressure. The soil prism in front of excavation face is divided into different zones to establish the force equilibrium. The calculated earth pressure is applied on top of soil wedges. The proposed analytical solution can analyze the stability of vertical and inclined excavation faces considering the influence of three-dimensional arching effect, as well as the contribution of soil cohesion. In the end, the effectiveness of the developed design framework is assessed by comparing calculations with experimental measurements of earth pressures on excavation face.

1. Introduction

As a representative alternative of trenchless technology, pipe jacking is attractive for use to install new pipelines especially in congested urban areas or river crossings. This construction technique can minimize excavation work as well as disturbance to ground traffic compared to conventional cut-and-cover methods. Different forms of pipes over 1.5 m in diameter and 30 m in length are commonly installed using the pipe jacking approach. Occasionally, much larger pipes can be installed using this technique, where Ji et al. (2017) reported a successful project of jacking a 3.5 m diameter reinforced concrete pipe in 1 km long below the Hunhe River in Shenyang, China. Pipe jacking has also been applied in pipe-roof projects, such as the excavation of the Xinle Ruins Museum metro station of Shenyang subway using 2 m diameter steel pipes (Yang, 2012; Yang et al., 2013), and the jacked roof using 1.62 m diameter steel pipes for the Gongbei tunnel (Zhang et al., 2016b).

Fig. 1 shows the schematics of pipe jacking. A launch shaft is excavated to fit guide frame, thrust wall, and main jacking station. Pipe segments are jacked consecutively behind a shield machine until it reaches a receiving shaft. The most important factor that influences the efficacy of a pipe jacking project is the determination of jacking force (Shou and Jiang, 2010). With the advance of shield machine, the applied jacking force F_J is reduced due to frictions mobilized between pipe segments and soils (e.g., shield friction F_S, pipe friction F_P, and edge resistance F_E), and the remaining force needs to be greater than the face resistance F_F.

$$F_J \geq F_F + F_E + F_S + F_P \tag{1}$$

Actually the jacking force needs to be designed adequately. If F_J is too large, pipe failure and ground heave could occur; if too small the advance speed will be reduced significantly, along with collapse at the excavation face (i.e., extremely dangerous for river crossings). The component of frictions at the soil-pipe interface can be minimized using lubricant slurries (Reilly, 2014; Reilly and Orr, 2017). It is therefore critical to evaluate the face resistance accurately.

Without considering arching effect, soil prism above the pipe will exert vertical pressures at the pipe crown as an increasing function of pipe burial depth. Actually the calculated vertical pressures could be conservative, since frictions will be mobilized between the soil column

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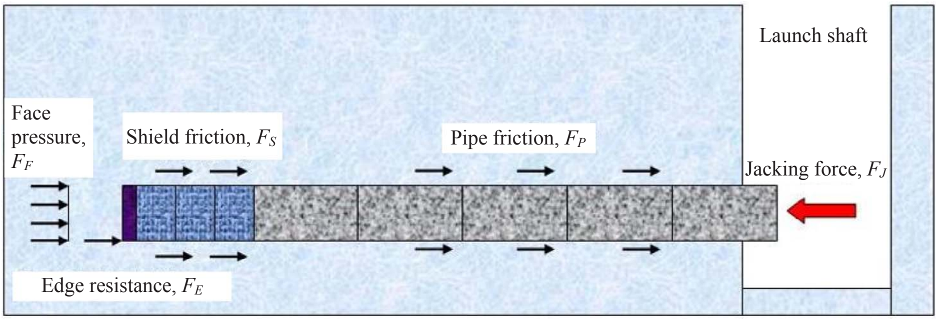

Fig. 1. Force equilibrium for pipe jacking.

above the pipe and adjacent soil columns. The Protodyakonov's arch theory was proposed in 1907, where a self-stable parabola was used to evaluate vertical pressures above a pipe, the details of which were summarized in Myrianthis (1975). Terzaghi et al. (1996) designed a trap-door test to demonstrate that soil arching did exist when relative displacement occurred within the soil. Due to mobilized shear resistance of soil, earth pressures acting on buried structures will be altered. In most current design guidelines (ATV-A 161 E-90, 1990; PJA, 1995; JMTA, 2000; ASCE, 2001; GB 50332-02, 2002), the Terzaghi arching model is still used by assuming that shear bands extend to a further distance outside the pipe diameter. Sladen and Oswell (1988) criticized the Terzaghi model especially on the assumption of geometry of the failure prism, and argued that the Terzaghi arching model can only produce reasonable estimates of earth pressures on the pipe at shallow burial depth within 5 m. In recent years, different arching models have been developed to better calculate the vertical pressures transferred from soil to burial structures, including the theory of silo (Röhner and Hoch, 2010), the layered stress arch system of 'stress arch bunch' (Huang and Zhang, 2012), the modified Protodyakonov's arch model (Yang, 2012; Yang et al., 2013), the homeostasis arch elliptic model for roadway controls (Huang and Liu, 2014; Huang and Zheng, 2016), the modified parabolic silo theory (Wu et al., 2015), and the modified Terzaghi arching model for deep burial jacked pipes (Zhang et al., 2016a).

