Which Method to Use When Estimating Maxi-HDD Installation Loads --ASTM F 1962 or the PRCI Method?

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Abstract

ASTM F 1962, *Standard Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings*, provides a convenient procedure for estimating installation loads and stresses on polyethylene (PE) pipe as primarily a function of the drilled path and buoyant weight of the pipe in the borehole. The ASTM theoretical model does not consider the impact of pipe bending stiffness on the associated tensile loads during maxi-horizontal directional drilling (maxi-HDD) installations, since it assumes that such effects may be ignored for flexible PE pipe material. In contrast, the method adopted by the Pipelines Research Council International (PRCI) was developed for application to steel pipe, and explicitly considers its relatively high bending stiffness. There are also other differences in the two techniques, including the approach for estimating the effect of fluidic drag as the pipe is pulled through the viscous drilling fluid, and consideration of the effect of tension at route bends. Both methods, or modified versions, have been applied to pipes of various materials. The present paper discusses the basic differences between the ASTM and PRCI methods, and the implications of their application to pipe materials other than that originally intended. In principle, either method may be applied to PE, steel, or other type pipe, but the degree of design margin, or effective safety factor, may be significantly different, depending on the method and installation details. In particular, the PRCI method tends to be more conservative due to its relatively high estimate of the fluidic drag contribution. This may be most significant for HDD installations with low frictional loads within the borehole due to relatively low buoyant weight, such as may occur for heavy (e.g., thick-walled steel) pipe, or where internal ballast is employed to reduce the otherwise high buoyant weight of the pipe.

1. Introduction

ASTM F 1962, *Standard Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings*, provides overall guidelines for a maxi-horizontal directional drilling (maxi-HDD) operation (ASTM, 2011) In particular, ASTM F 1962 provides an analytical method for selecting the polyethylene pipe strength requirements based upon the estimated installation loads on the polyethylene (PE) pipe, as well as for helping determine the required capacity of the HDD equipment. Due to its convenience, the procedure has been widely utilized, both within the United States and abroad (Petroff, 2010). Furthermore, although not originally intended for such applications, the ASTM procedure is sometimes adapted for estimating the pull loads for non-PE pipe materials, including steel (Zeng, 2013).

Within the same general time frame that ASTM F 1962 was developed, a method was developed by the Pipeline Research Council International (PRCI) of the American Gas Association specifically intended to be applied to the placement of steel pipe by maxi-HDD (Huey, Hair and McLeod, 1996). Besides the obvious differences in strength and weight between PE and steel pipes, the most significant difference relates to the effect of their bending stiffness on the tensile load, which is explicitly considered in the PRCI method. The latter method, however, is not quite as convenient to apply as the ASTM procedure since it requires an iterative technique to estimate the associated bending/reaction forces. The PRCI method has been widely and successfully employed for the placement of steel pipe, and has also been considered for estimating the pull loads for other type pipe, including PE (Knight and Adedamola, 2003).

The present paper addresses the potential validity and implications of applying these two alternate procedures (ASTM F 1962 and PRCI) to pipe materials for which they were not originally intended – e.g., applying the ASTM F 1962 method to steel pipe and/or applying the PRCI method to high density polyethylene (HDPE) pipe.

2. Description

ASTM F 1962 (PE)

Figure 1 illustrates a typical geometry for a maxi-HDD operation, corresponding to a river crossing, similar to that shown in ASTM F 1962, as originally intended for PE pipe. The term H represents the depth of the installation relative to the elevation at the pipe entry and exit points. The horizontal projection of the pipe path comprises four segments, including those spanning the pipe entry to exit point (L_2, L_3, L_4) and the additional length L_1. The quantity L_1 allows for handling at both ends and possible other effects (path curvature, thermal contraction, stretching, ...). ASTM F 1962 provides the following equations to conveniently estimate the required pull force -- T_A, T_B, T_C, and T_D -- corresponding to the leading end of the polyethylene pipe reaching point A, B, C and D:

$$T_A = e^{\nu_a \alpha} \cdot \nu_a \cdot w_a \cdot (L_1 + L_2 + L_3 + L_4) \quad [1a]$$

$$T_B = e^{\nu_b \alpha} \cdot (T_A + \nu_b \cdot |w_b| \cdot L_2 + w_b \cdot H - \nu_a \cdot w_a \cdot L_2 \cdot e^{\nu_a \alpha}) \quad [1b]$$

