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A jacking force study of curved steel pipe roof in Gongbei tunnel: Calculation review and monitoring data analysis

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ABSTRACT

Jacking force is one of the crucial parameters for pipe structure design, selection of pipe jacking machine and shaft structure design during jacking process. To predict the jacking force more accurately, this paper summarizes four calculation methods of curved jacking force. The Japan Micro Tunneling Association (JMTA) Method is based on Terzaghi arching theory with full contact between pipe and soil. However, according to the elastic contact theories, Hertz contact method, Shimada method and Persson contact method assume that pipe and soil contact partially in stable excavation cavity. The three methods are considering the influences of frictional resistance of pipe-soil and pipe-mud concurrently. By field monitoring of jacking force data in different types of soil and cover depth in the curved pipe jacking roof of Gongbei tunnel, the cutterhead resistance, dynamic and static frictional resistance have been analyzed. Also, the additional frictional resistance caused by stoppage effect has been presented. The results show that the mud pressure is more convenient to calculate the cutterhead resistance than active soil pressure. The Persson contact model is applicable to calculate the friction in stable condition of excavation cavity while the Shimada model is capable of predicting frictional resistance values for unstable condition.

1. Introduction

The pipe jacking force is an ongoing research topic since this technology has been invented and applied. It controls the pipe wall thickness, reaction structures of shafts, location and quantity of intermediate jacking stations, selection of jacking machine, and lubrication requirements. By reducing the jacking load, the risks of pipe and shaft wall damage can be minimized. Simultaneously, the project cost will be reduced significantly. Generally, in the process of pipe jacking construction, the total jacking force has been analyzed theoretically, is composed of resistance at the head of boring machine and friction around pipes. Many researchers have conducted both laboratory and field studies to understand the jacking force during linear pipe jacking. A series of pipe-soil interface behavior field tests and jacking fore calculation models were carried out (Haslem, 1986; O'Reilly and Rogers, 1987; Norris, 1992; Marshall, 1998; Pellet and Kastner, 2002; Sofianos et al., 2004), considering the parameters of soil conditions, pipe surface, depth, overcut size, pipe joint deflection, lubrication and stoppage. Most research results were applied by the pipe jacking standards and handbooks (PJA, 1995; ASCE, 2001; FSTT, 2006; JMTA, 2013).

Except the traditional linear pipe jacking, the curved pipe jacking has been used in the populous cities for the last two decades. The pipes are jacked as curve and pipe joints naturally opened in V-shapes. It can avoid a potential obstacle in the jacking path of initial design and reduce the number of shafts limited by the surrounding buildings. The curved jacking is more complicated than a linear one, not only does it require high quality guidance systems, but also it is hard to predict the eccentric jacking force accurately induced by the V-shape joints. The exaggerated eccentric jacking force will cause instability of the first pipe at the curve and make greater bending stress in the pipe (Nanno, 1996). It may lead pipe failure because of cracks in the pipe or particular spalling at the external pipe joint edge (Beckmann et al., 2007). However, the additional friction in the outside of curved area should be considered due to the lateral jacking force as well. It makes the curved pipe jacking force is more complicated to calculate and predict in practice.

Two main calculation methods, full contact model and partial contact model of pipe-soil, are used to predict the jacking force in practice based on the stability conditions of excavation cavity. In assumption of full contact model for an unstable excavation cavity, the JMTA empirical equation is the unique model used in practice to estimate curved jacking force (JMTA, 2013). The soil pressure acting on

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pipes is calculated by Terzaghi arching theory. Considering the additional lateral pressure and static soil pressure, a new jacking force model was deduced with static equilibrium method (Chen, 2008; Shou and Jiang, 2010), calibrated by JMTA empirical equation. By assuming the stable excavation cavity contribution of hard soil or lubrication mud pressure, the frictional resistance of pipe-soil and pipe-mud should be considered. Khazaei et al. (2004) utilized the Hertz contact theory to calculate the contact width. Subsequently, a modified model to calculate the curved jacking force was presented by Shimada et al. (2004) with assumption of 1/3 pipe-soil contact surface and 2/3 pipe-mud contact surface. Due to the deficiency of Hertz elastic contact theory, Zhang et al. (2017a,b) proposed a new jacking force calculation method by Persson contact model with considering effects of vertical pipe buoyancy, nonuniform contact pressure distribution and contact angle between pipe and soil.

In order to evaluate the applicability of curved pipe jacking force prediction models, a thorough literature review of calculation methods has been performed in this paper. With five fields monitored jacking force results selected in curved pipe roof of Gongbei tunnel, monitored cutterhead resistance and lateral frictional resistance are discussed and compared with that of calculated by the methods in literature review. Due to extremely overestimating jacking force and calibrated by JMTA method, the model presented by Chen (2008), Shou and Jiang (2010) is exclusive summary of the jacking force calculation methods. Actually, the calculated values of this method are the same with that of JMTA empirical equation.

