Drilling Fluid Considerations in Design of Engineered Horizontal Directional Drilling Installations

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Abstract: A literature review is presented that identifies a number of areas where procedures for the engineering design of bored installations in soil using horizontal directional drilling (HDD) can be improved through a more realistic consideration of drilling fluid drag effects and skin friction coefficients. The current HDD practice of calculating annular frictional pressure loss caused by drilling fluid drag based on the assumption of concentric annular flow of a Bingham plastic fluid is demonstrated to be overly conservative. Consequently, critical design parameters, such as depth of cover, which affects crossing length, and drilling equipment size, which is selected based on anticipated pulling load, cannot be optimized. This can result in overly conservative design and unnecessary construction costs. Parameter values currently employed in HDD pulling load prediction are challenged suggesting that the viscous shear of drilling fluid is significantly less than typically quoted and that the friction coefficients often employed are not representative of all skin friction effects in HDD. A new real-time monitoring cell for large-scale HDD is described that can be used to optimize installations and to assess and update current prediction models.

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Introduction

An analysis of small nonengineered commercial horizontal directional drilling (HDD) installations was presented by Baumert et al. (2003). An important observation made was that a clean borehole was not achieved in the majority of these installations. This led to the proposal of an empirical design approach for predicting HDD pull loads based on a combination of the expected degree of construction effort—high, medium or low, and the most likely soil type to be encountered—gravely, sandy, silty, or clayey soil. A sample design table for selected soil types was proposed with "pull load coefficients" (expressed in kiloNewtons/meter) derived based on field results for steel and polyethylene pipes with external diameters between 200 and 300 mm. Extensive data collection on a wide variety of HDD installations would be required to complete a full range of design tables for different pipe product types [steel, high density polyethylene (HDPE), polyvinyl chloride (PVC)] and pipe diameter ranges.

The aforementioned paper also presented some preliminary drilling fluid pressure monitoring results during pipe installation. In these cases drilling fluid pressure was monitored between the reamer and pipe pull head during the pipe pullback operation. The pressure results were analyzed primarily in terms of their contribution to the total tensile load measured by the monitoring cell. It was found that a component of the tensile load measured by the load cell could be attributed to the borehole pressurization that exists in the space between the reamer and the pull head. For small-scale installations this load can comprise a significant portion of the total measured tensile load.

While some of the insight gained by studying small-scale HDD installations can be applied to large-scale engineered crossings, the latter is an area that merits a focused research effort. In these crossings, the ability to understand and control fluid pressure is critical to installation success, more so than in small-scale crossings due to the installation length (often greater than 500 m) and depth (commonly 20–35 m). An accurate prediction of pulling loads is also important for proper rig sizing. The few drilling rigs in North America that have thrust capabilities over 2,225 kN are widely dispersed. The ability to properly size the rig can translate into substantial savings in both mobilization and operational costs (Baik et al. 2003). On large-scale HDD installations the construction effort needed to create the borehole itself, and the cost associated with the procurement and fabrication of the pipe string, results in a financial risk substantially higher than that associated with small-scale installations. Thus, more elaborate design and monitoring efforts are warranted. Finally, a high level of construction effort is normally expended on large-scale installations to ensure a clean, open borehole, a critical requirement for minimizing installation risk. This level of construction effort results in a different physical environment in the borehole compared to small-scale installations, where the portion of the spoil removed from the borehole tends to be significantly lower.

This paper presents a literature review that covers fluid pressure topics pertinent to HDD and examines the origin of the borehole friction coefficients and drilling fluid viscous shear factors

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Fig. 1. 670 kN capacity loadcell attached to 406 mm diameter pullhead

used in HDD pulling load prediction. The review provides the necessary background to support field investigation of large-scale HDD installations using new monitoring technology that provides real-time fluid pressure and load measurement (Fig. 1). The paper is presented in seven sections. The first section presents a review of drilling fluid basics, starting with basic rheology terminology and moving progressively to solutions for concentric annular flow. The second section presents a state-of-the-art review of drilling fluid pressure topics in HDD. During the literature review it was found that the breadth of research conducted in the field of HDD is dwarfed by research conducted in the oil drilling industry that has potential application to HDD, and this is reflected in the two subsequent sections: the third section which considers numerical solutions for eccentric annular flow, drawing heavily on oil industry research, particularly in the area of cuttings transport in extended reach horizontal wells; and the fourth section that describes the oil industry origins of the borehole friction coefficients that are currently accepted as the industry standard in HDD practice. The fifth section summarizes the implications of the literature review on the calculation of HDD pulling loads. The sixth section introduces the concept of real-time drilling fluid pressure monitoring as a tool to assist in prediction model assessment and development, and as a tool for optimizing large-scale HDD construction practices. The paper closes with a summary and conclusions.

Drilling Fluid Rheology

Basic Terminology

Rheology is defined as the science and study of the deformation and flow of matter, including its elasticity, plasticity, and viscosity. The term is also used to describe the properties of a given fluid. Drilling fluid rheology thus refers to the rheological properties of a given drilling fluid mixture.

Viscosity, designated by the symbol μ (CP) is an important rheological property that influences a fluid's resistance to flow. A centipoise (CP) is 1/100 of a poise (P) and is equal to 0.001 $N/s/m^2$. The viscosity of water at 20°C is approximately 1 CP. Viscosity is defined as the ratio of viscous shear stress τ to shear rate γ

$$\mu = \tau/\gamma \text{ (CP)} \tag{1}$$

where the shear rate γ in inverse seconds (1/s)=velocity gradient measured perpendicular to the fluid flow (d_u/d_r in Fig. 2) and the viscous shear stress τ (N/m^2)=force per unit area required to move the fluid at the given shear rate. Fluids for which the shearing stress τ is linearly related to the shear rate γ are called Newtonian fluids. Fluids that do not meet this criterion are designated non-Newtonian fluids, with most drilling fluids falling in this second category.

