Real Time Data Acquisition and Prediction Model Comparison using Maxi Directional Drills

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Kyle Verwey

Abstract

Horizontal Directional Drilling (HDD) is used around the world when traditional open cut methods are not practical or impossible for installing pipelines. Maxi-sized drill rigs are the largest and most powerful directional drills and are more common in the field than ever before with over 5,000 rigs in operation world wide. The complexity of installations and the design associated with them continues to increase.

This research has two main objectives.

1. Develop a real time data acquisition system for monitoring pullback forces on the product pipe; and,
2. Compare data gathered using maxi-sized drill rigs with current modelling methods using BoreAid.

The first portion of the research, as listed above, required attaching multiple pressure transducers to the drilling display panel in an American Auger DD-1100 drill rig and recording, in real time, the carriage, rotation, and mud pressure as seen by the operator. This research also describes the various challenges and issues associated with developing real time in-the-bore data acquisition processes. Finally, future recommendations for further development of the in-the-bore data acquisition are discussed.

The second portion of this research describes how the gathered data was processed into a workable data set. The field data was then compared to theoretical models by using the drill assistant tool BoreAid. The results of this comparison show that these models are appropriate for all size drill rigs, although some limitations are present.

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First and foremost I would like to thank my supervisor, Dr. Mark Knight, for his experience, insight, and guidance throughout this long process. Without his industry connections and expert knowledge of this subject, none of this would be possible.

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I would also like to extend my sincerest appreciation to the following individuals for their assistance in this research:

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Chapter 1 - Introduction

1.1 General

Horizontal Directional Drilling (HDD) has been used as an alternative in new pipeline installation since the 1970s (Allouche et al. 2000). Originally, the relatively complicated and inaccurate steering system did not build confidence in the technology, resulting in only 36 HDD installations to be completed from 1971 to 1979 (Allouche et al. 2000). The early 80s was a time of vast advancements in the technology, including smaller more powerful rigs and new navigation tools for steering. The number of directional drilling rigs increased from 12 rigs in 1984 to over 6,000 worldwide (Allouche et al. 2000). As HDD continues to become a more common approach to pipeline installations, certain quality assurance and quality control methods must be followed. American Society for Testing and Materials (ASTM) standard F1962-11 is the most recent standard for HDD installations.

The rate and force applied to the product pipe is of particular importance, since improper installation loads can severely damage the product pipe. If pull forces are too high, stretching and weakening of the pipe walls can occur. If pull rates are too high, stretching, necking and general wall thinning can appear in visible pipe sections. Currently, this pull force is controlled by the drill operator through the rate at which the drill rods are pulled back. The only reading visible to the operator is from a pressure gauge located on the main console. This reading can change drastically as the pipe is pulled through the ground. If the product pipe catches on a rock or the drill path suffers a collapse, the pressure can spike and cause damage to the pipe.

Since more than 95% of the pipe is below ground it is very difficult to survey the status of the pipe after installation. If, after months or years of use, the pipe fails before its design life is up, the installation methods or material quality is questioned. The most significant impact on the product pipe would have been the installation pressures or, in the case of High Density Polyethylene (HDPE), the fusion procedure as per ASTM 2620. To ensure the pipe was installed within manufacture recommended specifications, installation data collection is critical.

1.2 Research Goals and Objectives

The main goals of the research are to:

1) Develop a system to monitor, in real time, the forces felt by the product pipe during HDD installation.

2) Better understand and compare theoretical design models to actual installation data.

To realize these goals, the following tasks were carried out:

1. Develop an 'ideal' framework for real time data acquisition of HDD pipe installations.
2. Build, install, and gather data using above ground data logging equipment.
3. Develop and troubleshoot underground real time data logging equipment.
4. Compare current mathematical models to gathered installation data.

To develop the necessary underground data acquisition systems required for the pressure readings, a number of wireless and wired data transfer options were explored.

1.3 Thesis Outline

Chapter 2 of this thesis provides an overview of Horizontal Directional Drilling (HDD), the various types of drill rigs, drilling fluids, and pipe materials in use, and current QA/QC systems available. Chapter 3 provides details about the design assistant program BoreAid and the various methods that it uses to develop theoretical installation designs. Chapter 4 presents the framework for real time data acquisition with all the various attempts to develop a wireless underground system. Chapter 5 presents the gathered data from four pipe installations with the data logging system in place. Chapter 6 discusses the analysis and comparisons of the gathered data with the developed models. Chapter 7 states conclusions and recommendations for future work.

Chapter 2 – Horizontal Directional Drilling Overview

HDD is used to install pipelines under rivers, creeks, cemeteries, gas pipelines, and any other obstruction that cannot easily be trenched. It can also be a preferred method when a pipeline is being installed at extreme depths, where trenching is an impractical solution.

2.1 Horizontal Directional Drilling Process

A HDD installation is a process that is broken down into three phases. First the initial pilot bore must be completed. This involves a steerable drill bit being pushed from the drill rig along a predetermined path. There are a variety of drill bits available depending on the type of soil material that will be drilled through. To control the direction of the drill bit, the most common system used is a magnetic signal transmitter, called a SONDE, is installed in the drill head. This transmits to the surface the orientation of the drill bit. To make the drill bit steerable, each drill bit will have one angled face and the drill bit will always push away from the direction that the angled face is facing. By controlling the orientation of that angled face, the driver/operator can steer the drill bit. If the drill bit needs to move in a straight line the angled face will be directed to spin in circles while it is being pushed. The entire time the drill bit is cutting through the ground, drilling fluid or mud is being forced out of the bit or reamer. The importance of this drill fluid will be detailed in Section 2.3. Figure 1 presents an example of a profile for an HDD installation.
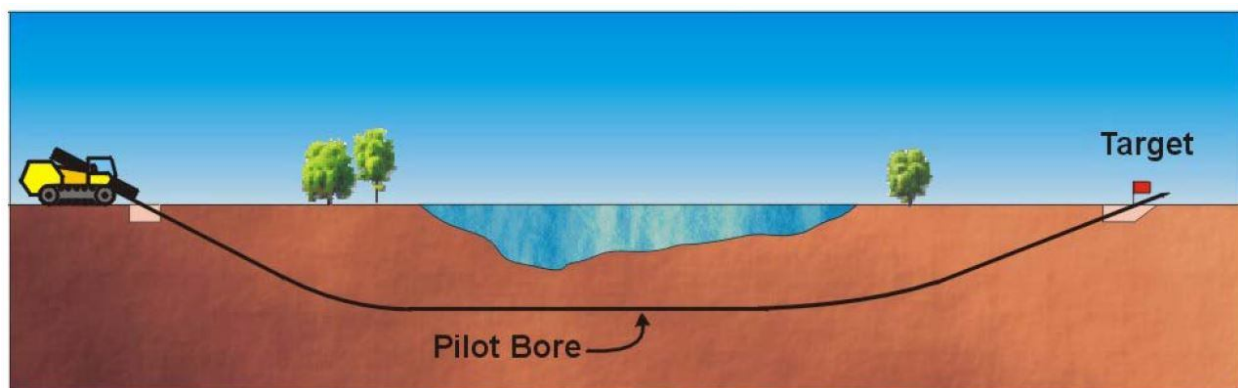
Figure 1: Profile of a typical HDD installation (NASTT Good Practices, 2001)

Once the bore path has been drilled with the steerable drill bit and the initial bore is completed, the second phase involves pulling back a series of reamers to expand the bore path. These reamers will gradually increase the size of the bore and the final dimension is based on the size of the product pipe. Table 1 details the recommended relationship between product pipe size and the reamed diameter of the

bore (Bennet et al, 2001). While these are recommended guidelines the actual reamed diameter will be up to the drill operator based on the situation and ground conditions.

