Thrust Force Requirements During Direct Steerable Pipeline Thrusting (DSPT):

Friction or Fiction?

By: Stefan Goerz, M.Sc., P.Eng., PE., CCI Group of Companies

1.0 INTRODUCTION

Pipe thrusting in the pipeline industry has become a very common technique for trenchless crossing installation. The most common technique is Direct Steerable Pipe Thrusting (DSPT); however the pipe thruster has also been commonly used in other applications such as casing installation or retraction, and support for other trenchless techniques. The focus of this article is to review the pipe thrusting requirements for small overcut (or annulus) applications. Since the overcut is generally smaller than that of horizontal directional drilling (HDD) there is a concern of friction dominating the total thrust force required for installation or retraction. As in traditional microtunnel applications with limited vertical geometry, such as curves, the friction generally dominates the jacking or thrusting force requirements. Traditional microtunneling is predominantly used for larger diameter applications than what is seen for pipeline applications in the oil and gas industry.

The topic of frictional contribution and its impact on the pipe thrusting activity is very important to advance design to a stage that can help assess contractor plans with a known degree of accuracy. Conservatism isn't an adequate method for design, especially when working with a contractor to optimize equipment due to availability, construction workspace or worksite layout.

2.0 BACKGROUND

Direct Steerable Pipe Thrusting (DSPT) is continuing to gain popularity in the oil and gas, as well as municipal sectors, as a trenchless tool to execute complex crossings. The purpose of this section is to review the components of friction as they relate to this technology and to understand how designers are able to make the frictional resistance calculations more representative.

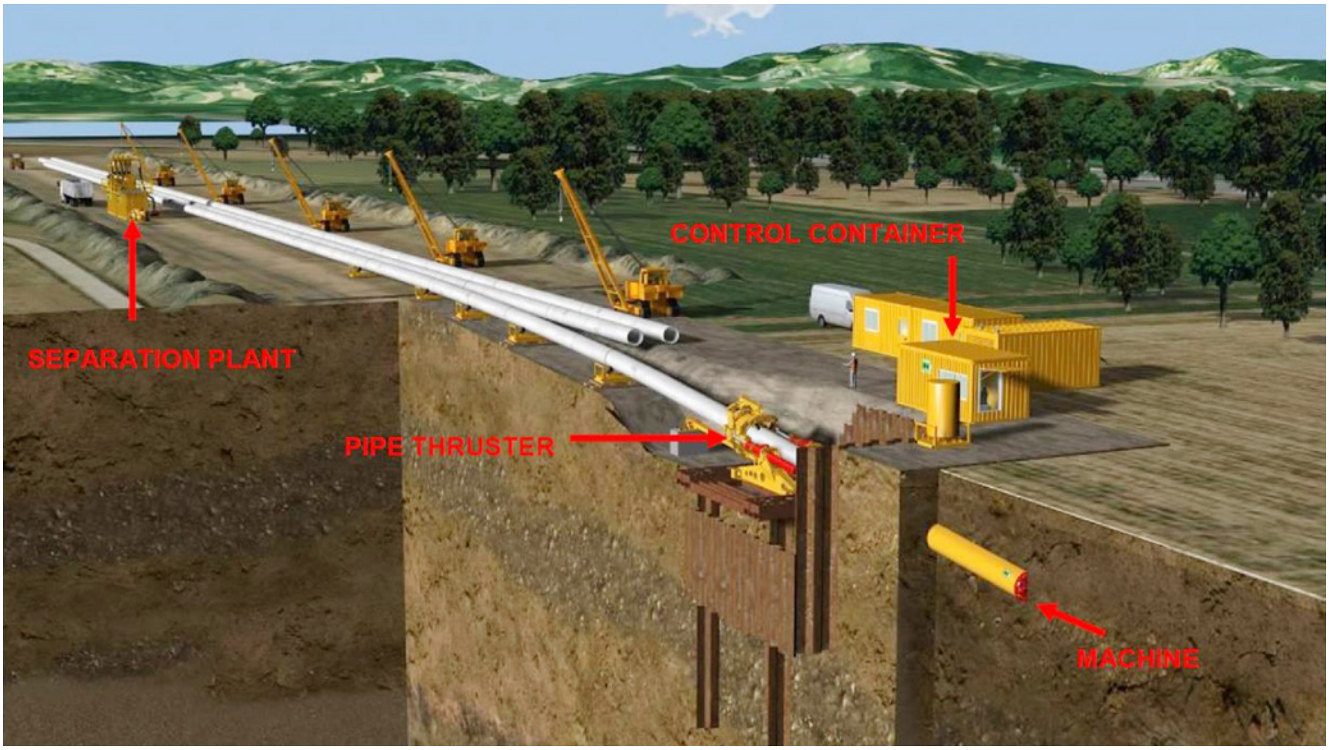

Figure 1. Typical DSPT worksite showing equipment at the launch area (Pfeff D., 2013)