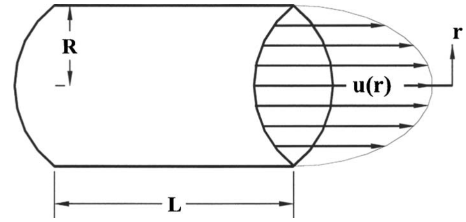

Fig. 2. Axisymmetric flow in pipe

The instrument used to measure viscosity is the viscometer. The instrument typically consists of a rotational cylindrical cup with a stationary bob. The cup is filled with a drill fluid sample and is then rotated at various angular speed settings (typically six: 3, 6, 100, 200, 300, and 600 rpm) with the torque exerted on the bob measured for each rotational speed.

Newtonian Pipe Flow

Referring to Fig. 2, for a pressure drop ΔP in Pascals (Pa=1 N/m^2) over a length of pipe L (m) and pipe inner radius R (m), the velocity distribution $u(r)$ (m/s) can be described by

$$u(r) = [\Delta P/4\mu L] \cdot (R^2 - r^2) \text{ (m/s)} \tag{2}$$

the volume flow rate $Q(m^3/s)$ can be expressed as

$$Q = \pi R^4 \Delta P/8\mu L \text{ (m}^3\text{/s)} \tag{3}$$

and the viscous shear stress $\tau(r)$ (Pa) at radial distance r (m) can be calculated from the following equation:

$$\tau(r) = r\Delta P/2L \text{ (Pa)} \tag{4}$$

Eq. (4) applies for steady laminar flow in circular pipes whether the fluid rheology is Newtonian or not.

Non-Newtonian Rheological Models

Most drilling fluids are non-Newtonian with their shear behavior characterized by one of the following three idealized rheological models:

Bingham Plastic Model

The Bingham plastic model assumes that fluid motion will not begin until stresses exceed the fluid's yield stress τ_y (Pa)

$$\tau = \tau_y + \mu \cdot \gamma \text{ (Pa)} \tag{5}$$

This model is frequently used to describe drilling fluids in HDD. Eq. (5) is often written as

$$\tau = \text{YP} + \text{PV} \cdot \gamma \text{ (Pa)} \tag{6}$$

where YP=yield point and PV=plastic viscosity. In a moving Bingham plastic fluid a "plug flow," moving as a solid body, is assumed to occur below a "plug radius" R_p (m) defined by

$$R_p = 2\tau_y L/\Delta P \text{ (m)} \tag{7}$$

Most drilling fluids are not fully Bingham plastic fluids. While the Bingham plastic model simulates the shear behavior of drilling fluids in the higher shear rate range (300–600 rpm), the model is inadequate in the low shear rate range, which is the area of inter-

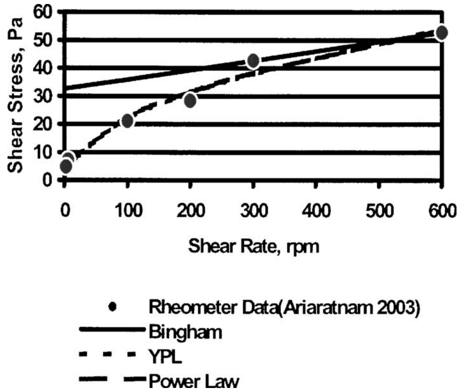

Fig. 3. Viscometer data fit with three rheological models: Bingham plastic, power law, and yield-power law

est for simulating annular flow behavior. As a general rule, shear stresses measured at high shear rates are usually poor indicators of fluid behavior at low shear rates (Hemphill et al. 1993).

Power Law Model

This model assumes that the fluid exhibits no yield stress, with the shear stress defined by the following expression:

$$\tau = k(\gamma)^n \quad \text{(Pa)} \tag{8}$$

where k (CP) is defined as the consistency index and n=fluid flow index. While this model provides reasonable predictions of fluid behavior at higher shear rates it also fails to capture the shear behavior of most drilling fluids in the low shear rate range (0–100 rpm) (Hemphill et al. 1993).

Hershel–Bulkley Model

Fluids characterized by this model, also referred to as the yield-power law, combine power law and yield stress characteristics in the following expression:

$$\tau = \tau_y + k(\gamma)^n \quad \text{(Pa)} \tag{9}$$

with n and k defined as in the power-law model and with a plug radius defined by Eq. (7). This model overcomes the limitations of the Bingham plastic and power law models by more accurately representing fluid behavior across the full shear rate range.

To demonstrate the application of the above models with an example, six speed viscometer data from the experimental work reported by Ariaratnam et al. (2003) is plotted in Fig. 3 with fitted curves generated using the Bingham plastic, power law, and yield-power law (Hershel–Bulkley) models. The viscometer data are for a bentonite based drilling fluid mixed with cuttings of clay marl with a combined density of 1,126 kg/m^3. Table 1 summarizes the viscometer data and derived drilling fluid rheological parameters. Fig. 3 clearly demonstrates that for this particular set of viscometer readings, the power law and yield-power law models more closely approximate the data, especially in the low shear rate range. In this particular case the power law and yield-power law representations of the data are almost identical with the exception that the power law predicts zero shear stress at zero shear rate, where the yield-power law predicts a yield stress of 1.84 Pa.

Concentric Annular Flow

For the case of annular flow, an exact, closed form, analytical solution only exists for the case of Newtonian flow in a concentric annulus. To model concentric non-Newtonian annular flows researchers have developed approximate solutions. The HDD industry has settled on one approximate solution that models laminar concentric annular flow based on the Bingham plastic model (Baroid 1997). This solution will be presented in greater detail in the next section.

