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Horizontal directional drilling pulling forces prediction methods – A critical review

Liangxue Cai[a,b,c], Guangli Xu[a,b], Maria Anna Polak[c,*], Mark Knight[c]

[a] School of Petroleum Engineering, Southwest Petroleum University, Chengdu 610500, China
[b] Oil & Gas Fire Protection Key Laboratory of Sichuan Province, Chengdu 611731, China
[c] Department of Civil Engineering, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada

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ABSTRACT

This work is motivated by the need for prediction of pulling forces during pulling back phase in the horizontal directional drilling (HDD) installations for steel or polyethylene pipe. Six current prediction models are reviewed and components of pulling force resistance used in calculations are discussed. Two HDD installations are used to evaluate the accuracies of six models, including a 1816.2 m steel pipe crossing of the Yangtze River, Nanjing, China, and a 200 m polyethylene pipe installation at the University of Waterloo, Waterloo, Canada. Comparison of the results show that Driscopipe method and Drillpath method underestimate the maximum pulling forces in both steel pipe and polyethylene pipe cases, ASTM F 1962 method underestimates the maximum pulling force in steel pipe case while PRCI method and NEN 3650 method overestimate the maximum pulling force in polyethylene case, PRCI method, NEN 3650 method and developed PipeForce method are suitable for steel pipe case, ASTM F 1962 method and the PipeForce method are acceptable for polyethylene pipe case.

1. Introduction

Horizontal directional drilling (HDD) technology has made great progress since the first HDD rig was built in 1964 (Mohammad and Sanjiv, 2004). At present, the maximum push-pull capacity of drill rig reaches 600t and the applicable formations extend from clay and sand to gravel, permafrost (Hair, 2011) and part of rock. HDD becomes more and more popular for installations of telecommunication cables, natural gas transmission and distribution network, oil and gas pipelines, water pipes and power cables (Yan, 2010). In the application of HDD technology, calculation of pulling forces is an important issue, which provides the basis for the design of a crossing project, selection of drill rigs, prediction of the pipe's stress during and after construction, and development of drag reduction technology. Several methods and modified versions (Driscopipe, 1993; Drillpath, 1996; Huey et al., 1996; NEN, 2003; ASTM, 2011; Cheng and Polak, 2007; Cai et al., 2012) of predicting pulling forces are proposed while there are still many difficulties to guarantee the accuracy and reliability of prediction results for various crossing projects (Bamert and Allouche, 2002; Francis et al., 2004), since HDD technology has a wide range of application, where installation lengths vary from dozens of meters to thousands of meters, pipe's diameters change from dozens of millimeters to over 1000 mm, materials of pipe include steel and nonmetal.

This paper reviews six models used in the design of HDD crossing projects, including Driscopipe method, Drillpath method, PRCI method, NEN 3650 method, ASTM F 1962 method, and prediction model developed by Polak and Cheng (2007) called PipeForce 2005. Brief introductions of these models are given herein and the current state of the art in determining values for inputting parameters is discussed. Two HDD installation cases including a steel pipe crossing and a polyethylene pipe crossing are used to evaluate the accuracies of prediction results for six methods.

2. Models for calculating pulling forces

2.1. Driscopipe method

Driscopipe method is a simple calculation procedure to predict the pulling forces during an HDD installation. It assumes the profile of borehole is composed of a series of straight lines linked together. Based on the length and angle of each line segment, frictional resistance between borehole and pipe inside borehole, frictional resistance between ground surface and pipe outside borehole, and buoyancy of the pipe inside borehole, which acts as a resistance when its direction is opposite to the pulling direction while a driving force when these two directions are same, are analyzed. The pulling force, denoted by T_h, to pull pipe

* Corresponding author.
E-mail address: polak@uwaterloo.ca (M.A. Polak).

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through the borehole can be calculated by summing resistances exerted on each pipe segment:

$$T_h = \sum_{1}^{i} wL(\mu\cos\theta \pm \sin\theta) \quad (1)$$

where i is the number of straight line segments; w is the net weight of per unit of pipe considering gravity of pipe and filled contents, buoyancy (N); L is the length of segment (m); μ is the friction coefficient, referring to friction coefficient between ground surface and pipe outside borehole, and friction coefficient between borehole and pipe inside borehole; θ is the angle between segment and horizontal line (rad).

The method is recommended to be used for polyethylene pipes and the following resistances exerted on pipe during HDD installation are not considered: (1) the resistance due to the Capstan Effect, i.e. the friction resulted from the normal reaction force led by component force of tensile force in the normal direction when the pipe is pulled through a corner, (2) the resistance due to pipe bending when the pipe is pulled through a corner, (3) fluidic drag friction induced by viscous slurry.

2.2. Drillpath method

Kirby et al. (1996) developed a computer program for the Gas Research Institute to design the profile of pilot bore and predict the pulling forces for plastic or steel pipes installed by HDD technology. The calculation procedure of pulling forces is proposed by Johancsik et al. (1984) for predicting the torque and drag of drilling string in directional oil wells, in which the normal contacting force is caused by the gravity of pipe and the tensile force to pull the pipe through curved borehole while Kirby et al. modified it by considering the Capstan Effect. The model assumed the pipe is made of short segments connected by joints that transmit tension and compression. The normal force N exerted on each segment can be calculated by

$$N = [(T\Delta\phi\cos\theta_N)^2 + (T\Delta\theta + W\cos\theta_N)^2]^{1/2} \quad (2)$$

and then the tension increment for each segment is given by:

$$\Delta T = e^{f(|\Delta\theta|+|\Delta\varphi|)}(-W\sin\theta_N + fN + T) - T \quad (3)$$

where N is the normal force (N); T is the axial tension force (N); $\Delta\varphi$ is the increment of azimuth angle (rad); θ_N is the inclination angle of segment at application of the normal force N (rad); $\Delta\theta$ is the increment of inclination angle (rad); W is the net weight of pipe segment (N); f is the friction coefficient.