$$T_C = T_B + \nu_b \cdot |w_b| \cdot L_3 - e^{\nu_b \alpha} \cdot (\nu_a \cdot w_a \cdot L_3 \cdot e^{\nu_a \alpha}) \quad [1c]$$

$$T_D = e^{\nu_b \beta} \cdot (T_C + \nu_b \cdot |w_b| \cdot L_4 - w_b \cdot H - e^{\nu_b \alpha} \cdot [\nu_a \cdot w_a \cdot L_4 \cdot e^{\nu_a \alpha}]) \quad [1d]$$

where w_a represents the empty aboveground weight (downward positive) of the pipe and w_b denotes the net buoyant weight (upward positive) of the pipe as submerged in slurry belowground; ν_a and ν_b. are the corresponding aboveground and belowground Coulomb "coefficients of friction". The buoyant weight may reflect the use of anti-buoyancy techniques, including the use of liquid ballast (e.g., water) inside the pipe. The pipe entry angle α and exit angle β are expressed in radians.

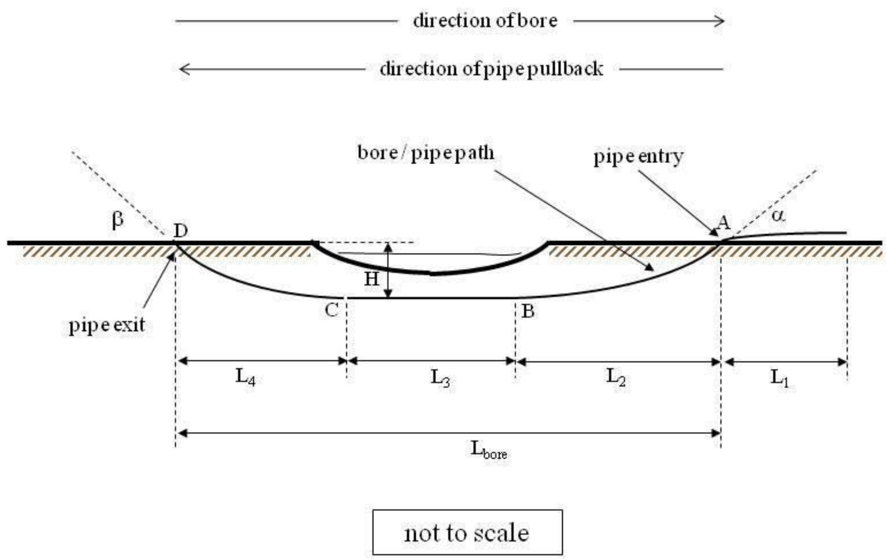

Figure 1 Typical maxi-HDD route (river crossing)
(Source: Outside Plant Consulting Services, Inc.)

In addition to the tensile loads at the individual stages of progress (points A, B, C, and D), an incremental tension, ΔT, must be added to account for the drag effect of the drilling fluid/mud ("fluidic drag"), which is determined from the magnitude of the "hydrokinetic pressure", ΔP:

$$\Delta T = \Delta P \cdot (\pi/8) \cdot (D^2_{hole} - D^2) \qquad [2]$$

where D_{hole} is the diameter of the borehole and D is the diameter of the pipe; ΔP is the incremental drilling fluid pressure in the borehole at the leading end of the pipe during the pullback operation, which is in addition to the hydrostatic pressure corresponding to the head (depth) of relatively dense drilling fluid. The incremental tension, ΔT, is properly added to the local tension T_A , T_B , T_C , or T_D as specified in Equations 1, for each of the four points, but is *not cumulative*; e.g., the value of T_A inserted into Equation 1b is that given by Equation 1a, as written, and *not* $T_A + \Delta T$. In any case, this estimate of ΔT is usually low compared to the tension estimates given by Equations 1.

The development of Equations 1, representing the basic ASTM model for estimating the required pulling load, assumed negligible pipe bending stiffness, as characteristic of PE material. Other pipe materials, including relatively rigid plastics (e.g., polyvinyl chloride, PVC) and, more obviously, iron or steel, might conceivably lead to appreciable reaction forces at route bends and path curvature, as the pipe is pulled along the borehole during the HDD operation. These local reaction forces correspond to concentrated sources of frictional drag on the pipe, impeding its placement, requiring greater installation pull loads than may otherwise be required considering only the frictional drag due to the pipe weight (including buoyancy) and tension at route bends ("capstan" effect), as well as any contribution due to fluidic drag.