Current Treatment of Pressure Loss in Horizontal Directional Drilling Research and Practice

There are three phases of operation during an HDD installation:

1. Phase 1: Pilot bore drilling (from entry to exit pits) during which fluid is discharged from a small upset-diameter drill bit at the cutting face and flows back to the free surface at the entry pit along the annulus between the drill pipe and the borehole wall. In the process the drilling fluid lubricates the drill pipe, carries cuttings to the surface, and stabilizes the borehole wall through the development of a filtercake. The relative risk of hydrofracture during this phase is high due to the high pressure at which the drilling fluids are discharged and a relatively small annulus for return flow.
2. Phase 2: Hole opening or prereaming during which drilling fluid is discharged from a large upset-diameter reamer or hole opener that is pulled or pushed through the borehole. In the process drilling fluids flow in the direction of least resistance to either the entry or exit pits carrying cuttings and maintaining borehole stability. The likelihood of a hydrofrac-

Table 1. Calculated Rheologic Parameters Based on Viscometer Data

Parameter	Bingham plastic	Power law	Yield-power law (Herschel–Bulkley)	rpm	Dial reading (lb_{force}/100 ft^2)	Dial reading (Pa)
Plastic viscosity (μ)	21 CP					
Yield point (τ_y)	32 Pa		1.84 Pa			
Fluid flow index (n)		0.48	1.788			
Consistency index (k)		2.42eq.CP	0.527 eq. CP			
Viscometer data (after Ariaratnam et al. 2003)				600	110	52.7
				300	89	42.6
				200	59	28.2
				100	44	21.1
				6	15	7.2
				3	10	4.8

ture during this phase is relatively low because of a larger flow annulus and lower drilling fluid pressure.

3 Phase 3: Pipe pulling during which drilling fluid is discharged from an upset-diameter reamer/swivel assembly immediately ahead of the installation pipe to mobilize any residual cuttings in the borehole, to lubricate the installation pipe, and to maintain borehole stability. The likelihood of the initiation of a hydrofracture during this phase is moderate to high, with borehole pressurization in many cases resulting in the reopening and widening of hydrofractures initiated during the pilot bore phase.

During HDD installations a slight positive pressure in the borehole is usually sufficient to maintain borehole stability. A typical positive pressure value of between 10 and 30 kPa above the in situ groundwater level is commonly quoted (Stein 2003). However, higher pressures may be required to maintain drilling fluid circulation velocities sufficient to transport cuttings out of the borehole. Thus, the minimum required pressure in the borehole is the sum of the pressure required to maintain return flow and the static hydraulic pressure needed to prevent collapse. Problems occur when the pressure required to maintain adequate drilling fluid circulation exceeds the hydrofracture limits of the formation. Hydrofracture thresholds generally increase with depth as the overburden confining pressure increases. Optimal HDD design requires balancing the overburden confining pressure (through selection of borehole depth) with the pressure required to maintain cuttings flow and borehole stability. Calculations of the required pressure are based on an estimate of the anticipated pressure losses along the flow circuit. For a constant borehole cross section, the net pressure (after discounting the elevation head) in the annular flow generally decreases in the direction of flow from a maximum value at the location of discharge into the borehole to zero at the free surface. This pressure loss is attributed to viscous shearing losses at the pipe–flow interface, the borehole–flow interface, and within the flow itself. Current treatment of pressure loss in HDD is summarized in the sections that follow.

Hair (1991) presented an analysis procedure to calculate maximum allowable downhole drilling fluid pressures for an 1,158 m long, 508 mm diameter steel pipe, natural gas installation in New Orleans, La. Frictional pressure loss calculations were made based on the assumption of an ideal Bingham plastic flow through a concentric annulus. For a given drilling fluid flow rate an average flow velocity for concentric laminar flow was computed and then used to calculate the associated pressure drop. Pressure profiles depicting borehole pressure versus position along the bore for each stage of the installation process, pilot bore, preream, and pullback, were plotted and compared to calculated overburden soil pressure profiles to identify any potential problem areas. The installation was completed in 1988 with no inadvertent returns except minor manageable flows at the shallower entry and exit sections, a result that Hair's analysis had predicted. No downhole pressure monitoring was carried out.

Staheli et al. (1998) completed a study of the installation of pipelines beneath levees using HDD as part of the U.S. Army Corps of Engineers construction productivity advancement research (CPAR) program. The maximum allowable drilling fluid pressure during installation was calculated using a method based on the cavity expansion theory developed by Delft Geotechnics (1997). The Delft equation was recently republished by the U.S. Corp of Engineers along with a number of case studies demonstrating its application (Conroy 2002). Minimum required drilling fluid circulating pressures were calculated assuming laminar flow of an ideal Bingham plastic fluid in a concentric annulus. Annular pressures 0.3 m behind the drill bit nozzles (rig side) were monitored in this research project and were found to vary within a narrow range of 324–358 kPa despite a large variance in pumping pressure within the drill stem itself.

Ariaratnam et al. (2003) began the task of cataloguing the rheologic properties of typical drilling fluid returns encountered in HDD. The first samples tested consisted of bentonite-based drilling fluids, mixed with varying amounts of clay marl. A six-speed viscometer was used to determine the bulk sample's yield point (YP) and plastic viscosity (PV). Pressure loss predictions were made using Bingham plastic flow equations (Baroid 1997), essentially the same as that used by Hair (1991). A series of graphs were presented correlating pressure loss with bore length for a range of bulk sample drilling fluid densities.

Stauber et al. (2003) presented a rational method for evaluating the risk of hydraulic fracturing in soil during HDD installations, updating Hair's approach. Pressure loss is again calculated assuming ideal Bingham plastic flow in a concentric annulus, while the upper pressure "overburden soil limit" is replaced with a more sophisticated calculation method developed by Lugar and Hergarden (1998). This approach is based on cavity expansion theory whereby the maximum allowable pressure depends on two limit criteria. The first is the maximum effective pressure based on the maximum allowable plastic zone around the borehole. The second is that this pressure be less than 90% of the effective limit pressure.

Keulen (2001) has expanded the Lugar and Hergarden model by introducing a second failure mechanism—hydraulic fracturing (strain criteria). His modification also includes the capacity to model stratified soil.