2.1 Construction Application

As noted, pipeline thrusting is generally utilized for installation or removal of pipeline through the DSPT methods. DSPT is a method of installing steel pipeline crossings, ranging in diameter from 914.4 mm to 1524 mm (36 to 60 inches), by thrusting a guidable, slurry supported MTBM along a pre-determined path (Pfeff D., 2013). An illustration of a typical DSPT launch area is shown in Figure 1.

The product pipeline section is prepared, welded to the proper length, and laid on the surface. The MTBM is connected to the front of the pipeline section. The MTBM is typically 25 mm larger, radially, than the product pipeline, creating an overcut. A stationary thruster is situated at a launch location where the MTBM and pipeline are threaded through the clamping inserts of the thruster at the design angle. The vulcanized rubber clamping inserts grab the outer surface of the pipeline and push the MTBM and pipeline section forward. Additionally, the DSPT system uses a bentonite fluid injected within the annular space created by the overcut. The bentonitic fluid is under pressure, intended to support the soil along the borehole wall and provide lubrication during tunnelling operations.

"The importance of estimating thrust forces during Direct Steerable Pipeline Thrusting (DSPT) techniques cannot be understated."

2.2 Soil Mechanics

The soil mechanics of sliding the pipeline through the ground is a complex problem, especially considering the variability of the natural soils in combination with the bentonite lubrication fluid injected into the overcut during installation. Influential soil properties are the peak and residual angle of internal friction (friction angle) and adhesion or cohesion. For this article, friction angle will be examined in depth and cohesion or adhesion will be considered negligible in short term or dynamic applications. Cohesion or adhesion properties become much more significant during longer term standstills and long periods without movement which is considered another important subject for research. Interface friction is the amount of frictional resistance between two surfaces of different materials.

The peak angle of internal friction, associated with the Mohr-Coulomb failure envelope, is a very common property in soil mechanics and helps determine the soil shear strength. Conceptually, it is an estimate of the frictional resistance between the soil particles – a soil to soil interface friction. The residual friction angle is associated with movement, after a shear failure plane develops, and represents the minimum (lowest frictional strength). Generally, clay soils have lower friction angles, and sands/gravels heave greater friction angles. Typical values for angle of internal soil friction are shown in Table 1.

Organic soils as shown in Table 1 often have extremely high moisture content and could be analogous to a bentonite mixture near its liquid limit. Gleason (1997) completed a series of direct shear tests on hydrated and remolded bentonite and determined the friction angle was ~10 degrees for these samples.

3.0 LITERATURE REVIEW

3.1 DSPT Thrust Force

Pruiksma, Pfeff, & Kruse (2012) investigated the thrust force in DPI using ABAQUS finite element software package. The authors found that, according to the software, the five (5) mechanisms that contribute to the thrust force are as follows:

1. Friction behind the thruster on rollers,
2. Friction between the pipeline and lubricant fluid,
3. Front force at the MTBM face,
4. Friction between the pipeline and tunnel wall, and
5. Friction due to pipe buckling.

The method described by Pruiksma, Pfeff, & Kruse (2012), is herein referred to as the "***current state of practice***". This article focuses on mechanisms 2 and 4.