The potential magnitude of the bending stiffness effect has been conservatively estimated by Slavin and Najafi (2012), based on an elastic pipe/beam model accounting for the local bending forces required to conform the pipe to the borehole curvature. The magnitude of the reaction forces, acting normal to the pipe surface at the entry or exit route bend, may be estimated by the quantity

$$6\ EI / \{2 \cdot [6\ (d_h - d_p) \cdot \rho_h^3]^{1/2}\} \qquad [3]$$

where EI is the bending stiffness of the pipe/beam, d_h the diameter of the borehole, d_p the pipe diameter, and ρ_h the radius of curvature of the route bend, at the pipe entry or exit point. However, the magnitude of this effect may be significantly reduced, or eliminated, by the mitigating effect of the buoyant forces acting laterally along the pipe in the vicinity of the curve.

PRCI Method (Steel)

Huey, Hair and McLeod (1996) provides the details of the PRCI method, as described for a route geometry equivalent to that of Figure 1. This method is, in general, based on similar principles to that used to develop ASTM F 1962, but with significant differences regarding the magnitude of the fluidic drag and the explicit consideration of the bending stiffness of the intended steel pipe.

In particular, the model considers frictional drag (“frict”) due to the pipe weight (or buoyancy) acting against the borehole surface, which is the major component of the predicted pull force of the ASTM model, and also calculates the reaction forces due the pipe stiffness as the pipe is pulled past the route bends at both the entry and exit segments of the bore path. The latter effect is estimated assuming a three-point beam bending configuration, and using relatively complex formulae reflecting non-linear effects associated with-the tensile loads present while installing the pipe (Roark, 1943), consistent with the nomenclature in Figure 2 (Huey, et al, 1996). The estimate of the reaction forces requires an iterative procedure since the tension depends on the to-be-determined reaction forces at the route bends.

The PRCI method considers the fluidic drag (“DRAG”) to be based on an assumed viscous drag force distributed over the pipe outer surface. The original recommended value was 0.05 psi, but was later reduced to 0.025 psi, based on more recent field results (Puckett, 2003).

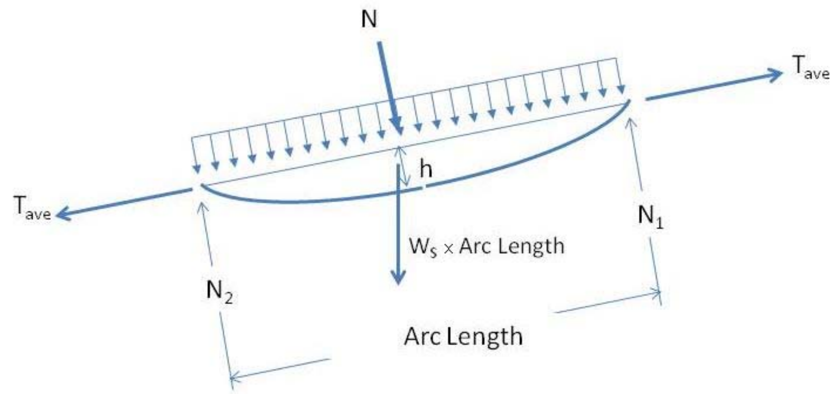

Figure 2 PRCI Model of Pipe at Route Bend

For convenience, this procedure is represented by the following somewhat over-simplified, equation, adopting the original nomenclature:

$$T_D = \Sigma(\text{DRAG}) + \Sigma_{\text{straight}}(|\text{frict}|) + \Sigma_{\text{curved}}(|\text{frict}|) + \Sigma(W_s\, L_i \cdot \text{Sin}\theta) \quad [4]$$

where the Σ summation applies to the individual linear segments of the steel pipe, including straight and curved length, as appropriate, and it is assumed that the peak pull force occurs when the pipe is fully installed. The term with the "Sinθ" corresponds to the downward (or upward) tendency of gravity (buoyancy) to inhibit or aid the movement of the pipe segment of effective (net buoyant) weight W_s as it changes depth, similar to analogous terms in Equations 1b and 1d.