The determined vertical earth pressure acting on the pipe can be subsequently used to estimate the face resistance. Limit analysis based on plasticity theory is often conducted by researchers. Leca and Dormieux (1990) followed the original assumptions of Davis et al. (1980), in which the upper and lower bound solutions for a sliding soil prism above a circular tunnel in purely cohesive ground were derived. The proposed design charts could be used to identify the limit states of face resistance for failure modes of face collapse and blow-out. Similarly, the failure modes of shield face in terms of face collapse and excessive ground heave were defined using two rigid cones and associated shear bands (Soubra, 2000). The impact of seepage force on the face stability was also investigated (Lee and Nam, 2001; Lee et al., 2003, 2004). Li et al., (2009) compared the calculations of an upper bound limit analysis with three-dimensional numerical simulations for the Shanghai Yangtze River Tunnel, and found consistent results of local failure and global failure in collapse and blow-out for the two analyses.

Alternatively, the force equilibrium based on silo theory can be established to evaluate the stability of shield face. Horn (1961) initially conceived the idea of dividing soil prims in front of shield face using three-dimensional wedges. Anagnostou and Kovari (1996) also used the equilibrium between soil wedges to assess the contribution of water pressure and effective pressure in the chamber. The developed normalized diagram for the assessment of tunnel face stability was revisited by Anagnostou (2012), where a prior knowledge of the distribution of horizontal stress was not needed any more. Broere (1998) considered the influence of time effect and seepage force on the stability of tunnel face. The mobilized earth pressure was found to be dependent of the soil displacement for retaining walls (Mei et al., 2009; Zhu and Zhao, 2014; Ni et al., 2017). Recent silo based models for tunnel face were derived by taking into account the influence of mobilized ground movement, where the arching effect in loosened soils at different regions was considered (Lei et al., 2010; Chen et al., 2013a; Lin et al., 2015; Wu et al., 2015).

To evaluate the proposed analytical solutions, numerical simulations and laboratory tests have been conducted. For example, Vermeer et al. (2002) studied the stability of tunnel heading in drained ground using nonlinear finite element analyses. Chen (2012) simulated the whole construction process of pipe jacking, with emphasis on the distribution of earth pressure on the shield face. Centrifuge tests were performed to understand the correlation between face pressures and ground deformations for tunnels in sands (Thorpe, 2007). Recently, transparent soils were used in model tests of shield tunnelling, where the associated soil movements could be measured directly (Ahmed and Iskander, 2012). Experimental efforts of conducting large-scale model tests on tunnel excavation was also reported in the literature (Chen et al., 2013b).

At present, the force equilibrium established for soil wedges based on silo theory cannot fully consider the influence of three-dimensional soil arching. The conventional Terzaghi arching model is only applicable to analyze vertical pressures on the pipe at shallow burial depth. In this investigation, the silo based model is refined by dividing the soil medium in front of excavation face into wedges and prisms. A modified Protodyakonov's arch model is proposed to estimate the vertical pressure of loosened soils above the pipe at deep burial depth. The calculation approach can consider both vertical and inclined shield faces. The effectiveness of the derived model is assessed by comparing estimated earth pressures with those measured in the laboratory.

2. Modified Protodyakonov's arch model for deeply buried pipes

The Terzaghi arching model for pipes buried at shallow depth assumed that failure planes initiate from the pipe springlines and propagate vertically to the ground surface with a width of one pipe diameter. This assumption has been successfully used to calculate loads acting on shallow buried pipes installed using the induced trench method (Sladen and Oswell, 1988). Alternatively, researchers derived new analytical models with a wider soil prism but the same vertical failure planes, some of which have been formulated in design guidelines (ATV-A 161 E-90, 1990; PJA, 1995; JMTA, 2000; ASCE, 2001; GB 50332-02, 2002). Zhang et al. (2016a) proposed a concept of the 'height of loosened soil' to evaluate the location where shear bands were diminished below the ground surface. They derived a formula for the 'height of loosened soil' as a function of soil volume bulking factors, overcut, and pipe misalignment, and found that 'deep burial' occurs generally when the burial depth is higher than 2 times the pipe diameter. Their calculation is similar to the estimation of the height of equal settlement plane above the pipe under high embankments (Qin et al., 2017). As a 'rule of thumb', Sladen and Oswell (1988) argued that the Terzaghi arching model is only applicable for pipes buried less than