Table 1: Recommended Relationship between Product PIpe Size and Reamed Diameter of a bore

Product Pipe Size	Reamed Diameter
< 8″	Diameter of product + 4″
8″-24″	Diameter of product x 1.5
> 24″	Diameter of product + 12″

The final phase of installation involves pulling the product pipe into the expanded bore path. The final reamer is again used to maintain the size of the bore path. Behind the reamer is a revolving joint, which is a type of swivel which stops the product pipe from rotating and adding additional stresses. Then a pipe bushing attaches the pipe to the swivel. This set up is shown in Figure 2 (Jiang et al, 2012). This system is then pulled through the entire bore path until the reamer is retrieved at the drill rig, Figure 3. Once the pipe has been installed, spot excavations are made at each end to complete the construction.
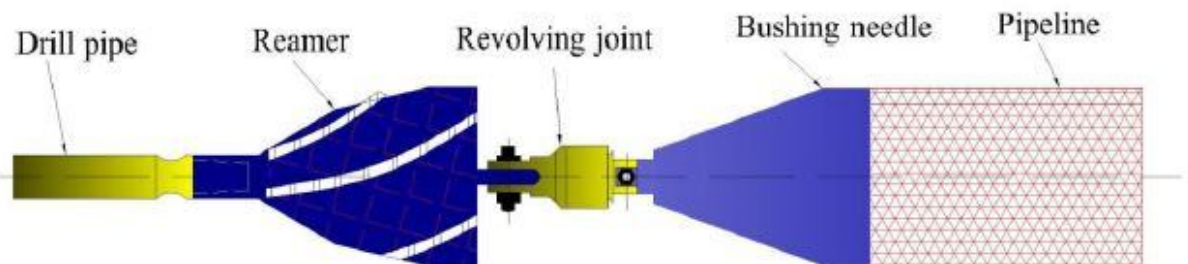
Figure 2: Pipe Pull back set up (Jiang et al. 2012)
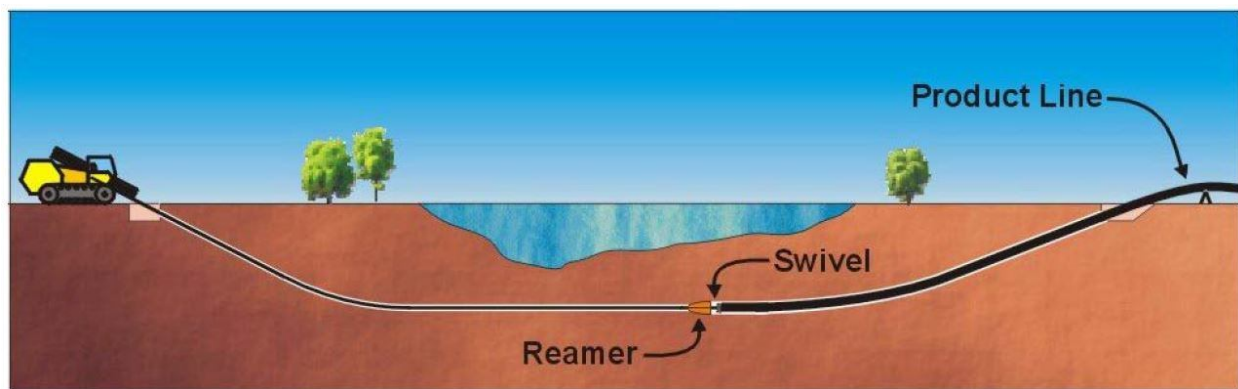
Figure 3: Pullback process for a HDD Installation (Bennet et al, 2001)

2.2 Drill Rig Types

There are three classifications for sizes of HDD rigs; mini, midi, and maxi. While each manufacturer has slight differences between each rating of rig, HDD rigs can pull from 5000 lbs for the smallest to over 1.3 million lbs of thrust (Vermeer D1320x900). Figure 4 shows a sample picture of each sized rig. While there is no distinct cut off point between rating a rig mini or midi there are some general guidelines. *Trenchless Technology Special Supplement: Horizontal Directional Drilling Guide* and NASTT Good Practice both define the size of HDD rigs, these are compared in Table 2.

Figure 4: Examples of Maxi, Midi and Mini HDD rigs

Table 2: NASTT Good Practices vs TT Magazine HDD Rig Size Rating

		NASTT Good Practices	TT Magazine HDD Guide
Mini HDD Rigs	Drilling Distance (ft)	≤ 700	≤ 600
	Thrust/Pullback (lbs)	< 40,000	≤ 20,000
	Torque (ft-lbs)	< 4,000	≤ 950
Midi HDD Rigs	Drilling Distance (ft)	≤ 2000	≤ 1000
	Thrust/Pullback (lbs)	40,000 – 100,000	> 20,000
	Torque (ft-lbs)	4,000 – 20,000	> 950
Maxi HDD Rigs	Drilling Distance (ft)	≤ 6000	> 1000
	Thrust/Pullback (lbs)	> 100,000	-------
	Torque (ft-lbs)	> 20,000	-------

When choosing which size of HDD rig will be used for any particular job, one must take into account design considerations, space limitations, time constraints, and contractor availability. Larger jobs cannot be done with smaller rigs, but sometimes having a slightly oversized rig is more advantageous than not.

2.3 Drilling Fluids

When beginning a HDD installation the most important consideration are the drilling fluids. The purpose of the drilling fluid is four fold. Firstly, it lubricates the reamer, drill rods, and product pipe. Second, during stoppages the drill fluid stabilizes the bore hole. Third, additives to the drill fluid help to prevent water and drill fluid from escaping the bore hole. And finally, it carries the soil cuttings out of the bore path. When drilling fluid mixes with the soil cuttings it is called 'slurry' and can either be discarded or recycled. An important consideration with regards to the drill fluid is the type of soil along the bore path, because depending on the type of soil along the bore path the drill fluid will change.

The drilling process depends on the drill fluid so much that it can only progress as fast as the drill fluid can flow. Since the fluid is removing the soil cuttings in the slurry, if the drilling progresses faster than the drill fluid can remove the cuttings the drill head or reamer can become stuck. The properties of the fluid are also very important, they must be tested before the drilling operation begins to make sure that the fluid is designed to complement the soil along the path.

Drilling fluids have a number of properties that must be balanced and tested based on in-situ soil conditions. Balancing these properties is very important to ensure a successful HDD installation. According to NASTT Good Practices these properties include:

- Viscosity, a fluids resistance to flow. If the mud is too thick or too thin it will not function properly
- Gel Strength, how well the 'mud' sticks together after stoppage of flow. The idea behind this is to make sure any solid cuttings do not settle on the bottom of the bore hole during changes but stay afloat in the slurry.
- Fluid Loss, how much filtrate (water) is lost from the mud into the soil surrounding the bore. Low fluid loss is key for a stable bore hole.
- Fluid Density, the weight per volume of the mud. As the fluid absorbs cuttings and becomes denser it must still be able to flow and move the cuttings from the bore hole.
- Filter Cake, the thickness of mud layered on the edges of the bore hole. A thicker filter cake will reduce the amount of filtrate that can flow out of the bore hole and support the surrounding soil.