The term $\Sigma_{\text{straight}}(|\text{frict}|)$ accounts for the friction between the pipe surface and the borehole wall, due to the net buoyant weight (up or down) of the pipe, again analogous to terms in Equations 1. The term $\Sigma_{\text{curved}}(|\text{frict}|)$ is considerably more complicated and requires the aforementioned iterative process to determine the friction at the bend due to the reaction forces, N, N_1 and N_2. The total effective friction is considered to be double that due to the calculated value, N -- i.e., 2N -- on the assumption that the sum of the lower reactions forces ($N_1 + N_2$) is also equal to N.

3. *Differences Between ASTM F 1962 and PRCI Methods*

In spite of efforts by the HDD industry to develop more accurate predictions of pulling loads in practical applications, it is generally acknowledged that present methods often produce installation forces that differ significantly from field observations. Attempts to align the predictions with field measurements, by selecting appropriate quantitative values of relevant parameters, are ultimately only useful if able to more accurately predict (a priori) the required pulling loads in subsequent applications, using the developed model. This ability has not yet been demonstrated, essentially because of the complexity and wide variability associated with operations in non-engineered materials and environments -- i.e., soil and rock. For example, controlled HDD field experiments have resulted in significantly different pull loads – by a factor of almost two to one -- in what would appear to be almost identical conditions (Knight et al, 2002). Thus, it is not surprising, nor inappropriate, that the

ASTM and PRCI methods would attempt to model the complex HDD operation in a non-identical manner. In particular, the alternate methods of considering the effect of the pipe bending stiffness lead to a somewhat more significant impact on the PRCI estimate than that for the ASTM F 1962 calculation.

The most significant difference, however, is that due to the means of accounting for the fluidic drag. Whereas the contribution to the ASTM estimate is based on Equation 2, resulting in only a minimal contribution to the calculated pull load, the present recommended viscous drag value of 0.025 psi for the PRCI method is responsible for a major difference between the two estimated pull loads. As described by Petroff (2004), the drag force depends on the fluid viscosity and cuttings removal efficiency. ASTM F 1962 estimates a drag pressure of 10 psi which typically gives a small calculated drag force, as may be expected for a well-prepared borehole. The PRCI method anticipates higher drag representing a less well-prepared bore. The different assumptions regarding fluidic drag may therefore be attributed to a different degree of conservatism in the estimates, recognizing the less than total control in the overall HDD operation.

4. Examples of ASTM F 1962 and PRCI Methods

Huey et al (1996) provides a detailed example to illustrate the application of the PRCI method; i.e., a 1500 ft (horizontal projected) borehole length; 100 ft maximum depth; 20° and 14° pipe entry and exit angles, respectively; and 1000 ft and 1200 ft bend radii, respectively. The product steel pipe is 12.75-in. outer diameter and 0.25-in. thick, with an elastic modulus (E) of 29 x 10^6 psi. The pipe has a net upward buoyant weight (no ballast added) of 46.4 lbs/ft, based on a drilling fluid with a conservatively high specific gravity density of 1.44 (12 ppg). The drilling fluid is also characterized by a coefficient of friction of 0.3 between the pipe and the borehole surface and the more recently adopted value of 0.025 psi for the fluidic drag (ASCE, 2005). Relative to the generic geometry of Figure 1, the excess length L_1 is assumed to be zero, consistent with the provided example for the PRCI method.

The resulting required tensile force of approximately 46,000 lbs (at the end of the installation) is illustrated in Figure 3 as determined by Equation 4, for the PRCI method. The contributing factors of Equation 4 are also indicated in Figure 3, including “stiffness”, “fluidic drag”, and “friction”. The net aggravating effect of the pipe “stiffness”, and corresponding friction force at the bends, may be calculated from double the reaction force (2N), as discussed above, but reduced by the magnitude of the buoyant weight along the length of the bend, which effect would be present independent of the route curvature and/or pipe stiffness. This is shown in Figure 3 as only 15% of the total, but is still significant for this case. It is evident that the contribution of the “fluidic drag” is approximately equal to the magnitude as the “friction” term in this example. For simplicity, the fourth term on the right side of Equation 4, corresponding to the direct effects of the net buoyant weight of the pipe at section AB and CD, are reflected in the “friction” term, since these contributions tend to cancel.