Eqs. (2) and (3) are used for curved segment, as well as straight segment by letting both $\Delta\varphi$ and $\Delta\theta$ are zero. The tension increments can be calculated and summed to produce the total pulling force.

2.3. PRCI method

Huey et al. (1996) presented a calculation method to predict the maximum pulling force for a steel pipe installed using HDD technology. The maximum pulling force is assumed to occur at the moment when the pipe emerges from the pipe exit point and the tension applied on pipe at the pipe entry point is equal to zero at the time. Based on the assumption of the final diameter of borehole being 300 mm larger than that of the pipe, the designed profile of pilot bore is broken into straight sections and curved sections in the two-dimensional plane, axial loads resulting from frictional drag, fluidic drag, gravity, or pipe stiffness applied on each pipe section are calculated from pipe entry to pipe exit point, the cumulative axial tension applied on pipe at the pipe exit point is the required maximum pulling force.

The following equations were proposed for straight sections:

$$T_2 = T_1 + |frict^1| + DRAG \pm wL\sin\theta \quad (4)$$

$$frict^1 = wL\cos\theta\mu_{soil} \quad (5)$$

$$DRAG = \pi DL\mu_{mud} \quad (6)$$

where T_2 is the tension applied on end of pipe section required to pull pipe (N); T_1 is the tension applied on end of pipe acting as a resistance for the pipe movement (N); *frict* is the friction between pipe and soil; *DRAG* is the fluidic drag between pipe and viscous slurry (N); w is the net weight of per unit of pipe considering gravity of pipe and filled contents, buoyancy (N/m); L is the length of pipe section (m); θ is the angle of the axis of borehole section relative to horizontal line (rad); μ_{soil} is the average frictional coefficient between pipe and soil, values between 0.21 and 0.30 were recommended; D is the outer diameter of pipe (m); μ_{mud} is the fluidic drag coefficient, recommended value 345 Pa (0.05 psi).

For curved sections, tension required to overcome resistances is calculated by:

$$T_2 = T_1 + 2 \times |frict^2| + DRAG \pm wL_{arc}\sin\theta \quad (7)$$

$$frict^2 = N\mu_{soil} \quad (8)$$

where L_{arc} is the arc length of pipe section (m); N is the normal reacting force between pipe and soil at the center of pipe section (N), an iterative calculation is needed to determine N using elastic beam equations.

2.4. NEN 3650 method

Netherlands Standardization Organisation (NEN) proposed a method to calculate pulling forces in its published standard NEN 3650 – 1. Frictions exerted on the pipe which is located in three different regions, i.e. ground surface, straight section and curved section of borehole, are calculated separately, denoted by T_1, T_2, and T_3. The friction between the pipe and the roller system or the ground surface is treated as T_1. The friction due to the drilling fluid and the friction between the pipe and the borehole wall are two components for the frictional resistance T_2 exerted on the pipe inside straight borehole. In analysis of T_3, same frictional resistance as T_2, friction resulted from pipe bending, and friction due to Capstan Effect are calculated, denoted by T_{3a}, T_{3b}, T_{3c} separately. The total pulling force is equal to the sum of three friction components.

$$T_1 = f \times L \times g \times f_1 \quad (9)$$

$$T_2 = f \times L_2 \times (\pi D_o \times f_2 + g_{eff} \times f_3) \quad (10)$$

$$T_{3a} = f \times L_b \times (\pi D_o \times f_2 + g_{eff} \times f_3) \quad (11)$$

$$T_{3b} = f \times 4 \times \frac{q_r}{2} \times D_o \times \frac{\pi}{\lambda} \times f_3 \quad (12)$$

$$T_{3c} = f \times L_B \times g_t \times f_3 \quad (13)$$

where f is a total factor of 1.4 or 2.0, for normal crossing cases or cases with gravel layer; L is the length of the pipe outside borehole (m); g is the weight of the pipe per unit length (N/m); f_1 is the friction coefficient between the pipe and ground surface, 0.3 is recommended while 0.1 is used when the roller system is adopted; L_2 is the pipe length in a straight section of borehole (m); D_o is the outside diameter of the pipe (m); f_2 is the viscous friction due to drilling fluid, 50 Pa is suggested; g_{eff} is the net weight of the pipe considering the buoyancy force (N/m); f_3 is the friction coefficient between the pipe and the borehole wall, $f_3 = 0.2$; L_b is the length of the bend (m); q_r is the maximum soil reaction near the end of the bend (N/m^2); L_B is the chord of the bend (m); g_t is the thrust force (N/m).

2.5. ASTM F1962 method

ASTM F1962 method is a calculating procedure for estimating pulling forces given by the American Society for Testing and Materials in its published standard ASTM F1962-11. In this model, several assumptions are used to derive the equations, namely: pipe bending effect