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# Horizontal directional drilling: State-of-the-art review of theory and applications

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## ABSTRACT

Historically, new underground utility pipelines have typically been installed by traditional open-cut methods, which sometimes results in environmental impacts or damage to existing infrastructure such as roadways and other surface structures. Furthermore, open-cut construction possesses challenges for installing pipelines beneath water bodies such as rivers and lakes. Horizontal Directional Drilling (HDD) provides a method for installing underground utility pipelines in conditions where open-cut methods are unsuitable. The adoption of HDD has increased over the past decade, as new pipelines are being installed in crowded urban areas. Subsequently, researchers have sought to develop basic engineering theoretical models and technological innovations to further increase its adoption. This paper provides a state-of-the-art review and evaluation on trends in the theoretical development of pullback loads, borehole stability and borehole mud pressure estimation models. Innovative techniques and new pipe materials are discussed that have served to expand the technological envelope of HDD.

## 1. Introduction

Horizontal Directional Drilling (HDD), with origins in the oil and gas industry, is a trenchless technology employed to install underground pipelines with minimal impacts on the environment or damage to existing infrastructure such as roadways and other surface structures. The process starts with the surface launched drilling of a pilot hole along the designed design path at an entry angle of 8–16° by a drill rig. The initial pilot bore is subsequently enlarged with a series of different diameter reamers before the product pipe is installed as shown in Fig. 1 (Ariaratnam and Lueke, 2002). During the drilling process, the contractor uses high performance drilling fluids to transport the drill cuttings to the surface, maintain borehole stability, and cool the drill bit (or reamers). The first installation using HDD was in 1971 for a crossing of the Pajaro River in Watsonville, California to install a 187.5 m steel natural gas pipe. Today, with the development of HDD innovations, it has become an important and effective method for pipeline installation for different uses including product oil, natural gas, water, sewer, electrical and telecommunications (Ma and Najafi, 2008).

In HDD practice, there are three main engineering concerns: (1) Pullback Load; (2) Borehole Instability; and (3) Mud Pressure Prediction. Since the pullback load balances the resistance forces during pipe installation, it becomes a key parameter in selecting the appropriate drill rig and evaluating the pipe stress level during pullback (Chehab, 2008). Borehole instability is the main reason that caused the mud loss, and it is related to the borehole mud pressure. When the borehole pressure exceeds the maximum allowable pressure of the soil, failure of the soil initiated, and the mud in the annular space region will erode into the overburden accordingly. With the development of soil failure, a considerable amount of mud will be lost, which is called a “hydro-fracture” or “blow-out” (Xia and Moore, 2006).

This paper provides a state-of-the-art review and evaluation on trends in the theoretical development of pullback loads, borehole stability and borehole mud pressure estimation models. It then discusses new techniques that improve the efficiency of HDD.

## 2. Development of HDD theory

### 2.1. Pullback load estimation

The pullback load balances the resistance forces during pipe installation using HDD. It is a key parameter for selecting a drill rig with appropriate pullback capacity and evaluating the stresses during product pipe installation. Therefore, it is necessary to accurately estimate the anticipated pullback load when designing HDD projects. The key resistance forces during pullback include: (1) resistance force between

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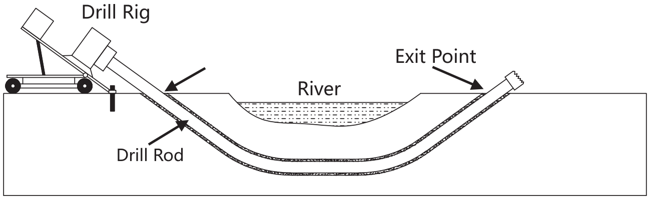
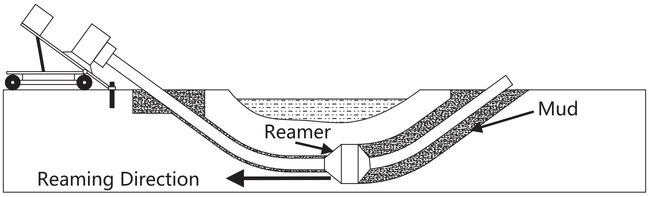
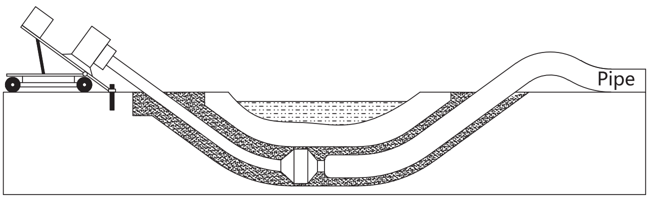


**(a)** Pilot hole drilling



**(b)** Reaming process



**(c)** Pullback process

**Fig. 1.** Horizontal directional drilling process.

pipe and ground surface and borehole wall (caused by gravity and buoyancy of pipe); (2) resistance force at the curves (caused by Capstan effect and bending/stiffness effect); and (3) drag force of drilling fluid (caused by its viscosity).

### 2.1.1. *Components of pullback load*

*2.1.1.1. Resistance force between pipe and ground surface.* The product pipe is on the ground surface prior to being pulled into the borehole. When the pullback process starts, the product pipe begins to transcend into the borehole and incurs a reverse friction force as a result of the interaction between the pipe and ground surface as illustrated in Fig.2.