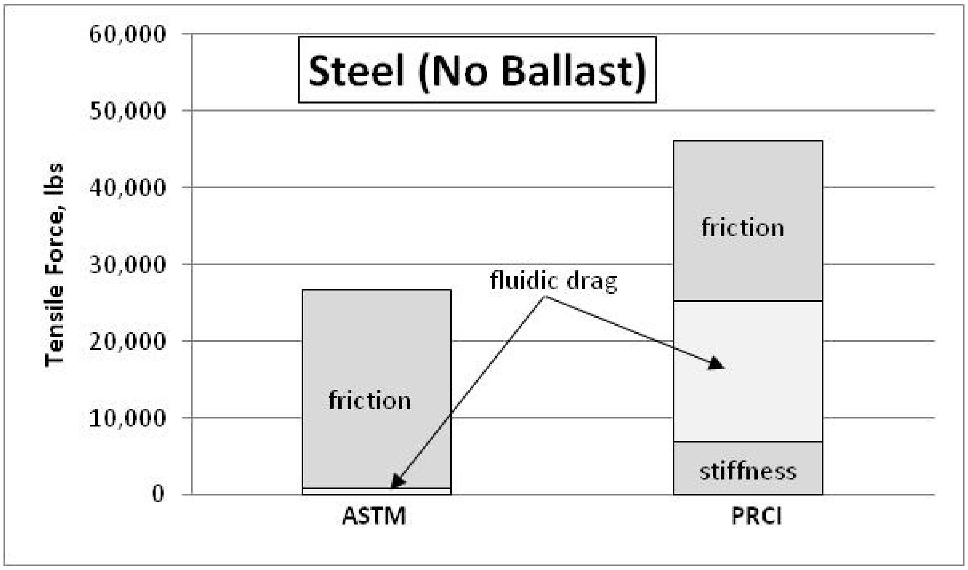

Figure 3 Estimated Tensile Force for Steel Pipe (No Ballast)

Figure 3 also shows the results of the basic ASTM method, which does not consider bending stiffness of the pipe, and uses the relatively low estimate of the fluidic drag, as given by Equation 2. However, the specific gravity of the drilling fluid is assumed to be the slightly more conservative value of 1.5, as recommended in ASTM F 1962, and the minimum suggested excess length (L_1) of 100 ft for Equation 1a is considered, along with a corresponding frictional coefficient (ν_a) of 0.1 (ASTM, 2011). The resulting installation load of approximately 27,000 lbs, as determined by the ASTM method, is much lower than that given by the PRCI method and is essentially due to the very dissimilar estimates of the magnitude of the fluidic drag, which is a major component of the PRCI result.

Figure 4 shows the results for the same 1500 ft installation, but assuming an HDPE pipe. The calculated installation loads are approximately 51,000 lbs for the PRCI method and 34,500 lbs using the ASTM procedure. The latter is again significantly lower than that of the PRCI method, but the differential is reduced due to the greater prominence of the frictional force relative to the PRCI estimate of the fluidic drag, since the HDPE pipe has a considerably greater buoyant weight than the steel pipe.