- Sand Content, how much sand is in the drilling fluid. High sand content will reduce the effectiveness of the drilling fluid and reduces the life expectancy of the drilling equipment.
- pH, the acidity or alkalinity of the fluid. Typically the pH of a drilling fluid should be 8 or 9 to give the additives the optimum environment for performance.
- Lubricity, how well the drill fluid reduces friction. When pulling pipe or moving cuttings the less friction is always better.

When the soil is very sandy, an expanding clay, usually bentonite, is added to the drill fluid. This clay will fill the voids of the walls of the bore path to stabilize them. When the soil contains large amounts of clay, a specific type of polymer can be added to support the clay and ensure the walls do not slump into the bore path. There are a variety of drill fluid additives and any HDD installer will have their own preference based on soil conditions.

The direction of flow of the drilling fluid also has an effect on the pullback forces required to move the product pipe. Fluid always tends to flow along the path of least resistance, the same is true with drilling mud. As reamer moves along the bore the slurry will flow in the opposite direction of the pipe that is being installed. When the reamer reaches approximately two thirds of the way to the pipe exit pit the flow of mud will switch directions and begin to flow in the same direction that the pipe is being installed (Duyvestyn et al, 2001).

2.4 Data Logging System

All pipes, for instance stainless steel, Carbon Steel, High-Density Polyethylene (HDPE) or Polyvinyl chloride (PVC), have a maximum yield strength. When pulling pipe, if the forces acting upon the pipe approach or attain the particular level of yield strength for the type of pipe being used, the pipe may become damaged or even break. The majority of pipes, if they ever fail, will do so during installation due to the active forces during installation.

In practice today, while installing pipe, the pull and rotation pressures are monitored by the drill operator. They are not recorded and human error can miss short spikes in pressures. After the installation if there are any problems with the pipe, because there is no recorded data the installer can have difficultly proving their install methods did not overstep the installation parameters. These short spikes can be caused by obstructions catching on the reamer or pipe and could cause gouges in the product pipe. The reading from

the drillers gauge is the pull force felt by the rig. Since when installing pipe there is a reamer with a larger diameter, the pull force is mostly attributed to the reamer and the force actually exerted on the product pipe will be significantly less. Without a data logger between the reamer and the product pipe it is very difficult to gauge the actual forces exerted on the pipe.

The TensiTrak, made by DigiTrak, is the one commercial data gathering and logging product currently on the market that can be installed between the swivel and the product pipe to record and display in real time the actual pull pressure felt by the pipe. This product is rated at 100,000 lbs of pull force and can only be used on the mini and midi sized drill rigs. A similar product was developed and used at the University of Western Ontario in 2003. These load cells were rated at different pull pressures, the largest being 670 kN (150,000 lbf) and the smallest being 36 kN (8,000 lbf) (Baumert, Allouche & Moore, 2003). Each load cell had a different method of downloading the data and it is unclear if the data can be viewed real-time.

Additionally, previous research done at the University of Waterloo Duyvestyn (2001), Adedapo (2001) and Ho (2007) using a DAQ system that was built inside an HDPE casing and fused directly to the HDPE product pipe. This head was then attached to the swivel and used to pull back the product pipe. This equipment monitored pull loads, mud pressures, pipe strain, temperatures and pipe wall deflection. The data recorded by this system was stored on an internal storage unit and was available for download after the HDPE casing was recovered. Table 3 presents a comparison of the different data logging equipment detailed in this research. Additional references for table 3 include Baumert, et al. (2003) and Duyvestyn (2009).

Table 3: Comparison of data logging equipment

Data Logger Origin	Installation Sizes	Pipe Material	Loading Capacity	Advantages	Disadvantages
University of Waterloo	Custom Built	PE/Steel	Same as installed Pipe	No additional unit between reamer and pipe	Must be custom sized to pipe. No real time data logging
University of Western Ontario	Based on Load	Any	150,000 lbf	Largest pull load capacity	No real time data logging. Causes turbulent mud flow.
DigiTrak TensiTrak	Based on Load	Any	100,000 lbf	Compatible with DigiTrak walkover equipment	Causes turbulent mud flow. Limited loading capacity. Power limitations
Phase 1 Data Logging System	Any	Any	Any	Real time data	Forces not measured at product pipe
Phase 2 Data Logging System	Any	Any	Any	Real time data	Signal Transmission limitations. Power limitations.

This research was completed using an American Auger DD-1100 which can pull up to 1,100,000 lbs. Currently, a data gathering and logging product does not exist that can be installed to withstand this pull force.

Figure 5: American Auger DD-1100 Set up in the field

Previous research and testing by Baumert, et al. (2003) and J. Ho (2007) have worked with data logging systems which record pipe pull forces and drilling mud pressures. However, this data was recorded using an internal unit, installed directly between the reamer and the product pipe, and cannot be accessed until after the pull is complete. While this can be helpful for quality assurance it does not help the installation process or quality control. Any problems during installation could still be missed and without the real time data problems may go unaddressed until well after the installation is complete. Those apparatus' mentioned were only rated for mini to midi sized drill rigs so the larger, riskier, and more expensive installations still do not have a real time quality assurance and quality control data logging system.

To further the previous research two main suggestions were put forth: first to gather data and display it real time so that quality control can be done during pipe installation, and secondly to gather this data for a large scale installation using a Maxi-sized drill rig. This data would not only benefit HDD contractors by confirming their installation procedures but it would also, after further study and testing, improve installation methods. The real time data will also be able to confirm or improve developed mathematical models which will enhance the engineer design aspect of HDD installations.

Chapter 3 - Designing On-line Data Acquisition System

This design of an on-line data acquisition system was developed and broken down into two phases. Phase one involved developing a real time data acquisition system that would record the desired data and display it so the driller would have immediate access to it. Phase two involved designing and developing an in-ground pressure sensor that would record pressures, strain, and forces and transmit them real time to the driller for use during installation. This real time data transmitter would also be designed to work with Maxi-sized drill rigs and not require a wired connection.

3.1 Developing an Ideal Data Framework
Before implementing any field equipment, an ideal data gathering framework was developed to determine what data would be ideally gathered during each installation. From the operators control panel; carriage pressure, rotary pressure, and mud fluid pressure would be recorded. From the drill rig frame the drilling mud flow rate would be recorded. From the drill rig CAT engine both the engine RPMs and fuel rates would be recorded. Finally, from the reamer head in the bore path; pull stress, shear stress, GPS location, and drilling mud fluid pressure would be recorded. All of this data would be available in real time within the drill cab via a wireless signal.