All of the above-cited HDD researchers calculated annular frictional pressure loss based on the assumption of laminar Bingham plastic flow in a concentric annulus. The equations used constitute an approximate solution, as an exact closed form analytical solution does not exist. To simplify calculations they use average velocity and average viscosity. The average velocity V_a(meter/second) of an ideal drilling fluid in a borehole annulus for a given discharge rate can be estimated using the following expression (Baroid 1997):

$$V_a = \frac{21.22 \cdot P_{\text{Output}}}{(D_{\text{Bore}}^2 - \text{OD}_{\text{pipe}}^2)} \quad \text{(m/s)} \tag{10}$$

where P_{Output}=drilling fluid pump output (L/min); D_{Bore}=diameter of the bore (mm); and OD_{Pipe}=outside diameter of the pipe/drillpipe (mm). Eq. (10) is the general form for calculating average velocity (Featherstone and Nalluri 1988) with constants adjusted for SI units. As a general rule the value of V_a will support the horizontal hydraulic transport of solids if it is either greater than the critical velocity (i.e., the flow velocity that separates the region with sedimentation from the region without sedimentation) or greater than 20 times the settlement rate of the solid particles (assuming homogeneous soil conditions) (Stein 2003). The value of V_a can then be substituted into the following equation to calculate the pressure drop gradient dP/dL (kPa/m) along the borehole annulus (Baroid 1997)

$$dP/dL = \frac{47.88(\text{PV} \times V_a)}{(D_{\text{Bore}} - \text{OD}_{\text{Pipe}})^2} + \frac{6 \cdot \text{YP}}{(D_{\text{Bore}} - \text{OD}_{\text{Pipe}})} \quad \text{(kPa/m)} \tag{11}$$

Eq. (11) is a theoretical derivation for the case of laminar flow between two parallel plates adapted to annular flow with con-

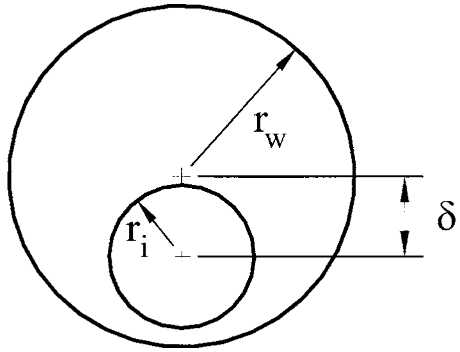

Fig. 4. Eccentric annulus geometry

stants adjusted for SI units. For the complex case of non-Newtonian flow in a noncircular borehole, with varying drillpipe eccentricity, with a rotating, whirling drill stem and changeable drilling fluid density (variable cuttings content), these approximations can be crude and can considerably overestimate pressure losses (Haciislamoglu and Langlinais 1990). While from the perspective of avoiding hydrofracture this is a conservative approach, a more detailed study of the physics of HDD borehole flow and the parameters that affect it may lead to a better understanding of downhole drilling fluid rheology and hydraulics. This in turn may result in modifications to drilling practices that will promote more efficient cuttings transport, fewer blocked boreholes, less lost circulation, and more effective design and installation procedures. In this regard considerable research has already been conducted in the oil drilling industry that has application in HDD.

Numerical Solutions

Annular Frictional Pressure Loss

The practical engineering value of numerical solutions lies in their ability to provide "comparative solutions" that can evaluate sensitivity with respect to changes in parameters, with the confirming knowledge that these solutions roughly agree with field data. Haciislamoglu and Langlinais (1990) used a numerical model to illustrate the effect of eccentricity on velocity and viscosity profiles, and the frictional pressure loss gradient. They analyzed the behavior of yield-power law fluids and concluded that:

1. Velocity profiles predicted in eccentric annuli are too complex to be represented by an average velocity. The existence of a complex nonlinear velocity profile implies that there is a correspondingly complex shear and thus viscosity profile.
2. Actual viscosities in annular flow are much higher than commonly used apparent viscosities. Apparent viscosity is derived by equating the frictional pressure loss of Newtonian and non-Newtonian fluids and solving for the Newtonian viscosity. The apparent viscosity is thus the viscosity of an equivalent Newtonian fluid that would exhibit the same pressure loss gradient as the non-Newtonian fluid.
3. For a constant flow rate, frictional pressure losses decrease with increasing eccentricity.

Referring to Fig. 4, eccentricity e is defined as

$$e = \frac{\delta}{r_w - r_i} \tag{12}$$

where δ (millimeter) = distance between the centers of the inner pipe and borehole wall; r_w (millimeter) = borehole wall radius; and r_i (millimeter) = inner pipe radius. In the specific case of a yield-power law fluid in the annulus between a 127 mm diameter (r_i=63.5 mm) inner pipe and a 254 mm diameter (r_w=127 mm) borehole, their model predicted that an eccentricity of 0.95 (inner pipe 3 mm from the borehole wall) would reduce the frictional pressure loss to 61% of the concentric value.

Chin (2001) demonstrates that approximate solutions that rely on average velocities and associated apparent viscosities lead to inaccurate results. He argues that a fundamental error in these approaches is the attempt to model downhole fluid flow behavior of non-Newtonian flow based on standard viscometer rheology data. In his view, viscometer results are not suitable for predicting actual downhole properties because actual shear rates, which can vary widely depending on the velocity profile, cannot be known in advance as they depend on the details of the actual annular geometry. He contends that the use of the viscometer should be restricted to the determination of intrinsic rheological parameters with computational software used to determine the characteristics of the flow field. As a typical example of the power of computational approaches to predict trends, he performed comparisons for concentric and eccentric flows for the case of a 254 mm diameter borehole and a 102 mm diameter drill pipe. With all other factors remaining constant, an imposed eccentricity of 51 mm (lowering the drill pipe by 51 mm) almost doubled the flow rate from 29 to 56 L/s, a result consistent with experimental observations indicating that higher eccentricities increase flow rates and reduce pressure losses.

Cuttings Transport Capacity

Cuttings transport capacity depends on the rheological properties of the flushing fluid (i.e., viscosity, density) and its flow characteristics (i.e., volume, velocity). In typical horizontal boreholes the transport capacity of a bentonite-based mixture is approximately 20% cuttings by weight, however, values up to 35% can be achieved using optimal formulation and suitable additives (Stein 2003).