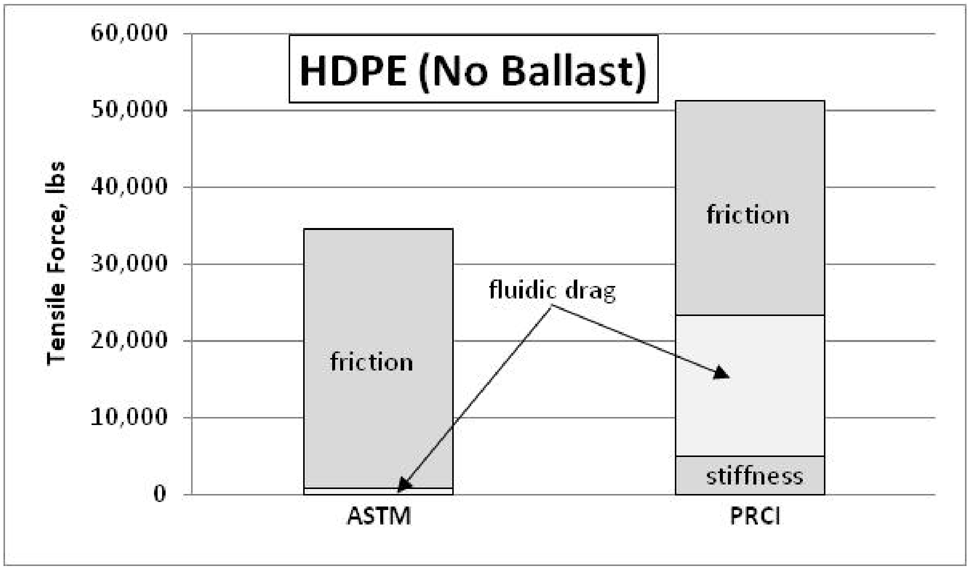

Figure 4 Estimated Tensile Force for HDPE Pipe (No Ballast)

Conversely, when using ballast to reduce the net buoyant weight of the steel or HDPE pipe, the associated grossly reduced magnitude of the frictional effects relative to the fluidic drag results in greater disparity between the ASTM and PRCI results. Figures 5 and 6 show the corresponding calculated installation loads for the steel and HDPE pipes, respectively. For these cases, the ASTM loads are much less than that determined by the PRCI method, especially for the steel pipe. Indeed, for the latter case, the extremely low net buoyant weight, acting downward, illustrates some important points.

HDPE pipe, even with internal (water) ballast, will always have a significant upward net buoyancy due to its inherent low material density (less than water). Thus, the assumption of a relatively high density for the drilling fluid (e.g., 1.5), as suggested in ASTM F 1962, will be conservative and provide a degree of design margin. Steel pipe, however, may have a very low net buoyant weight when ballast is employed, possibly close to or at neutral buoyancy, as in the present example (Figure 5). In this case, a conservative assumption for the drilling fluid would be a relatively low value for the drilling fluid density, rather than the present relatively high values (1.5 or 1.44), especially for the ASTM method.

Furthermore, for very low net buoyant weight, it is possible that the peak tensile load may occur at the beginning of the installation, as the pre-assembled steel pipe, resting on rollers, is initially drawn into the borehole. This situation is indicated in Figure 5 where the ASTM method provides an estimated peak installation load at the beginning of the installation which is several times that of the load at the end. This is due to the effect of the aboveground weight of the empty steel pipe, albeit on low friction roller supports, representing greater frictional resistance than the almost neutral buoyant weight of the steel pipe (with ballast) within the borehole. This situation is not evident with the PRCI method for which the relatively high assumed fluidic drag component represents a dominant effect.

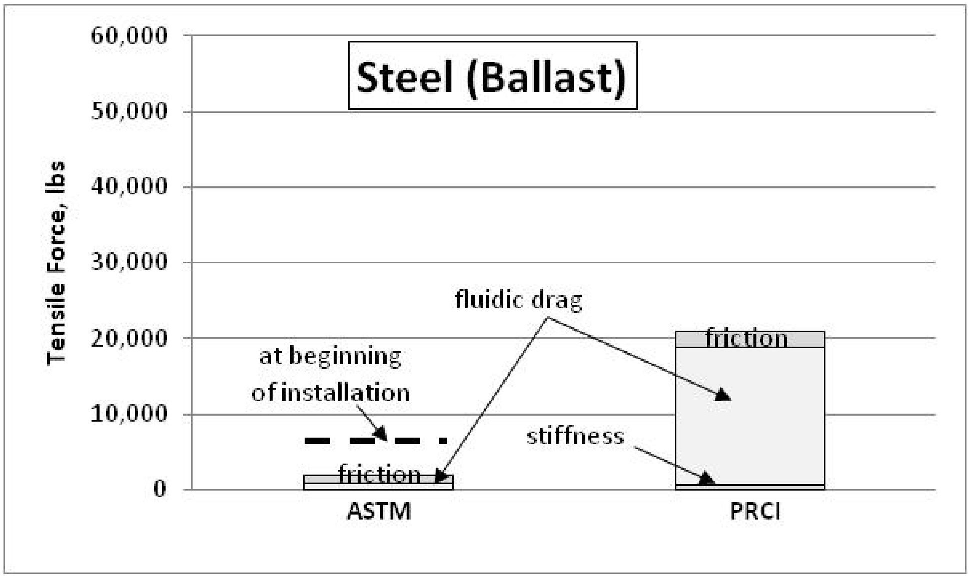

Figure 5 Estimated Tensile Force for Steel Pipe (with Ballast)