Table 1. Average drained friction angles of various soils (Praetorius and Schoser, 2017)

Soil Type	Angle of Internal Friction (degrees)
Sand, loosely compacted	30 to 32.5
Sand, densely compacted	32.5 to 35
Sand and Gravel, loosely compacted	30 to 35
Sand and Gravel, densely compacted	35 to 40
Broken stone / ballast mixes	35 to 45
Weakly cohesive soils	25 to 27.5
Highly cohesive soils	15 to 25
Organic Soils	5 to 15

3.2 Effect of Soil to Pipeline Interface Friction

The frictional forces that develop along the length of the casing or pipeline alignment are dependent on many factors. The magnitudes of frictional forces are mostly dependent on the interface shear of the pipe material, and the soil type along the tunnel sidewall. Many works of literature have examined the pipe to soil interface shear characteristics including Staheli 2006, Iscimen 2004, and Uesugi & Kishida, 1986. It is suggested to refer to the source literature to gain further understanding, as these works of literature go into much greater depth than this article. The research provides evidence that surface roughness of pipe material has a large influence on the amount of frictional resistance for pipe to soil contact.

Additionally, a “bi-linear” friction envelope appears to be present where the interface friction is unable to increase past the internal friction angle of the soil with which the material is in contact, providing insight into maximum frictional resistance in unlubricated sections of DSPT alignments. The relationship is shown on the illustration in Figure 2.

The concept that is shown from Figure 2 is that the maximum interface friction possible is the angle of internal friction of the soil in contact with the interface. This is because at that point of critical roughness, the shearing plane changes from the interface, to a point within the soil mass.

The residual friction angle to be used in the jacking or thrust force calculations for the soil which contacts the pipe is recommended by Bennett and Cording (2000) and Staheli (2006).

Iscimen 2004 determined frictional interface values of curved interfaces from research. The interface friction values obtained at various normal stresses is summarized in Table 2.

Table 2. The Coefficient of Friction at Various Pipe-Ottawa 20/30 Sand Interfaces (Iscimen, 2004)

Pipe Type	Coefficient of Friction					
	N = 40 kPa		N = 80 kPa		N = 120 kPa	
	peak	residual	peak	residual	peak	Residual
Hobas™ FRP	0.51	0.43	0.50	0.44	0.48	0.42
Polycrete	0.50	0.42	0.49	0.43	0.47	0.43
Steel	0.68	0.49	0.62	0.44	0.62	0.47
Wet-cast Con.	0.68	0.49	0.65	0.48	0.63	0.45
Vitrified Clay	0.71	0.50	0.63	0.48	0.65	0.49
Packerhead™ Con.	0.81	0.54	0.73	0.53	0.73	0.52
Sandpaper No.60	0.80	0.60	0.77	0.55	0.75	0.55
Sandpaper No.36	0.82	0.61	0.76	0.56	0.74	0.54

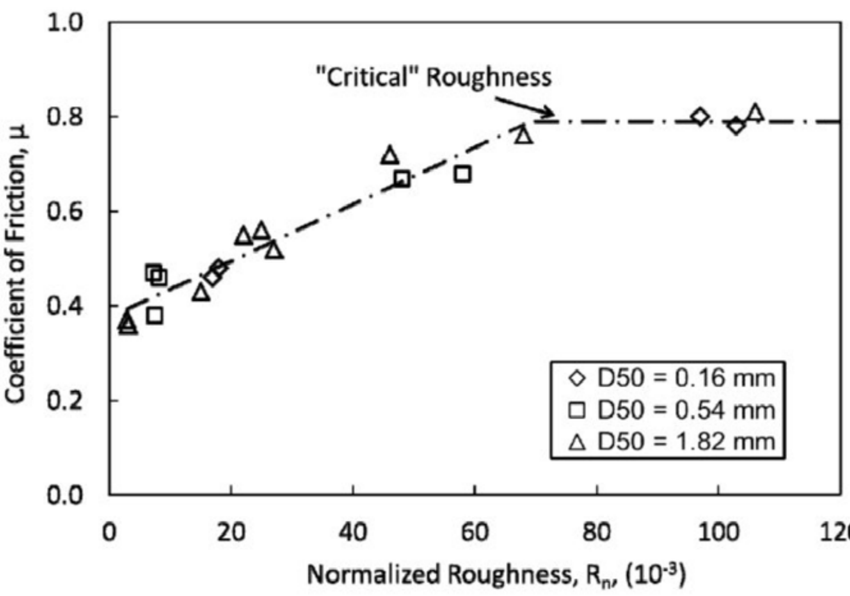

Figure 2. Illustration of the Bi-Linear relationship between coefficient of friction and surface roughness (Uesugi & Kishida, 1986)