Becker et al. (1989) tested 15 bentonite–polymer, water based drilling fluids, at three average flow rates (0.58, 0.87, and 1.16 m/s), at three borehole inclinations from vertical (30, 45, and 70°). Inclinations of 70 and 45° from vertical can be considered to represent typical and maximum theoretical approach angles in shallow HDD practice. The annular geometry consisted of a 102 mm diameter pipe displaced downward by 38 mm in a 254 mm diameter borehole. To form a cuttings bed, 6 mm limestone gravel was introduced at a steady rate into a flow with a preestablished flow rate. When the cuttings discharge rate stabilized, cuttings injection was stopped and the cuttings concentration was determined. Volumetric annular concentrations ranged from 1.5% (30° from vertical, 1.16 m/s) to 32% (45°, 0.58 m/s). The writers cross plotted the nondimensional cuttings concentration against particular rheological properties for each of the drilling fluids used. The rheological properties used included PV, YP, YP/PV ratio, apparent viscosity, effective viscosity, power-law consistency index k, shear stress at the borehole wall, shear stress corresponding to average annular shear rate (the rate of change of velocity at which one layer of fluid passes over an adjacent layer; units=L/s), initial and 10 min gel strengths, and viscometer readings at various speeds. Overall, the correlations of the selected rheological properties with cuttings concentrations were poor, with one exception. The best data fit was obtained with low shear rate parameters, particularly viscometer readings at low rotary speeds (6 rpm, corresponding to a shear rate of 10/s). This led Becker to recommend that "low rpm" viscometer data be used for the prediction of cuttings concentration in highly inclined flow.

Chin (2001) modeled Becker's experiments numerically. His results yielded averaged shear rates of 7–9/s for all drilling fluid samples at flow rates of 0.58 m/s; similarly, 11–14/s at flow rates of 0.87 m/s, and 14–19/s at flow rates of 1.16 m/s. These shear rates are close to the 10/s range and explain why good correlations with the experimental data were observed using the 6 rpm viscometer readings. These results support Becker's "low rpm" recommendation. Typical viscous stress values calculated by Chin for one of the 12 drilling fluids tested at a flow rate of 0.58 m/s ranged from 1.2 Pa at the bottom of the drillpipe to 5.7 Pa at the top of the drillpipe.

The Petroleum Research Council International (PRCI) HDD model (Huey et al. 1996) is commonly used in current HDD practice to predict pulling loads during product pipe installation. In this model the value of drilling fluid viscous shear at the boundary between a steel pipe and the annular flow of a bentonite-based drilling fluid is quoted to be 350 Pa (0.05 psi) based on *NEN 3650* (NEN 1992). When this value is compared to the above reported range of shear values for a similar interface condition (Chin 2001) it appears to overstate the numerically predicted dynamic drilling fluid drag by nearly 2 orders of magnitude. In addition, industry has shown that the quoted PRCI fluid drag value has not always proven applicable (Gratton and Venton 2002)

ASTM F-1962-99—"Standard guide for use of maxi-horizontal directional drilling for placement of polyethylene pipe or conduit under obstacles, including rivers," accounts for viscous drag on the pipe using the following equation:

$$\Delta T = \Delta P \frac{\pi}{8}(D_{\text{Bore}}^2 - \text{OD}_{\text{pipe}}^2) \quad (\text{N}) \tag{13}$$

where ΔT (N)=pulling force increment; ΔP (Pa)=hydrokinetic pressure; and D_{Bore} and OD_{pipe} (mm)=bore and pipe diameters, respectively. This equation can be rewritten as

$$\Delta T = \frac{\Delta P}{2} \cdot A_{\text{annulus}} \quad (\text{N}) \tag{14}$$

where A_{annulus} (m^2)=cross sectional area of the annulus. Written in this form it is evident that the viscous drag at the borehole wall has been equated to the viscous drag on the pipe. Considering that viscous drag is proportional to surface area, this approximation will overstate the viscous drag on the pipe. Furthermore, the standard recommends a value of 70 Pa for ΔP, without qualification. The pressure gradient ΔP, can vary considerably, depending on bore and pipe diameters, pipe eccentricity, and drilling fluid rheology.

Discussion

Recent advances in knowledge and understanding of drilling fluid hydraulics and rheology gained in the oil industry and reported in the above references with regard to annular frictional pressure loss in horizontal wells, cuttings transport and fluid viscous shear are yet to be incorporated into current HDD design practice. It appears that the current HDD practice of calculating annular pressure loss using an approximate analytic solution based on the assumption of laminar flow of a Bingham plastic fluid in a concentric annulus is overly conservative. The above described published research identifies the following weaknesses in this approach:

1. Even for concentric annular flow the assumptions of average velocity oversimplifies the mathematical representation of the complex flow regime and can lead to inaccurate results that overestimate annular frictional pressure losses;
2. By failing to account for the effect of eccentricity in the borehole, annular frictional pressure losses can be substantially overestimated; and
3. Applying drilling fluid rheology parameters that are applicable to high shear rate flows, where low shear rate flows are the norm, can again lead to substantially overestimated frictional pressure losses.

Numerical methods and proper drilling fluid characterization could greatly assist in overcoming these limitations. However, the prediction of drilling fluid flow characteristics in absolute terms in HDD is not a realistic goal as there are many variables that cannot be accurately known beforehand (i.e., soil type, soil stratification, cuttings concentration, and borehole geometry). In addition, few HDD designers have the background required to use sophisticated numerical prediction techniques, nor to interpret the validity of the results. The HDD industry requires solutions that are easy to understand, simple to use, and provide reliable results. Approximate analytical solutions fall in this category and represent a necessary and practical compromise between ease of use and reliability.

In view of the above discussion the writers propose to use the current approximate method employed in HDD for calculating frictional pressure loss in concentric annuli (Baroid 1997), however, using low shear rate parameters instead of the conventional high shear rate Bingham plastic parameters. The average velocity is calculated as before with no change using Eq. (10). The computed velocity, V_a, is then substituted into Eq. (11) to calculate the pressure drop gradient dP/dL (kPa/m) along the borehole annulus using the Bingham plastic flow parameters, PV (CP) and YP (Pa), for low shear rate behavior (i.e., 6 and 100 rpm dial readings in place of the standard 300 and 600 rpm dial readings). Bingham PV (CP) and YP (Pa) parameters for low shear rate behavior are not readily available. However, they can be derived from viscometer data provided by researchers such as Ariaratnam et al. (2003). As the body of viscometer data expands to include a comprehensive range of typical HDD drilling fluids, mixed in various concentrations with representative soil types, a table of low shear rate Bingham parameters PV (CP) and YP (Pa) could be developed for use by HDD designers.