The ground friction is maximum at first, but then decreases as more pipes are pulled into the borehole. This ground friction is based on the Coulomb Friction law and can be expressed as:

$$T_g = (w_p g \mu_g \cos\beta_0 + w_p g \sin\beta_0) L_g \tag{1}$$

where $T_g$ is the ground friction force, $w_p$ is the pipe weight per unit length, $\beta_0$ is the angle of ground surface, $L_g$ is the total length of pipe lying on the ground surface, $\mu_g$ is the friction factor between pipe and ground surface (ranges from 0.1 to 0.5, depend on the pipe material and roughness, ground surface condition, Baumert and Allouche, 2002; Baumert et al., 2004). In practice, constructors usually use rollers, slings or even water ditches to minimize friction (Fig. 3), and thus $\mu_g$ could be as small as 0.1 (ASTM F 1962 – 99).

*2.1.1.2. Resistance force between pipe and borehole wall.* When the product pipe is pulled into the borehole, the interaction between the pipe and borehole wall produces a resistance force that counters movement of the pipe. The drill path is not a perfect horizontal line or a skew line, and therefore can be assumed to be a polyline comprised by several skew lines ($L_{b1}$, $L_{b2}$…$L_{bi}$…). The resistance force for one skew segment includes: (1) friction force between pipe and borehole wall; and (2) the net buoyancy force component along the pipe axial direction as illustrated in Fig.4.

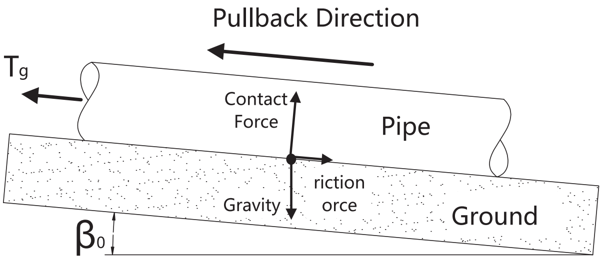


**Fig. 2.** Resistance force between product pipe and ground surface.

The total borehole resistance force is the sum of all skew segments resistance forces as shown in Eq. (2):

$$T_b = \sum_{i=1}^{k} (|w_b g \mu_b \cos\beta_{bi} L_{bi}| + w_b g \sin\beta_{bi} L_{bi}) \tag{2}$$

where $T_b$ is the borehole resistance force, $w_b$ is the net buoyancy force per unit length, $\beta_{bi}$ is the pipe inclination to horizontal of the pipe segment $L_{bi}$, $\mu_b$ is the friction factor between pipe and borehole wall (the suggested values for this variable range from 0.21 to 0.3 (Maidla and Wojtanowicz, 1987; Driscopipe, 1993)). The suggested values for HDPE pipe and the borehole range from 0.2 to 0.5 (El Chazli, 2005; Rabiei et al., 2016). In practice, product pipes may be filled with water for additional weight to reduce friction and lower the contact pressure caused by buoyancy within the borehole, especially when crossing water bodies.

*2.1.1.3. Resistance force at the curves.* Resistance force at the curves is produced by capstan and bending (stiffness) effects. When the product pipe is pulled crossing a curve section, the direction of the pull force changes, resulting in an increase in the contact pressure between the pipe and borehole wall. The increase in frictional force at the curve section is referred to as the Capstan effect (Fig. 5) (Lasheen and Polak, 2001). In addition, because of the flexural rigidity of the product pipe, the increasing bending stress will also result in an increase of normal force between the pipe and borehole wall during crossing of curve sections. The frictional force increases and is referred to as the bending/stiffness effect (Fig. 6) (Huey et al., 1996). The capstan effect usually occurs in flexible pipe, while the bending effect is more prevalent in large diameter steel pipes (ASTM F 1962-05).

Assuming the capstan effect and bending effect are independent, and the borepath does not change during pullback, the resistance force caused by the capstan effect can be shown in Eq. (3) (Chehab, 2008):

$$(T_b)_i = (T_b)_{i-1} e^{\mu_b \cdot \Delta\beta} \tag{3}$$

where $(T_b)_i$ and $(T_b)_{i-1}$ are the tensile forces before and after the curve, respectively, and $\Delta\beta$ is the curve angle.

Based on the mechanics of materials, the additional force caused by the bending effect was investigated by various researchers (Dareing and Ahlers, 1991; Polak and Lasheen, 2001; Polak and Chu, 2005). Assuming the borehole is rigid, and the contact pressure between pipe and borehole wall is concentrated, the resistance force related to the bending effect can be calculated using Eq. (4). In reality, the contact force between the pipe and borehole wall is a non-uniform pressure acting on a contact area around the middle span of the curved section (Hair, 2002).

$$T_{bc} = \frac{3\mu_b E_p I_p}{L_{bc}^2} \frac{(\Delta\beta)^2 \cdot \left(1 + 4\cos\frac{\Delta\beta}{2}\right)}{\sin(\Delta\beta) \cdot \left(1 + \cos\frac{\Delta\beta}{2}\right)} \tag{4}$$

where $T_{bc}$ is the additional force caused by bending effect, $L_{bc}$ is the curved length, $E_p$ is the elastic modulus of pipe material, $I_p$ is the moment of inertia of the pipe ($I = \pi(D_{op}^4 - D_{ip}^4)/64$), $D_{op}$ is the outer diameter of pipe and $D_{ip}$ is the inner diameter of pipe.

*2.1.1.4. Drag force of drilling fluid.* When the product pipe is pulled through the borehole, the relative movement between pipe and viscous drilling fluid produces a drag force as illustrate in Fig. 7. Huey et al.