3.2 Phase 1: Real time surface data
For the purposes of this study Honeywell Model LM 5000psi pressure transducers were installed in the drill cab and attached directly to the operators' pressure gauge for carriage pressure, rotary pressure, and drilling mud pressure. This data gathered by the transducers was recorded at an interval of 0.01 seconds by a SoMat eDAQlite system and monitored directly during installation via the InField software. The SoMat data logging system is a high accuracy customizable series of controller layers which can be set and organized to record an infinite amount of data. InField is the interface program that can gather and display the recorded data from the SoMat and display it in a variety of different ways. The three pressure transducers had their calibration checked at the University of Waterloo using a dead weight testing unit. This dead weight testing unit is similar to a scale, except the weight is converted to pressure in hydraulic fluid. The transducers were hooked up to the hydraulic fluid to confirm their calibration. The calibration was checked before the first field data gather and between the second and third field data gathering session. The pressure transducers were installed using tees directly into the hydraulic lines that supply the

pressure for the operators' gauges. It should be noted that for the first data gathering only the carriage pressure (pull force) was recorded due to a limited of availability of transducers.

The surface data acquisition system was used in four separate pipe pulls. Each pipe installation was done by the same drilling team using an American Auger DD-1100 Maxi HDD drill rig. The data was monitored and recorded for each installation during continuous pull back. The data was originally presented via InField, the SoMat data control software. However this data was exported and converted to MS Excel and later TecPlot, a powerful data analysis program, for analysis. Each drill rod is 9.33 m (30 ft) long and data was recorded and broken down over each length of drill rod pulled. Since each rod needs to be unthreaded from the string and removed, the pull stops every rod length. Due to this stoppage in pull force the data was processed to discount the time when the product pipe was not being moved. This reduces the amount of data involved with movement to the product pipe.

With the high resolution of 0.01 seconds there are many micro spikes recorded by the data logger. However, these spikes are not representative of what is actually exerted on the pipe and are attributed to transducer noise. To more accurately present the data an Excel algorithm was developed to change the resolution of the data to present the average pull force value over 1 second. This allows a more appropriate presentation of the data and removes much of the transducer noise which may skew the results.

Due to the high resolution of data, the accuracy is somewhat misleading. While each individual spike was recorded, the actual representation of this spike is difficult to comprehend. Since the pressure transducers record what the drill rig gauges display, this does not directly correspond to the product pipe. It is however, what the reamer feels. The reamer, since it is larger than the product pipe (in almost all cases), is constantly scraping against the walls of the bore path. Each of the mini spikes can easily be described as the reamer making a small cut into the curving bore path wall.

3.3 Phase 2: Real time In-the-hole Data

During the research of the wireless data logger and transmitter, a number of problems were identified. Soil is notoriously difficult to transmit a conventional data signal through. The most effective way to transmit through soil is with an electro-magnetic (EM) signal. However even EM signals are limited by the amount of power within the transmitter unit. The DigiTrak TensiTrak is limited to 18 m (60 ft) depth and runs on three D batteries. Maxi-sized drill rigs can install pipe at depths of over 20 m, which are deep

enough to reduce the effectiveness of EM signals. The first problem identified was how to get the data signal from the underground transmitter.

A number of potential solutions were explored including using a short range wireless Bluetooth transmitter to jump the signal over the ream and link into the wire line that is sometimes used within the drill rod. This option was not viable because not all installations use a wire line, and when a wire line is used it adds a significant amount of time to each pipe connection and disconnection. A variation of this solution was to use a short range Bluetooth transmitter to jump into the hollow product pipe and transmit the signal through the empty pipe. Unfortunately, during most large product pipe installations the product pipe is filled with water to ensure the pipe does not float in the drilling mud and create extra friction on the top of the bore path. Water is also a difficult medium for wireless signals to transmit though so this simple solution was also not viable. A further variation of this option was to piggy back a signal in or along the tracer wire that is installed with plastic pipes. The tracer wire is subject to breakage and is not always installed with pipes.

The second major problem identified was the cost associated with the hardware required. To realistically approve the installation of another unit between the reamer and the swivel, the unit must be able to maintain a safety factor of at least 2. There are units that exist that can withstand upwards of 1,000,000 lbs of force which have built in strain gauges. These units are substantially expensive and the budget on this research did not support acquiring one.

Additionally, most maxi-sized rig installations involve a long string of product pipe which involve a long installation session. The size of battery required to power the transmitter for the required amount of time was a major problem. One such transmitter that was examined for use required a 24 V battery. To power this for an estimated 35 hours would require at least three 24 V batteries. These batteries would take up substantial space inside the design unit.

These problems made it unrealistic to complete phase two with the available resources. For future studies, with additional resources it will be very practical to develop phase two of this research.

Chapter 4 - Data Results

The data for this research was gathered at four separate pipe installations. Two separate materials and pipe diameters were used during these installations. The length of these installations ranged from 950 ft to 2523 ft. The data presented in this chapter is presented as pressures versus distance. The distance of product pipe refers to the location of the end of the pipe that was attached to the swivel behind the reamer with relation to the start of the installation. It was assumed that each drill rod was pulled through at an approximately constant velocity. This is not necessarily accurate for all drill rods as during certain pulls the rod was pulled at a faster rate. During installations the pull force was kept below a point where the product pipe could be endangered. However this changed in velocity is reflected in a drop in carriage pressure which is still represented in the data. It should also be noted that during the final three sessions of data gathering, the mud pressure had a constant zero reading. The constant zero reading was not a transducer error, but instead was caused by a lack of hydraulic fluid within the drill rig.

4.1 June 22, 2011 Pullback

The June 22, 2011 pullback involved installing 1500 ft of 400 mm diameter Fusible PVC SDR 18 pipe. This pipe was installed underneath Major Mackenzie Drive along Islington Avenue, in Ontario, Canada, with approximately 10ft of cover. This was the first set of data gathered in the research and only had a single transducer connected to carriage pressure. This carriage pressure is related to force by a calibration table provided by American Auger, the drill rig manufacturer, and table is represented by Figure 6. The linear equations for the 3rd and 4th gears of the engine are shown. This study only required the 3rd and 4th gears were used in the operation of the drill rigs during pull back.