The marked impact of the proposed modifications on the calculated pressure loss can be demonstrated with a simple example of the pressure loss in the concentric annulus between a 229 mm diameter borehole and a 127 mm diameter drillpipe based on the assumption of Bingham plastic flow. The PV and YP parameters were derived from the viscometer data listed in Table 1 and plotted in Fig. 3. The results are summarized in Table 2. For a flow

Table 2. Bingham Parameters and Pressure Loss Results

Viscometer readings	Plastic viscosity (CP)	Yield point (Pa)	V_a (m/s)	dP/dL (kPa/m)
300 and 600	21	32.6	0.44	1.96
6 and 100	93	6.3	0.44	0.56

Table 3. Field Study Summary and Friction Coefficients (after Maidla and Wojtanowicz 1987)

Well number	Depth (m)	Maximum inclination (deg) depth (m)	Remarks	Model	μ_B run-in	μ_B pull-out
1	3,435	39.2° 1,533	Casing	3-D	0.43	0.27
				2-D	0.44	0.28
			Drill-string	3-D	—	0.21
				2-D	—	0.24
			Core guns	3-D	0.27	0.30
				2-D	0.29	0.33
2	2,929	48.3° 1,537	Casing	3-D	0.43	—
				2-D	0.46	—
			Drill-string	3-D	—	0.25
				2-D	—	0.28
3	3,516	16.35° 3,109	Casing	3-D	0.83	0.44
				2-D	1.14	0.64
4	2,733	52.25° 2,075	Casing	3-D	0.38	—
				2-D	0.47	—

rate of 760 L/min the pressure drop over 1,000 m was calculated to be approximately 1,960 kPa using Eq. (11) and standard viscometer readings of 300 and 600 rpm. If low shear rate readings from the 6 and 100 rpm dial readings had been used instead, the calculated pressure drop over the same distance would have been 560 kPa, a 70% lower value.

Another modification proposed to current HDD design practice is to account for the effect of eccentricity on pressure loss calculations. A possible approach could take the following form, modifying Eq. (11) with a factor e_{factor} to account for eccentricity

$$dP/dL = \left[\frac{47.88(\text{PV} \times V_a)}{(D_{\text{Bore}} - \text{OD}^2_{\text{Pipe}})^2} + \frac{6 \cdot \text{YP}}{(D_{\text{Bore}} - \text{OD}_{\text{Pipe}})} \right] \cdot e_{\text{factor}} \quad (\text{kPa/m}) \tag{15}$$

where e_{factor}=value less than or equal to unity, and is a function of borehole profile, drilling fluid rheology, flow rate, and drill pipe to borehole diameter ratio. A comprehensive study using numerical modeling software such as that described by Chin (2001) could be used to develop values for the eccentricity factor.

The writers believe that the proposed approach has the potential to improve the prediction of annular frictional pressure loss while maintaining a simple approximate solution commensurate with the variability inherent in HDD.

Borehole Friction

Friction coefficients adopted by the PRCI model for HDD pipe installation were based on data reported by Maidla and Wojtanowicz (1987). A description of their research and a summary of their results follow.

Maidla and Wojtanowicz (1987) presented two general procedures for borehole drag prediction based on the borehole friction concept. They evaluated two-dimensional and three-dimensional models and compared the results with measured hook loads to determine borehole friction factors. Hook load is defined as the weight of the drill string in air, the drill collars and any ancillary equipment, less any force that tends to reduce that weight such as buoyant forces on the drill string caused by its immersion in the drilling fluid. They defined the borehole friction factor μ_{Bore} as

$$\mu_{\text{Bore}} = \frac{|F_H - Q_V \pm F_D|}{\int^D q_N(l)dl} \tag{16}$$

where F_H=hook load (kN); Q_V=vertical projected buoyant weight of the pipe (kN); F_D=hydrodynamic viscous drag (kN); q_N=unit buoyant weight projection on the principal normal direction (kN/m); l=length of the pipe (m); and D=measured depth (m). The $\pm$ sign is for the pulling-out and running-in scenarios, respectively. The accuracy of the calculated borehole friction value μ_{Bore} depends on properly accounting for all possible contributions to borehole drag.

Maidla and Wojtanowicz collected field data from four casing runs in the Louisiana Gulf Coast area. Table 3 provides a description of the four wells in the field study and summarizes the friction factors calculated for each well. Based on field results, the friction coefficient for most cases was concluded to be 0.21–0.30 for pulling conditions. This range is referenced in the PRCI model for HDD installations as an applicable range in the calculation of HDD friction resistance.

In a follow up paper, Maidla and Wojtanowicz (1990) reported the results of a laboratory study of the borehole friction factor using a dynamic-filtration apparatus designed to simulate the rubbing/sliding action of the downhole tool surface against the rock surface in the presence of drilling fluid and its filtercake. Samples of oil based mud (OBM) and water based mud (WBM) were collected from drilling sites in Louisiana and were tested. Eighty percent of the experimentally determined friction factors were between 0.2 and 0.3. They noted that for runs with short alternating periods of motion and no motion (connection), the borehole friction could be entirely controlled by the deformation properties of filtercakes.

Another approach to determining borehole friction factors is laboratory measurement. Potyondy (1961) conducted several hundred experiments to determine the magnitude of skin friction of various construction materials (smooth steel, rough steel, wood, smooth concrete, and rough concrete) in contact with various soils (sand, cohesionless silt, cohesive granular soil, and clay). He investigated the change of skin friction as a function of grain distribution of soils, moisture content, normal load, type of con-

Table 4. Proposed Skin Friction Ratios between Soil and Steel (after Potyondy 1961)

	Sand 0.06 < D < 2.0 mm		Cohesionless slit 0.002 < D < 0.06 mm			Cohesive granular soil 50% clay+ 50% sand		Clay $D \leqslant 0.06$ mm		
	Dry dense	Saturated	Dry dense	Saturated loose	Dense	Consistency index = 1.0–0.5		Consistency index = 1.0–0.73		
Material	f_ϕ	f_ϕ	f_ϕ	f_ϕ	f_ϕ	f_ϕ	f_c	f_ϕ	f_c	f_c^{Max}
Smooth steel (polished)	0.54	0.64	0.79	0.40	0.68	0.40	—	0.50	0.25	0.50
Rough steel (rusted)	0.76	0.80	0.95	0.48	0.75	0.65	0.35	0.50	0.50	0.80

struction material, and difference of surface finish. Both strain and stress controlled shear boxes were used with specimens of construction materials placed in the lower portion of the box, and soil placed in the upper half. Skin friction was expressed in a similar form to that of Coulomb

$$\text{skin friction} = f_c c + \sigma \tan(f_\phi \phi) \tag{17}$$

where

$$f_c = c_a / c$$

and

$$f_\phi = \delta / \phi \tag{18}$$

c_a (Pa) = adhesion; c (Pa) = cohesion; δ(degree) = angle of skin friction; and ϕ (degree) = internalangle of friction of the soil. The ratios f_c and f_ϕ relate skin friction of different interface materials to the characteristics of the soil. Neither c nor ϕ are inherent properties of the soil, but are dependent on the conditions operative during the test. A partial summary of Potyondy's experiments is shown in Table 4.