2. Curved pipe jacking forces calculation models

2.1. Full contact model

2.1.1. JMTA method

If the excavation cavity is unstable, specially in loose soils, the collapsed soil will contact with the entire pipes. So, the soil pressure and frictional coefficient between pipe and soil will determine the frictional resistance (O'Reilly and Rogers, 1987). Compared to the linear jacking, the additional friction of outside components in the curved area will appear due to the lateral jacking force, which makes the process of theoretical jacking force estimation complicated and difficult to calculate in the field. By using Terzaghi arching theory (Terzaghi, 1943) to calculate the pipe-soil contact stress, an empirical model has been presented by JMTA to estimate the jacking force for a general curved pipe jacking (see Fig. 1).

$$F = (F_0 + f_1 L_1)K_1^n + \lambda f_1 L_c + f_1 L_2 \tag{1}$$

$$f_1 = (\pi D_p q + w)\mu_s + \pi D_p C_s \tag{2}$$

$$K_1 = \frac{1}{\cos\Phi - \mu_s \sin\Phi} \tag{3}$$

$$\lambda = \frac{K_1^{n+1} - K_1}{n(K_1 - 1)} \tag{4}$$

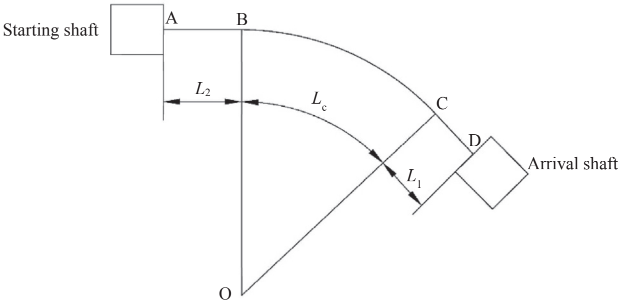

Fig. 1. The geometry feature of curved pipe jacking.

where n is the number of pipes. L_1 is the distance from curve end point C to the arrival shaft. L_c is the length of the curved segment. L_2 is the distance from the launch shaft to curve starting point B. f_1 is the pipe-soil frictional resistance per unit length in linear jacking. D_p is the pipe external diameter. q is the pipe-soil contact stress determined by Terzaghi arching theory. μ_s is the frictional coefficient of pipe-soil interface and empirically equal to $\tan(\varphi/2)$, where φ is the internal friction angle of natural soil. w is the pipe weight of unit length. C_s is the cohesion of pipe-soil interface. K_1 is the correction factor of curved segment. Φ is the deflection angle of pipe joint. λ is the resistance ratio of the curved to straight line.

There are two main methods in JMPA handbook to calculate the resistance at cutterhead F_o for slurry pipe jacking. One empirical formula is related to the SPT N-value as shown in Eq. (5), and the resistance of the other one is equal to balance pressure multiplied by cutterhead area as shown in Eq. (6).

$$F_0 = 13.2\pi D_t N \tag{5}$$

$$F_0 = (p_m + p_s)\pi D_t^2/4 \tag{6}$$

where D_t is external diameter of jacking machine. N is the SPT N-value. p_m is mud pressure acting on excavation face and equals to the ground water pressure plus 20 kPa. p_s is the soil cutting resistance. When $N < 15$, $p_s = 150$ kPa; when $15 \le N \le 50$, $p_s = 10.0 \times N$; when $N > 50$, $p_s = 500$ kPa.

2.1.2. Soil pressure calculation

In practice, most of pipe soil pressure calculation methods in pipe jacking or microtunnelling standards are based on Terzaghi model (PJA, 1995; ASCE, 2001; FSTT, 2006; JMTA, 2013; DWA, 2010). However, the calculation parameters vary among different methods, specially for some empirical parameters, such as K_0, φ and B_1, in which they determine the accuracy of the vertical soil calculation.

By comparison of experimental results and various analytical models, it has been demonstrated that the frictional resistance calculated by Terzaghi method is slightly larger than the measured friction values (Pellet and Kastner, 2002). Furthermore, the vertical stress calculated by JMTA is a little bit less than the Terzaghi model (H. Zhang et al., 2016). Therefore, the frictional resistance calculated by the JMTA model is closest to the reality. The JMTA approach is applied to calculate the soil stress on the pipes and has been shown in below. The equation of vertical soil pressure on pipe crown in the uniform stratum (see Fig. 2a) is shown as follows

$$q = \frac{B_1(\gamma - c/B_1)}{K_0\tan\phi}\left(1 - e^{-K_0\tan\phi\cdot\left(\frac{H}{B_1}\right)}\right) + p_0 e^{-K_0\tan\phi\cdot\left(\frac{H}{B_1}\right)} \tag{7}$$

$$B_1 = R_0\cdot\cot\left(\frac{\pi}{8} + \frac{\phi}{4}\right) \tag{8}$$

where q is the average soil pressure acting on the pipe. γ_n is the natural soil density. K_0 is soil horizontal lateral pressure coefficient, which is equal to 1. φ is the internal friction angle of natural soil. c is the cohesion of natural soil. B_1 is half ideal silo width of soil above the pipe. H is the height of overburden at pipe crown. p_0 is surface pressure of the ground and normally equal to 10kN/m^2. R_0 is the radius of excavation tunnel and equal to $R_p + 0.04$ m. R_p is the radius of pipe external.

In multiple stratums (see Fig. 2b), the soil pressure is accumulated one stratum by one stratum from the ground surface to pipe crown (JMTA, 2013).

$$\sigma_{v1} = \frac{B_1(\gamma_1 - c_1/B_1)}{K_0\tan\phi_1}\left(1 - e^{-K_0\tan\phi_1\cdot\left(\frac{H_1}{B_1}\right)}\right) + p_0 e^{-K_0\tan\phi_1\cdot\left(\frac{H_1}{B_1}\right)} \tag{9}$$

$$\sigma_{v2} = \frac{B_1(\gamma_2 - c_2/B_1)}{K_0\tan\phi_2}\left(1 - e^{-K_0\tan\phi_2\cdot\left(\frac{H_2}{B_1}\right)}\right) + \sigma_{v1} e^{-K_0\tan\phi_2\cdot\left(\frac{H_2}{B_1}\right)} \tag{10}$$