The data has been divided by each individual drill rod involved in the installation, each of which has a length of 30 ft. As each drill rod has been fully cleared from the drill carriage, the pull must be paused to remove the cleared rod. While processing the data it was assumed that when the carriage drill pressure drops below 1100 psi that the pipe ceases to move. This was used as the breaking point between each separate set of rod data and aided to more accurately detail chainage measurements. This assumption also assists to pin point mid rod stoppage points, so that these points could be removed to avoid the potential for skewing the data.
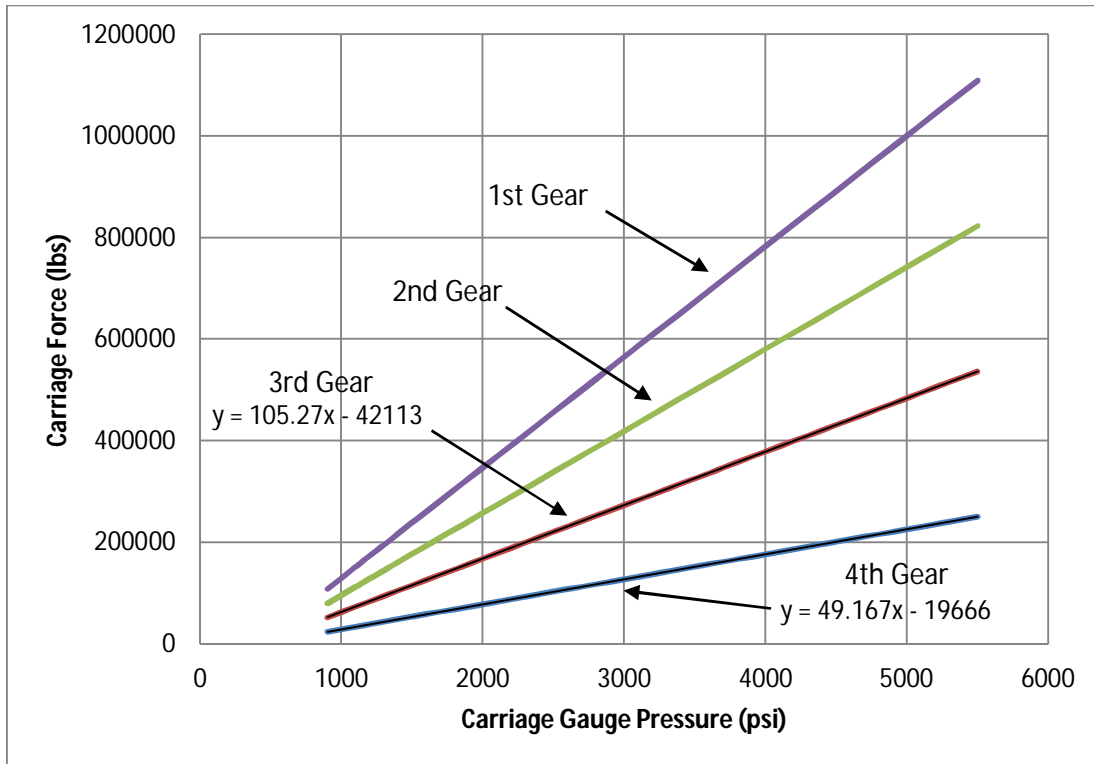
Figure 6: Carriage Gauge conversion Pressure to Force

The data presented in Figure 7 is the processed data at high resolution. Since the friction caused by the reamer stays approximately the same throughout the pull the increase in pull force is caused by the pipe entering the bore path.

As shown in Figure 7, the pull force remains approximately constant until the final quarter of the pull. This should correspond approximately to where the product pipe begins to return to surface. PVC is a brittle plastic material and is likely making contact with the walls of the bore path in this final length. The peak pull force more than doubles the average pull force in the rest of the pull.

There are a number of points throughout this pull where the pull force reaches a local maximum and then drops drastically. This is done by the driller as he monitors the pull, and when the pressure starts to build he can reduce the rate at which the pipe is being pulled, thereby causing a drop in the force to slow down the pull.
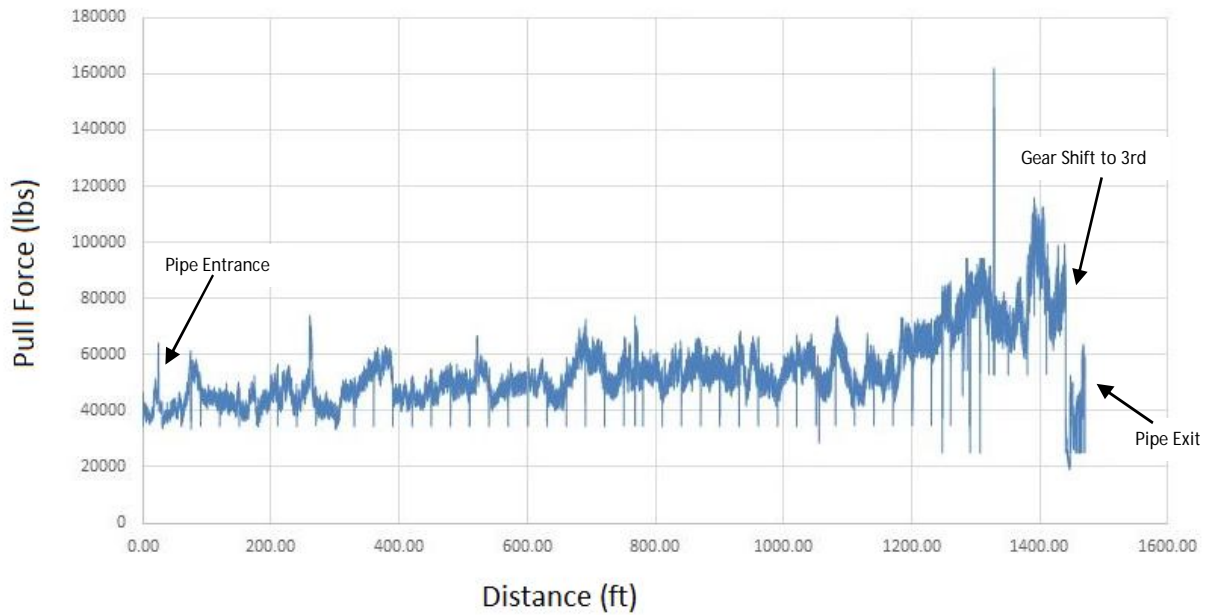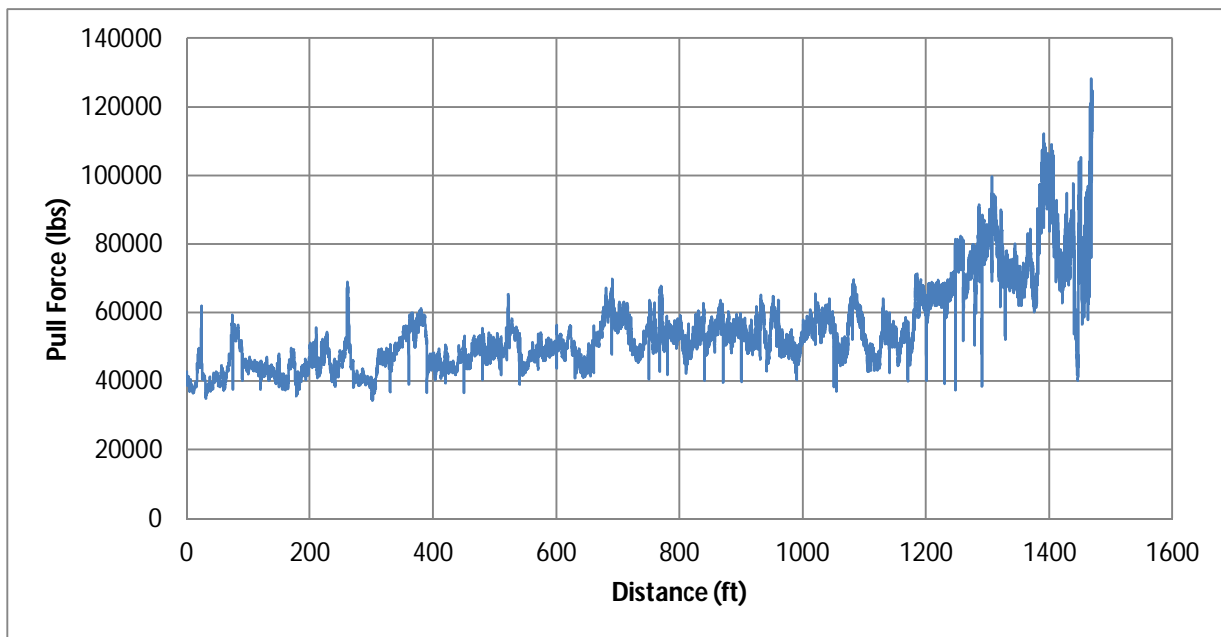
Figure 7: June 22, 2011 Pull Force vs Distance

Figure 8 details the data for one individual drill rod in high resolution. As shown in Figure 8, the pull force during a single drill rod does increase slowly over the duration of the pull. Then as the rod nears its end, and stopping point, the driller decreases the pull rate of this particular rod to bring the force required to finish the pull below 60,000 lbs.