3.3 Effect of Lubrication Bentonite

During installation of casings or pipelines by pipe thrusting, the bentonite lubrication would be expected to remain within the overcut in most soils. Therefore, the soil to pipeline contact may be limited. Marshall (1998) suggests that, depending on its stability, lubrication introduced in cohesive soil can work its way over the whole pipe surface, resulting in reduced friction along the entire length. The findings indicate that the average frictional resistance drops rapidly once bentonite lubrication is introduced; the decrease was found to be between 44 and 90 percent in Marshall’s research. Additionally, this research showed that in soil with peak friction angles of 37.5 to 38 degrees, the interface friction angle fell to 14 degrees once bentonite fluid was injected. This bentonite was introduced when jacking forces became excessive, which is known as partial lubrication. When using mass lubrication, where bentonite fluid is injected into the overcut continuously, the results of Marshalls research show friction angles may approach zero. Staheli (2006) reproduces similar findings in a portion of her Ph.D. thesis. She provides evidence in various case studies that there is marked difference in frictional resistance for lubricated versus non-lubricated intervals. Review of the

Research provides evidence that surface roughness of pipe material largely influences the amount of frictional resistance.

case study information revealed that by applying mass lubrication, a 90 percent reduction in jacking forces was observed in sandy soils. The information from case studies reviewed by both Marshall (1998) and Staheli (2006) reveal that mass lubrication techniques used in most pipe thrusting installation methods are likely to reduce significantly the amount of pipe to soil interface frictional resistance.

Furthermore, the impact of the magnitude of fluidic pressure within the overcut on the frictional resistance is an interesting concept. A drop in fluidic pressure within the overcut indicates a potential loss of fluid to the formation, and it is uncertain if this severely impacts the bentonite's performance. The effect of lubrication pressure was examined by Namli & Guler (2017), and their work suggests that the benefits of bentonite application under constant pressure can be achieved with minimal injection pressures. Namli & Guler suggest that it is not the amount of pressure that reduces pipe-soil friction to 10 percent of its original value; but the mere presence of pressure ensures that bentonite is coating the entire pipe surface area. If pressure is present in lubrication chamber, it is likely that the entire surface area is coated in this lubrication, and the interface friction could be comprised entirely of pipe-bentonite contact, rather than pipe-soil (Namli & Guler, 2017).

Consideration needs to be given to potential deterioration of bentonite lubrication during longer drives. Unlike in conventional microtunnelling where lubrication ports may be installed throughout the drive, during DSPT there are only bentonite injection ports at the front end near the MTBM during installation. This makes targeted injection of the bentonite impossible in the case of deteriorating bentonite. Deteriorating, or non-performing lubrication will significantly affect the thrusting requirements. An added function of the bentonite lubrication is to support the soil surrounding the pipe being thrusted. Consideration needs to be given to the specific gravity and particle size of the soil being supported. If high specific gravity soil particles are present, there is a higher probability that over the duration of pipe thrusting, more soil will be in contact with the pipeline and negate the effect of the lubrication bentonite.

4.0 PLANE OF SHEAR

The plane on which the sliding occurs would determine the interface friction properties during pipe thrusting. The frictional resistance develops due to interface friction between the various materials along the length of the pipeline. The possible interfaces that may impact the overall frictional resistance of the pipeline thrusting may include:

1. Pipeline to Bentonite Lubrication
2. Pipeline to Natural Soil
3. Bentonite Lubrication to Natural Soil

In addition, the angle of internal friction between the same soil materials may be the plane on which shearing takes place.

1. Bentonite to Bentonite
2. Natural soil to natural soil

Figure 3 shows the layers where shear may occur in the annulus and just adjacent to the annulus of the pipeline installation.

Shear would be expected to occur along the interface or material with the lowest frictional coefficient. This is similar to the concept of critical roughness described by Uesugi & Kishida in 1986.