Potyondy concluded that four major factors determine skin friction: moisture content of soil, roughness of the surface, soil composition, and the intensity of the normal load. Based on the experimental results, he also recommended that both adhesion and friction be considered in the evaluation of the skin resistance of cohesive soils. Eqs. (17) and (18) are not directly applicable to HDD because they do not account for the lubricating effect of the base drilling fluid and filter.

Conner (1998) conducted a series of tests to determine the maximum load required to drag a pipeline over soil or through a borehole in soil. Samples consisting of rectangular coupons cut from 152 and 1,500 mm diameter ductile iron pipes and 203 mm diameter HDPE pipe were pressed into the surface of formed soil beds and were then horizontally pulled across the surface of the soil with a known mass holding the coupon against the soil. The test conditions included wet and dry soils, and contact surfaces with and without the presence of a bentonite-based drilling fluid film on the soil surface. Selected results are summarized in Table 5. For clean sand, the static coefficient of friction falls within the 0.21–0.3 range determined by Maidla and Wojtanowicz (1990) for a steel–filtercake–rock interface. The coefficients for the cohesive clay/sand mixture showed considerable variation (0.08–0.46). This variation demonstrates the effect of different soil/material interface combinations, and the effect of adhesion in the case of cohesive soils. Based on the above literature review the writers argue that the calculation of a single static coefficient for the cohesive soil group is incorrect, as it combines the individual contributions of adhesion (which is not dependent on normal load) and friction (which is dependent on normal load) into a single coefficient. In Conner's experiments no attempt was made to model the filtercake, with drilling fluid simply used to wet the contact surface. However, the results were consistent with Potyondy's findings that the evaluation of skin friction must consider a number of factors.

Discussion

In HDD, skin friction is likely a combined function of the four factors considered by Potyondy plus three additional factors, two associated with the formation of a filter cake, and the other with the drilling fluid itself. These seven factors are: the moisture content of the soil, the roughness of the pipe surface, the grain size distribution of the soil, the intensity of the normal load, the thickness of the filtercake, the shearing properties of the filter cake, and the lubricating effect of the drilling fluid. No HDD research has been identified that fully considers the above factors in determining the range of skin friction values to be expected during HDD installations for different soil/drilling fluid/pipe interface combinations. In addition, the effect of lubricating additives in reducing skin friction has not been adequately quantified. This greatly limits the practical application of current HDD prediction models considering that the accuracy of their results relies heavily on the proper input of representative skin friction factors (Baumert and Allouche 2002).

Table 5. Laboratory Friction Tests of Pipe Coupons on Soil (after Conner 1998)

Pipe coupon	Soil type	Moisture content	Drilling mud	Normal force (lb)	Force/move average (lb)	Static coefficient friction
6 in. DIP	Clean sand	Wet	Yes	7.56	2.28	0.3
60 in. DIP	Clean sand	Wet	Yes	4.44	1.3	0.29
8 in. HDPE	Clean sand	Wet	Yes	6.00	1.41	0.24
6 in. DIP	Clay with sand	Wet	Yes	7.56	1.5	0.2
60 in. DIP	Clay with sand	Wet	Yes	4.44	2.06	0.46
8 in. HDPE	Clay with sand	Wet	Yes	6.00	0.45	0.08

Horizontal Directional Drilling Design

Baumert and Allouche (2002) reported the results of a sensitivity analysis of current design methods used to calculate pull loads during HDD installations. The analysis identified drilling fluid density and drag as the two parameters to which the models were most sensitive. The drilling fluid density affects the net weight (pipe weight less buoyancy) and thereby determines the normal load intensity used in the calculation of skin friction. The literature review of borehole friction research suggests that the 0.21–0.3 friction coefficient range (Maidla and Wojtanowicz 1987) quoted by the PRCI model may be reasonable for the installation of steel and HDPE pipe in stable boreholes formed in granular soils. However, in cohesive soils, other ranges may be more applicable due to the contribution of adhesion and a different grain size distribution.

The PRCI model also quoted a viscous shear value of 350 Pa for steel pipe being dragged through clean bentonite-based drilling fluid, a value derived from auger boring installations performed in the Netherlands (NEN 1992). In calculating the pulling load component attributable to drilling fluid drag, this value is multiplied by the surface area of the pipe and can lead to substantial loads for large diameter and/or long installations. The literature review of drilling fluid behavior presented earlier in this paper suggests that the adoption of one value of viscous shear (drilling fluid drag) for all borehole geometries, drilling fluid compositions and pipe material is ill advised. Furthermore, the value of 350 Pa appears to be almost 2 orders of magnitude too high (see Fig. 5). The two other models considered for HDD design, *Drillpath theory and user's manual* (1996) and Driscopipe (1993) both claimed drilling fluid drag to be negligible.

In HDD design a borehole friction coefficient of 0.21–0.3 and a fluid drag factor of 350 Pa are frequently quoted and used by HDD designers. Designers should be aware that when these values are applied as standard values applicable to all HDD installations, inconsistent pulling load predictions may result (Baumert and Allouche 2002).