Figure 9 shows the details of the carriage pull force as converted to low resolution via the excel algorithm. It should be noted that the dip at a chainage of 1450 ft is the driller switching to 3rd gear. This same pull is described in Figure 6, after it is converted to pounds.
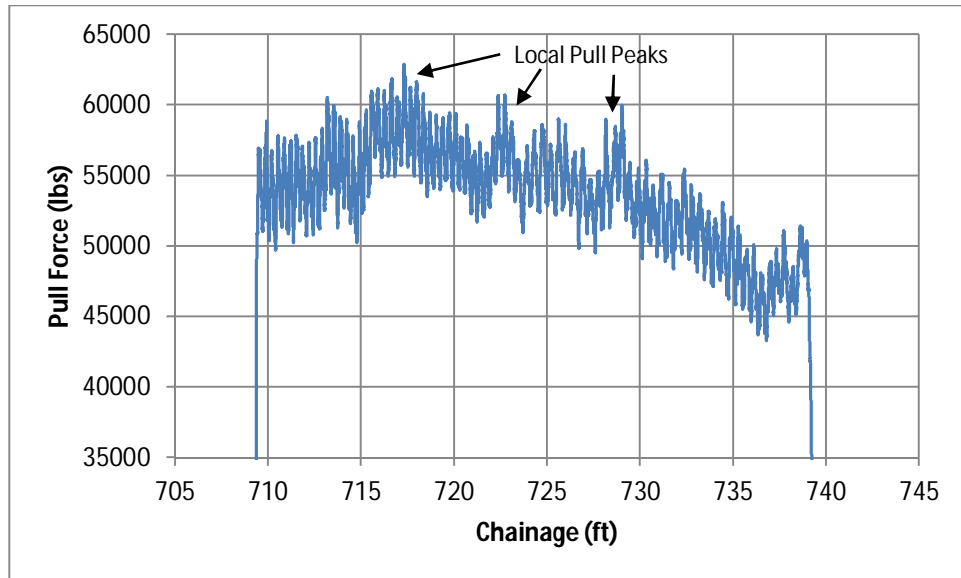
**Figure 8: June 22, 2011 Rod 34 Pull Force vs Distance**

**Figure 9: June 22, 2011 Low Resolution Pull Force vs Distance**

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4.2 August 24, 2011 Pullback

The August 24, 2011 pullback involved installing 2523 ft of 750 mm diameter HDPE SDR 11 pipe. This pipe was installed underneath a cemetery along Huntington Road with approximately 15ft of cover. This was the second set of data gathered for this research, and the largest. This was also the first pull with pressure transducers recording data from carriage pressure gauge, rotary pressure gauge, and drilling mud pressure gauge. The carriage pressure is related to force by a calibration table provided by American Auger, the drill rig manufacturer, and is presented in Figure 6 which can be found in section 4.1. The rotary pressure is related to force by a calibration table provided by American Auger, the drill rig manufacturer, and this table is represented in Figure 10.
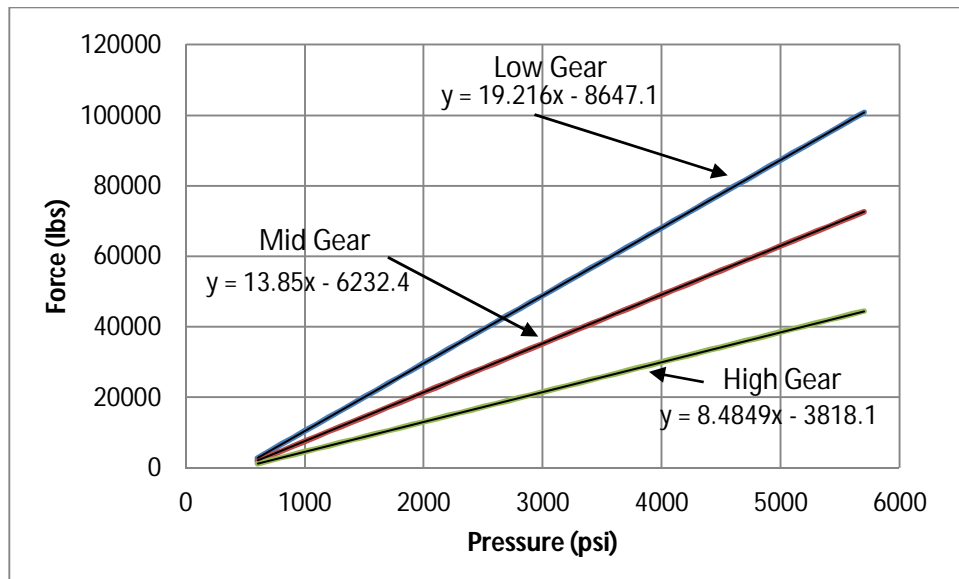
**Figure 10: Rotation Gauge conversion Pressure to Force**

It should be noted that the drilling mud pressure gauge read zero for all data gathered, and thus will not be presented in this research. This was due to a hydraulic fluid leak being present somewhere in the drill rig system, inhibiting the pressure from being visible on the drillers gauge. Figure 11 is the high resolution data for the August 24th pull back.
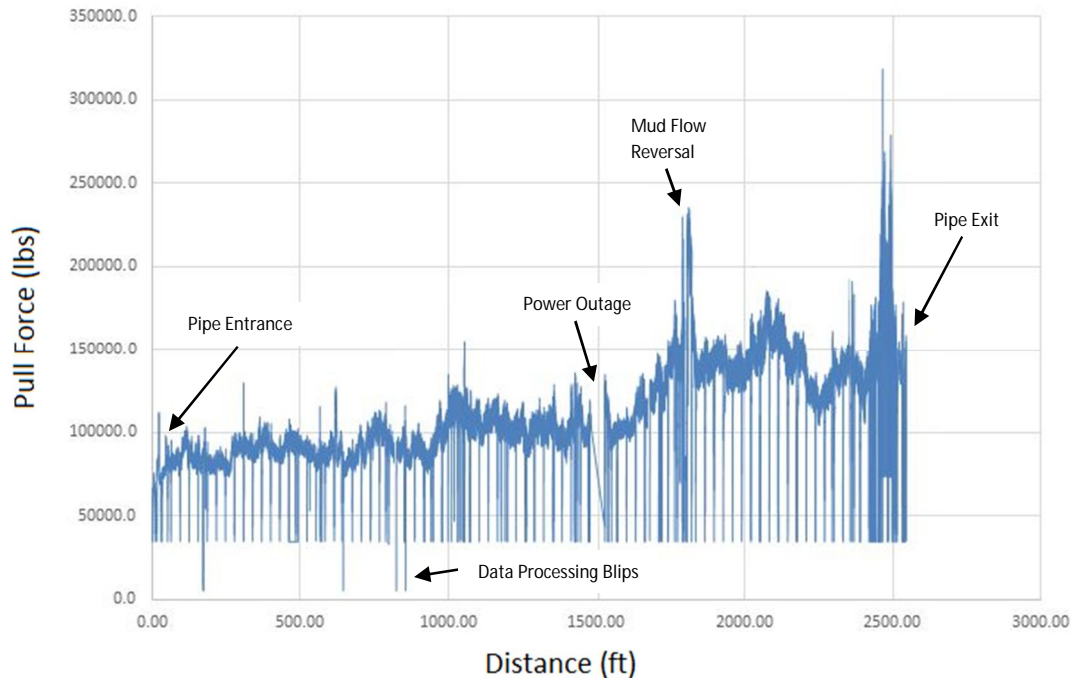
Figure 11: August 24, 2011 Pull Force vs Distance

There are a few discrepancies in the data presented in Figure 11 that need to be discussed. The four dips that are below the data baseline are data points that were not adjusted through the data processing. It is important to note that they do not affect the average or have any significant impact on the data or resulting analysis. The data gap from approximately 1450 ft to 1500 ft is due to data that was not logged due to a power outage that occurred during the pull back, which interfered with the ability to record the data.