Shear stress is a function of normal stress and the frictional coefficient of the materials in contact along the plane of shear. In order to determine feasible

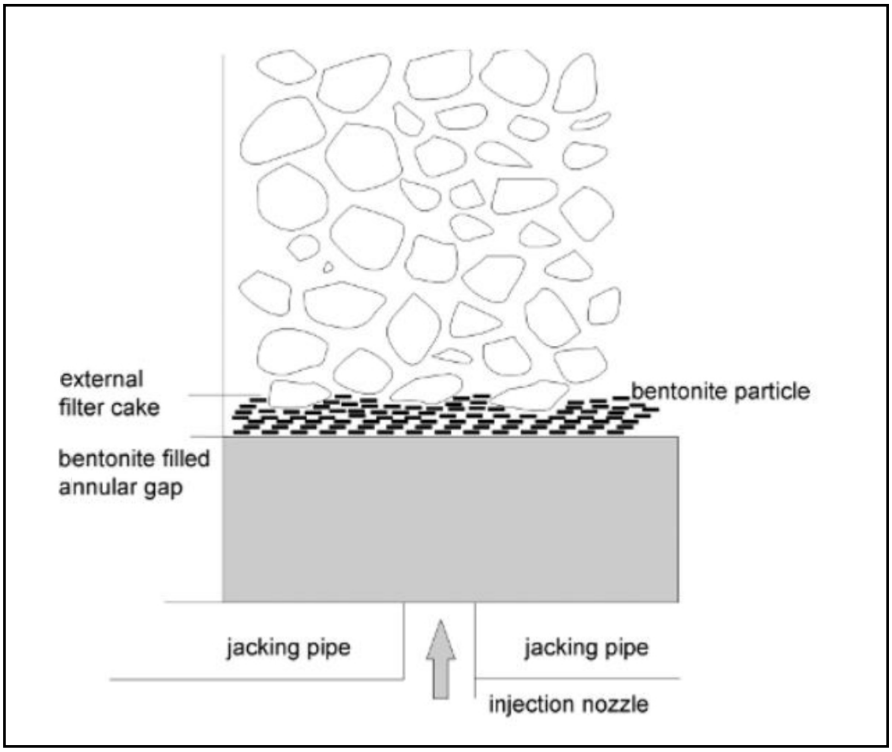

Figure 3. Layers of potential frictional resistance (Praetorius and Schoser, 2017)

Table 3. Back Calculated Friction Coefficients from Case Studies

Case Study	Lubrication Friction Coefficient (N/m^2)	Soil Friction Coefficient ([]) *
Case Study 1	65	N/A
Case Study 3	45	N/A
Case Study 4	7	0.045

* Only Case study 4 had data that was suitable to assess the soil frictional coefficient.

mechanisms for failure of each failure plane there are important considerations such as normal stress, soil hydraulic conductivity as well as lubrication fluid yield point and stability. Deteriorating bentonite fluid could allow additional soil to come into contact with the thrusted pipeline and cause additional friction.

5.0 PREVIOUS CASE STUDY RESULTS

Thrust force during DSPT was evaluated by using case studies and comparing the data obtained to the current ***state of practice calculation method*** (Goerz, 2019). The frictional resistance coefficients embedded within the state of practice calculation method were modified and normalized to best fit the case study data for specific intervals of the drives. It should be noted that this data was mainly obtained for drives through clayey soils. The lubrication friction coefficient and the soil to pipeline interface frictional coefficient are reported in Table 3.

As shown in Table 3, the Case Study 1, Case Study 3, and Case Study 4 lubrication friction coefficients range from 7.0 N/m2 to 65.0 N/m2, which agree well with the recommended value of 50 N/m2 (Pruiksma, Pfeff, & Kruse, 2012).

The soil to pipeline interface friction value was measured through the analysis of Case Study 4. The value obtained was 0.045, which is substantially smaller than the recommended value of 0.2 (Pruiksma, Pfeff, & Kruse, 2012). Although the value is very small, considering that the clayey soil conditions provide a stable tunnel wall, this may be a frictional value more representative of a bentonite lubrication-coated clay wall (or no pipe-soil interaction). The coefficient of friction value determined from the Case Study 4 Data results in an interface friction angle of ~2.5 degrees, which isn't unrealistic for a hydrated bentonite.

6.0 OPPORTUNITIES

When designers use the ***state of practice calculation method*** for determining thrusting requirements there are opportunities to improve the frictional assessment.