The location, length and relative magnitude of pressure zones along the borehole is an area that has not been considered in HDD design. Baumert et al. (2003) reported drilling fluid pressures of up to 250 kPa between the reamer and pipe pullhead during pipe pullback in shallow installations of 1.2 m depth. This pressure may increase the normal load intensity between the pipe and borehole wall and consequently may dramatically increase skin friction. Consider a 203 mm o.d., 4.8 mm wall steel pipe submerged in a 305 mm diameter borehole in drilling fluid with a density of 1,440 kg/m^3 pressurized to 200 kPa. The net buoyant force is calculated to be 0.23 kN/m. If one assumes that the pipe is in contact with the borehole wall over an arc length of 75 mm, the differential drilling fluid pressure of 200 kPa would result in an increase of 15 kN/m in the normal load intensity. In this scenario, the net buoyant force contribution to normal load intensity of 0.23 kN/m is negligible compared to the fluid pressure effect of 15 kN/m. Assuming a coefficient of friction of 0.3, this pressure effect would lead to a friction resistance of 4.5 kN/m, a value substantially higher than the 0.4 kN/m noted by the writers for a similarly pressurized bore in the field (Baumert et al. 2003). This discrepancy implies that the high pressure zones that develop in the vicinity of the pull head during HDD installations are localized in nature. This area requires further research to develop a better understanding of the location, lengths, and relative magnitude of the various pressure zones that develop along the borehole during the various stages of HDD installations.

Horizontal Directional Drilling Monitoring Technology

General

In a manner analogous to the research conducted by Maidla and Wojtanowicz (1987) current mathematical expressions for calculating axial loads during HDD pipe pullback need to be re-evaluated and compared with actual pull loads and fluid pressures now provided by downhole monitoring technology such as the monitoring cell developed at the Univ. of Western Ontario (Fig. 1). The monitoring cell is capable of measuring axial load up to 670 kN, borehole pressure up to 1,000 kPa, as well as temperature. The data are transmitted from the cell to a surface computer at a rate of 0.5 Hz. The field study should be complimented with laboratory experiments to validate the input parameters, particularly, filter cake lubricating properties (skin friction), and drilling fluid lubricity (viscous drag). Pressure effects should also be investigated as possible contributors to enhanced skin friction. These efforts should lead to the development of more accurate axial load prediction models for HDD installations.

Downhole pressure data combined with observations of drilling fluid returns could also lead to the improvement of pressure loss prediction models. The accuracy of models such as the proposed low shear rate Bingham plastic model could be evaluated. The practice of drilling excessively deep crossings to provide a factor of safety against hydrofracture based on a circulating pressure prediction that is highly conservative adds unnecessarily to drilling expense. Setback distances are greater, bend radii are potentially sharper, and the overall drilled length and length of installed pipe are also greater than needed. Improved pressure loss prediction models should be able to provide more accurate predictions, thereby reducing costs, while still providing a sufficient margin of safety against hydrofracture.

The value of real-time pressure measurement lies in the identification of pressure trends that can potentially indicate the early onset of flow problems before they become serious. Numerical simulation can be used to model flow problems and suggest specific methods for dealing with them. The simulation results for problems frequently encountered in the field can be summarized and presented as an easy-to-follow flow chart guide for field use. For example, a steady incremental increase in pressure may indicate a gradual accumulation of cuttings in the borehole. Early detection and appropriate adjustments to penetration rate, pumping pressure, drilling fluid properties or a combination thereof, may avoid the eventual occurrence of blocked circulation and a potentially stuck pipe. A sudden pressure increase may indicate a borehole stability problem caused by partial borehole collapse, a situation that will demand an alternate response. On the other hand, a sudden decrease in the borehole pressure may serve as an indication of a rapid loss of drilling fluids into the formation due to the presence of a highly porous medium, with a subsequent reduction in the effective stress in the soil mass and a potential borehole collapse. Based on their experience, HDD drilling contractors have already developed standard responses to the problems that they encounter. Real-time pressure and load data may alert crews in a timelier manner and allow them to avoid expensive drilling setbacks.

Summary and Conclusion

Based on an extensive literature review it was concluded that the current method used in HDD design for calculating annular frictional pressure loss, based on the assumption of Bingham plastic flow in a concentric annulus, is overly conservative. It is suggested that improvements to the accuracy of the prediction can be made by: (1) characterizing annular flow in HDD with low shear rate drilling fluid rheology parameters; and (2) considering the effect of eccentricity in reducing annular frictional pressure loss. Both of these suggestions require further validation before they can be incorporated into HDD design practice.

A further finding was that the calculation of fluid drag using either the PRCI method or that suggested by *ASTM F1962-99* (ASTM 1999) is also overly conservative, by as much as 1–2 orders of magnitude. Numerical modeling techniques need to be employed to better estimate the magnitude of drilling fluid viscous shear acting on the pipe during pullback for various soil conditions, drilling fluid densities, pipe materials, and borehole/pipe geometries.

The industry standard borehole friction coefficient range of 0.21–0.3 appears to apply for steel and HDPE pipes installed in stable boreholes in granular soils. However, the range for cohesive soils in HDD has not been adequately investigated and the effect of lubricating additives has not been quantified.

The distribution of drilling fluid pressure in the annulus between the pipe and the borehole wall along the length of the bore needs to be investigated. High pressure zones could contribute to increased contact pressures between the pipe and borehole wall and thus to greater skin friction (differential sticking).

The 670 kN (axial) and 1,000 kPa (pressure) capacity HDD monitoring cell developed at the Univ. of Western Ontario provides the means to collect high quality field data that will facilitate the development and verification of more accurate design procedures for large-scale HDD installations. The routine use of monitoring cells would promote quality assurance during HDD installations, making HDD construction practices more transparent. Another benefit is a shorter response time to emerging problems. The real-time feedback from the monitoring cell could potentially alert the drilling crew, which could than make drilling adjustments before emerging complications developed into serious problems.

The HDD designers should be aware of the limitations of current HDD design models and their overall tendency to substantially overestimate axial pulling loads and the minimum required drilling fluid-circulating pressures. These estimates can lead to expensive oversizing of the rig and longer deeper profiles than are reasonably required to provide safety against hydrofracture. As the industry begins to adopt downhole monitoring technology during pipe pullback, the models should evolve to keep pace and provide more reliable, accurate estimations of pulling loads, and circulating pressures.

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