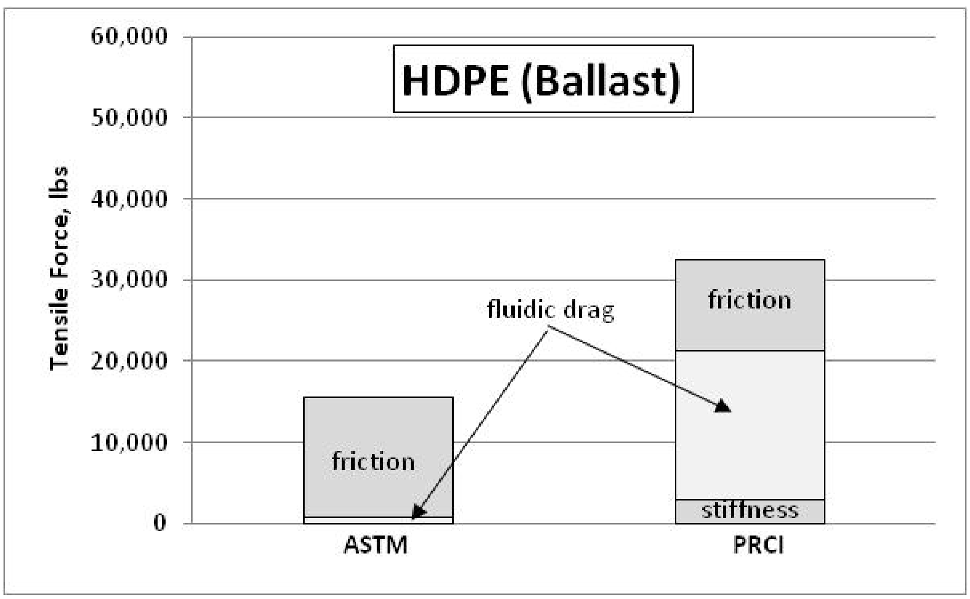

Figure 6 Estimated Tensile Force for HDPE Pipe (with Ballast)

5. Possible Adjustments to ASTM F 1962 and PRCI Methodologies

As in virtually all mathematical models, convenient assumptions and approximations have been incorporated into both the ASTM F 1962 and PRCI methodologies. The three-point beam bending model in Figure 2 has the advantage of accounting for the pipe stiffness in some manner, but is not compatible with the interaction of the pipe with the borehole, including the alignment of the force vectors indicated in Figure 2 which are not aligned with the axial tension on the pipe and the (perpendicular) normal pressure applied by the borehole on the pipe surface. This detail may inhibit the ability to properly reflect the capstan effect for which the direction of the tension can add to the effect of the (upward) buoyant weight. For maxi-HDD operations, however, the capstan effect is generally not major.

Although the basic ASTM model inherently ignores pipe stiffness, Equation 3 may be used to conservatively estimate the effect of the reaction forces as a function of the pipe and borehole characteristics for the purpose of extending the application of the ASTM methodology to pipe materials of relatively high stiffness -- e.g., steel. However, the net effect of the pipe stiffness, with respect to either the ASTM or PRCI methods, may be shown to be effectively nil or minor for many cases, including the present examples.

Analogous to the mitigating effect of the buoyant weight on reducing the effect of bending stiffness as otherwise estimated by Equation 3 for the ASTM method, the use of the "2N" term for estimating the reaction forces for the PRCI method should be reduced, depending on the magnitude and direction of the buoyant weight and reaction force N. Based on a direct balance of the lateral forces acting on the pipe, as indicated in Figure 2, it may be seen that the quantity ($N_1 + N_2$) is not equal to N, but depends on the magnitude and direction of the upper reaction force, N, and the buoyant weight, W_s. Based on these considerations, the "stiffness" contribution may also be ignored for the PRCI method for the examples presented, except for the steel pipe with ballast. For the other three examples (HDPE pipe, with or without ballast, and steel pipe, without ballast) these considerations would somewhat reduce the apparent discrepancies between the PRCI and ASTM F 1962 methods by the magnitude of the PRCI stiffness contributions shown in Figures 3, 4 and 6. For the case of the steel pipe with ballast, the stiffness contribution should be three times the otherwise smaller contribution indicated in Figure 5, but which is still relatively small compared to the total estimated load.