Figure 12 presents the low resolution pull force for the August 24th pull. When compared to the high resolution data, the general data path is the same. This confirms that the resolution conversion method is accurate in remodelling the data. Figure 13 presents the low resolution rotation force for the August 24th pull. The data shows that the rotational forces stay roughly constant at around 26,000 lbs as the pipe moves along the bore path. The only significant change occurs during the last 600 ft of the pull. This corresponds to the leveling of the pull force, which coincides with the timing of when the drilling fluid switches direction to flow in the direction of the pull. This direction change occurs naturally since the fluid will flow in the direction of least resistance.
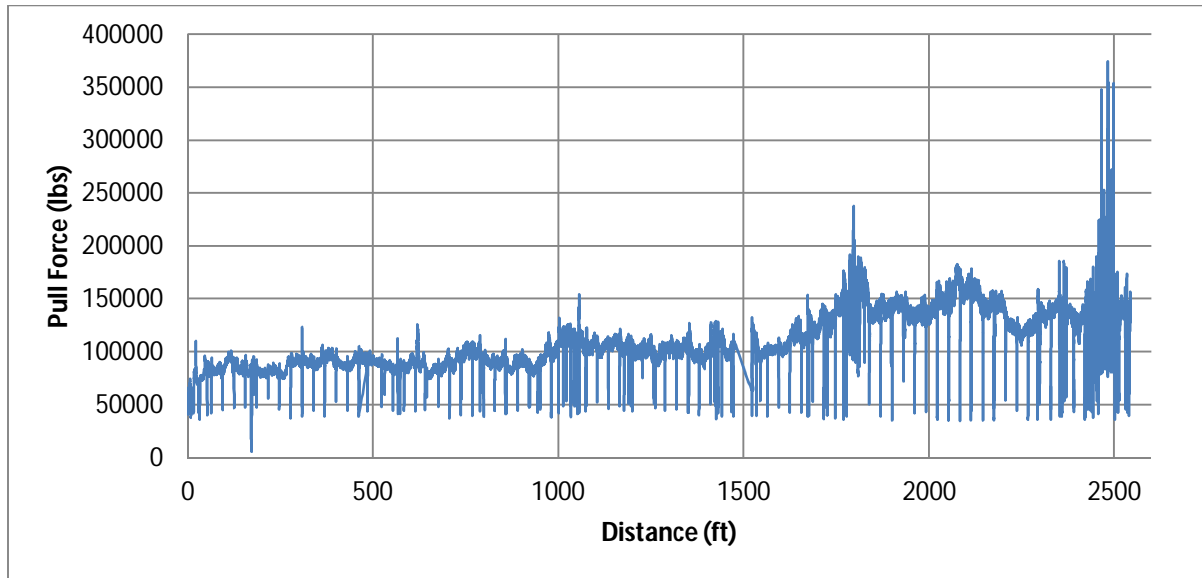
**Figure 12: August 24, 2011 Low Resolution Pull Force**
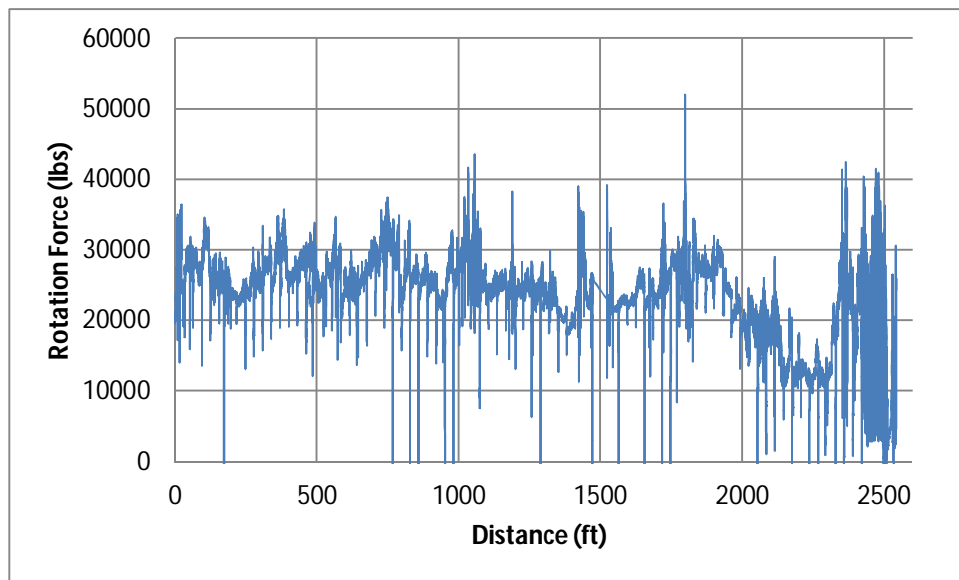
Figure 13: August 24, 2011 Low Resolution Rotation Force
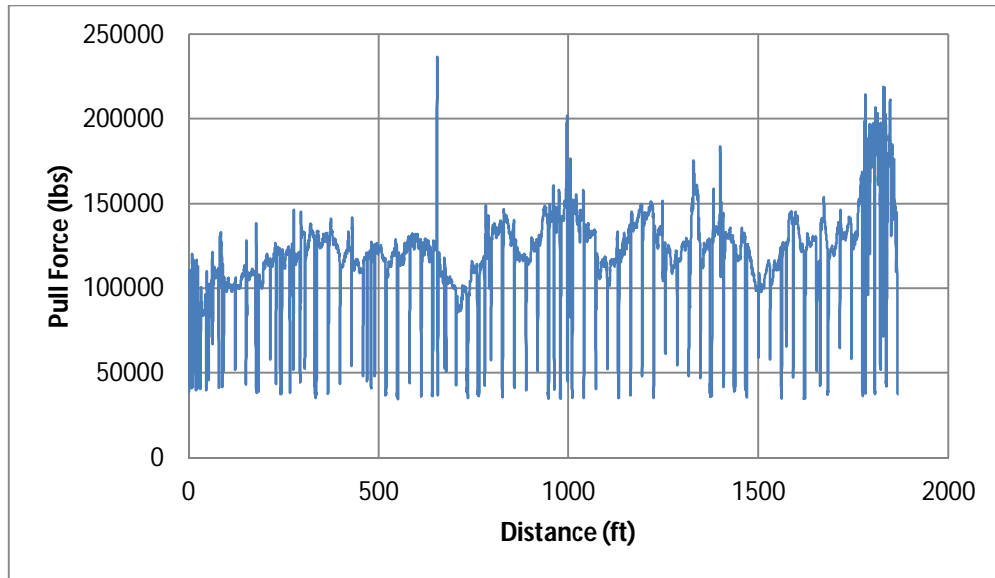
4.3 December 15, 2011 Pullback