Currently the ***state of practice calculation method*** considers both bentonite lubrication-to-pipe and soil-to-pipe interface friction acting through the entirety of the drive. There could be consideration to use three cases when evaluating the frictional resistance to develop risk profile for various unanticipated construction events. The first case could consider the case that the lubricating bentonite or bentonite coated soil (stable sidewall) is the only interface friction during construction. This calculation would utilize the lubrication bentonite frictional coefficient for the entire drive. A second case would assess the potential areas of a specific drive where the bentonite lubrication may deteriorate and added soil to pipe interface friction becomes more apparent. These locations would be areas of coarse granular soils in the drive, or depending on the schedule of the construction, these could be areas near the beginning of the drive where the lubrication has been in use for significant time. A third case could consider a "Worst Case" scenario to assess a collapse of soil onto the pipeline for a significant section if likely, or worse, soil-to-pipeline interface friction for the entirety of the drive.

Another very important consideration which wasn't as much of a focus in this article is the magnitude of normal force the pipeline exerts on the tunnel sidewall. More research is needed in this area, however at the vertical curves or build sections of the design, a normal force may be significant enough to cause "plowing" or a case where the bentonite lubrication is scraped off the wall and a shear plane within the soil mass develops. In this case the soil internal angle of friction would be considered and, as one could imagine, would significantly increase the amount of resistance.

7.0 CONCLUSIONS

Conclusions of this research are:

1. The importance of understanding the soil mechanics and frictional properties of the soil through which the tunnel is constructed is imperative. These properties can significantly affect the analysis.
2. Assessment of the various cases during pipe thrusting is imperative to assist in determining the risk profile for specific crossings.
3. Assessment of normal force should be re-examined to assist with estimating the frictional forces in build sections of the DSPT profile.
4. Additional research is warranted to determine the shear strength properties of bentonite lubrication, as well as shearing angles of resistance. This would not only assist with frictional resistance estimation but would also assist in determining potential hydraulic pressures developing within the overcut.

> *DSPT is continuing to gain popularity as a trenchless tool to execute complex crossings.*

8.0 REFERENCES

Bennett, D., & Cording, E. J. (2000). Jacking Loads & Ground Deformations Associated with Microtunneling. No-Dig 2000 Conference (pp. 19-35). Anaheim: North American Society for Trenchless Technology.

Gleason, M.H., Daniel, D. E. and Eykholt, G.R., (1997) "Calcium and Sodium Bentonite for Hydraulic Containment Applications." J. Geotech. And Geoenv Engrg., ASCE, 123, pp 438-445 Iscimen, M. (2004). Shearing Behavior of Curved Interfaces. Atlanta: Georgia Institute of Technology.

Marshall, M. A. (1998). Pipe-Jacked Tunnelling: Jacking Loads and Ground Movements. Oxford: Magdalen College, University of Oxford.

Namli, M., & Guler, E. (2017). Effect of Bentonite Slurry Pressure on Interface Friction of Pipe Jacking. Journal of Pipeline Systems Engineering and Practice, 04016016.

Praetorius, S., Schoser, B., (2017). Bentonite Handbook Lubrication for Pipe Jacking, Wilhelm Ernst & Sohn, Archirektur und technische Wissenschaften GmbH & Co., Rotherstrase 21, 10245 Berlin Germany

Pruiksma, J., Pfeff, D., & Kruse, H. (2012). The calculation of the thrust force for pipeline installation using the Direct Pipe method. Deltares/National Institute Unit Geo-engineering.

Staheli, K. (2006). Jacking Force Prediction: An Interface Friction Approach Based on Pipe Surface Roughness. Atlanta: Georgia Institute of Technology.

Uesugi, M., & Kishida, H. (1986, December). Frictional Resistance at Yield Between Dry Sand and Mild Steel. Soils and Foundations, 26(4), 139 to 141.

ABOUT THE AUTHOR:

__Mr. Stefan Goerz, M.Sc., P.Eng., P.E.__ is the Geotechnical Manager for CCI Inc. and CCI & Associates Inc., a Canadian and US Engineering Firm, respectively, specializing in pipeline engineering including trenchless methods. He has over 11 years of directly related experience in projects related to trenchless pipeline construction, geotechnical investigation and assessment for pipeline and trenchless design, geotechnics for tunnel/microtunnel design as well as geohazard assessment for linear infrastructure projects. Stefan completed his Bachelors Degree (2013) and Thesis based Masters Degree (2019) specializing in Geotechnical Engineering at the University of Alberta. In 2020, Stefan became registered in the USA as a Professional Engineer completing both the Fundamentals of Engineering (FE) and the Practice of Engineering (PE) exams.