6. Other Related Investigations

Duyvestyn (2009) discusses both the ASTM F 1962 and PRCI methods, and compares the results to a new recommended technique that presumably better estimates the fluidic drag due to the dynamics of the drilling fluid. The proposed method is applied to three well-documented field installations of HDPE pipe and the results are compared to those based on the ASTM- and PRCI-type models and the actual field data. The results confirm that the PRCI method provides greater margin than the ASTM-based procedure, but both appear to be useful for this purpose.

Knight and Ademola (2003) compared various methods of estimating the pull loads, based on several mini-HDD (or midi-HDD) laboratory field installations of HDPE and MDPE pipe. Their conclusion was that the ASTM estimate is too low and the PRCI too high. However, the application of ASTM F 1962 (as well as the PRCI method), assumes a relatively well-controlled *maxi*-HDD type operation, for which additional unplanned path curvatures, and associated frictional forces, would be minimized. In contrast, this effect and additional load should be included in estimates for mini-HDD, and possibly midi-HDD, installations (PPI, 2009), and is explicitly discussed by Slavin (2007) with respect to these particular installations, and can account for the observed increase in pull force. Based on these considerations, the observed results for the laboratory field installations in question suggest that the pull load for a typically well-controlled maxi-HDD installation may be estimated by either the ASTM or PRCI method, with the latter providing greater design margin, as expected.

Zeng (2013) compares the results of three methods for estimating the pull force on (steel) pipe in four major river crossings in China, one of which is ASTM F 1962 and another which appears equivalent to the PRCI method. As may be anticipated, the PRCI-type procedure estimated greater loads than the ASTM method. In two cases, both the ASTM and PRCI methods over-estimated the observed load at the drill rig. In another case, the observed load was between those determined by the ASTM and PRCI methods. In a fourth case, however, both these procedures (as well as the third procedure adopted in China for application to HDD installation of urban water and sewer lines) underestimated the required pull force and is believed to be due to borehole instability and collapse around the pipe. The PRCI-type procedure was reasonably close to the observed load, indicating its additional design margin may be useful to help account for such situations.

7. Discussion & Conclusions

The two most widely used procedures for estimating the pull loads on pipes during a maxi-HDD installation are ASTM F 1962 and that adopted by the Pipelines Research Council International of the American Gas Association, designated as the PRCI method. Although the ASTM method is explicitly intended for use with polyethylene (e.g., HDPE) pipe, and the PRCI method was initially developed for steel pipe, accounting for the relatively high bending stiffness of this product, both procedures have been used for estimating HDD pull loads for pipes of various materials. The present paper discusses and analyzes the potential issues in the application of these methods to various materials, based on specific examples considering HDPE and steel pipe, with and without the deployment of ballast to reduce the buoyant weight and associated friction and installation forces.

The results indicate that the major difference between the magnitude of the calculated pull loads for the ASTM and PRCI techniques is their method for accounting for the fluidic drag acting along the pipe surface. In contrast, the effect of the bending stiffness is relatively low. The significant difference in the determination of the fluidic drag may be considered to be due to the assumed conditions in the borehole, with the PRCI prescription based on less optimal conditions than the ASTM formula, thereby resulting in a greater estimated pull loads. However, since neither method represents an attempt to predict the actual pull, but rather a means of providing a somewhat conservative design procedure based on the suggested values of relevant parameters, it is not surprising that there would be a significant difference in their estimates and associated design margins. In particular, since the design margin in ASTM F 1962 is primarily due to the high suggested value (1.5) for the specific gravity of the drilling fluid, and corresponding high buoyant weight, a nonetheless low calculated effective buoyancy due to the use of internal water ballast, for example, would significantly reduce the available design margin for this method, in the event of less ideal borehole conditions. This is especially important for steel pipe, which may have a close to neutral calculated net buoyancy based on the artificially high assumed specific gravity for the drilling fluid. In this case, a lower assumed specific gravity would provide more conservative results for either the ASTM or PRCI method.

In general, when these methods are considered in regard to other reported investigations, it appears they both are capable of providing reasonable results for design purposes for maxi-HDD installations, with the PRCI method providing greater design margin, as anticipated, possibly accounting for a degree of borehole instability.

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