The December 15, 2011 pullback involved installing 1870 ft of 750 mm diameter HDPE SDR 11 pipe. This pipe was installed underneath a creek and two gas lines with small diameters along Huntington Road in

Ontario, Canada with approximately 15 ft of cover. This was the third set of data gathered in this research. This pull used pressure transducers recording data from carriage pressure gauge, rotary pressure gauge, and drilling mud pressure gauge. The carriage pressure is related to force by a calibration table provided by American Auger, the drill rig manufacturer, and this table is represented in Figure 6 which can be found in section 4.1. The rotary pressure is related to force by a calibration table provided by American Auger, the drill rig manufacturer, and is represented as Figure 10 which can be found in section 4.2. Figure 14 details the high resolution pull force data for this pull.
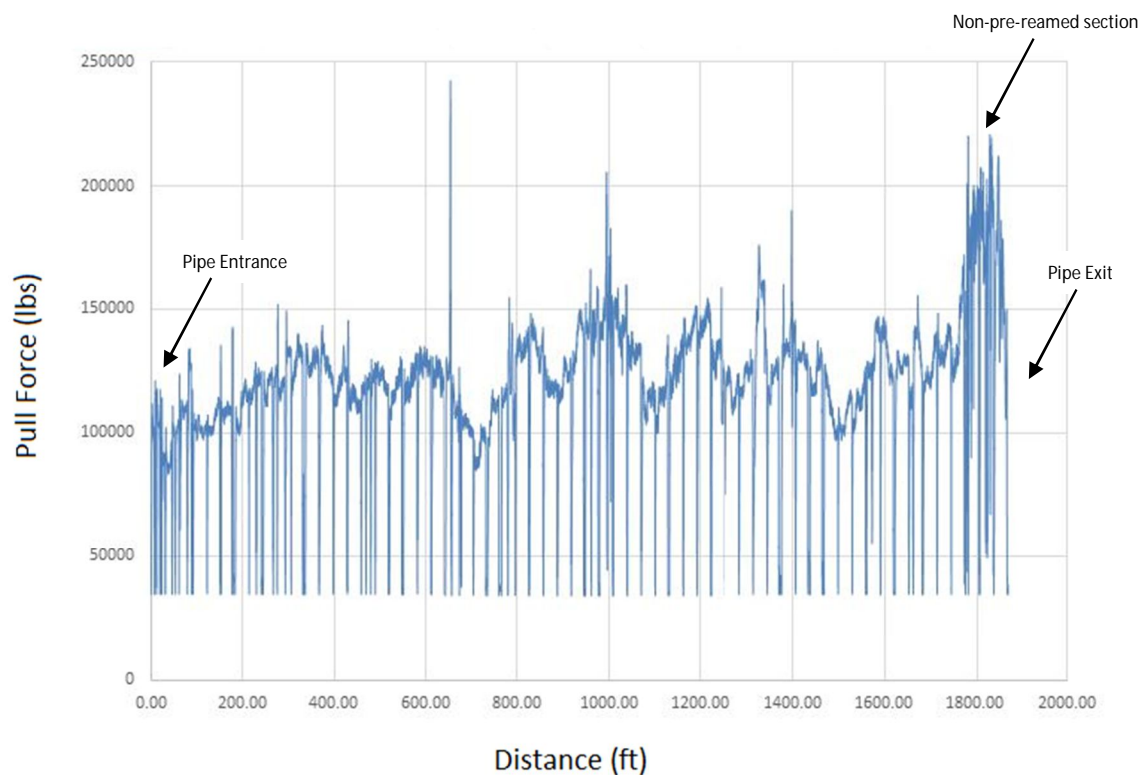
Figure 14: December 15, 2011 Pull Force vs Distance

The data trend for this pull does not show the same increase in pressure as the first two pulls until the very end of the pull back. The final 100ft of this pull was not pre-reamed, causing the pressure to spike drastically as the reamer attempted to cut out the virgin soil while also pulling the pipe. Figure 15 presents the low resolution pull force data. Figure 16 presents the low resolution rotational force data. The rotational force has a decreasing trend until the final 100 ft where the rotational forces are higher to cut the virgin soil.

Figure 15: December 15, 2011 Low Resolution Pull Force vs Distance

Figure 16: December 15, 2011 Rotation Force vs Distance

4.4 February 8th, 2012 Pullback

The February 8, 2012 pullback involved installing 950 ft of 750 mm diameter HDPE SDR 11 pipe. This pipe was installed underneath two small diameter gas lines along Huntington Road, Ontario, Canada with approximately 15 ft of cover. This was the shortest and last data gathered in this research. This pull used pressure transducers recording data from carriage pressure gauge, rotary pressure gauge, and drilling

mud pressure gauge. The carriage pressure is related to force by a calibration table provided by American Auger, the drill rig manufacturer, and is represented as Figure 6, in section 4.1. The rotary pressure is related to force by a calibration table provided by American Auger, the drill rig manufacturer, and this table is presented as Figure 10, in section 4.2. Figure 17 details the high resolution pull force data for this pull.
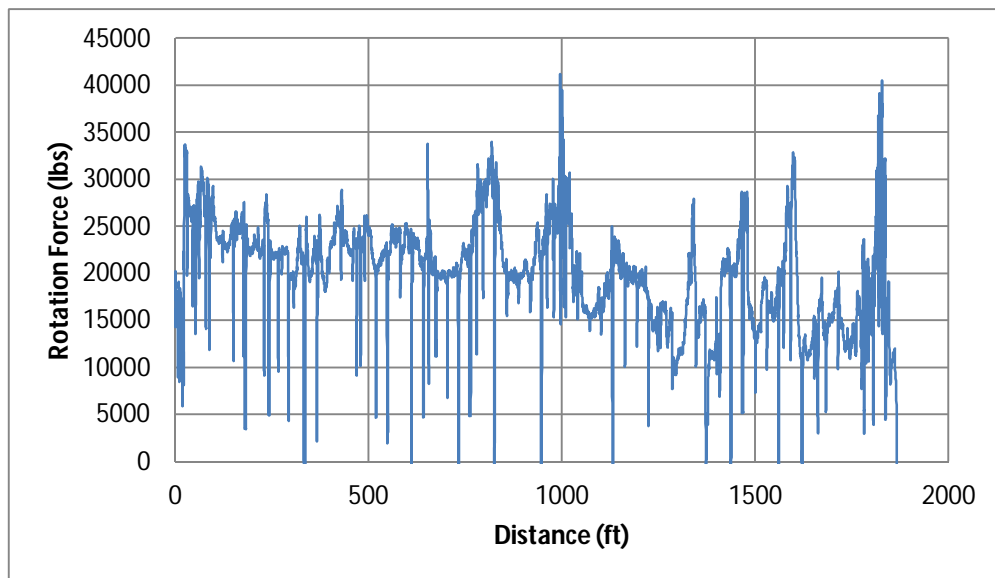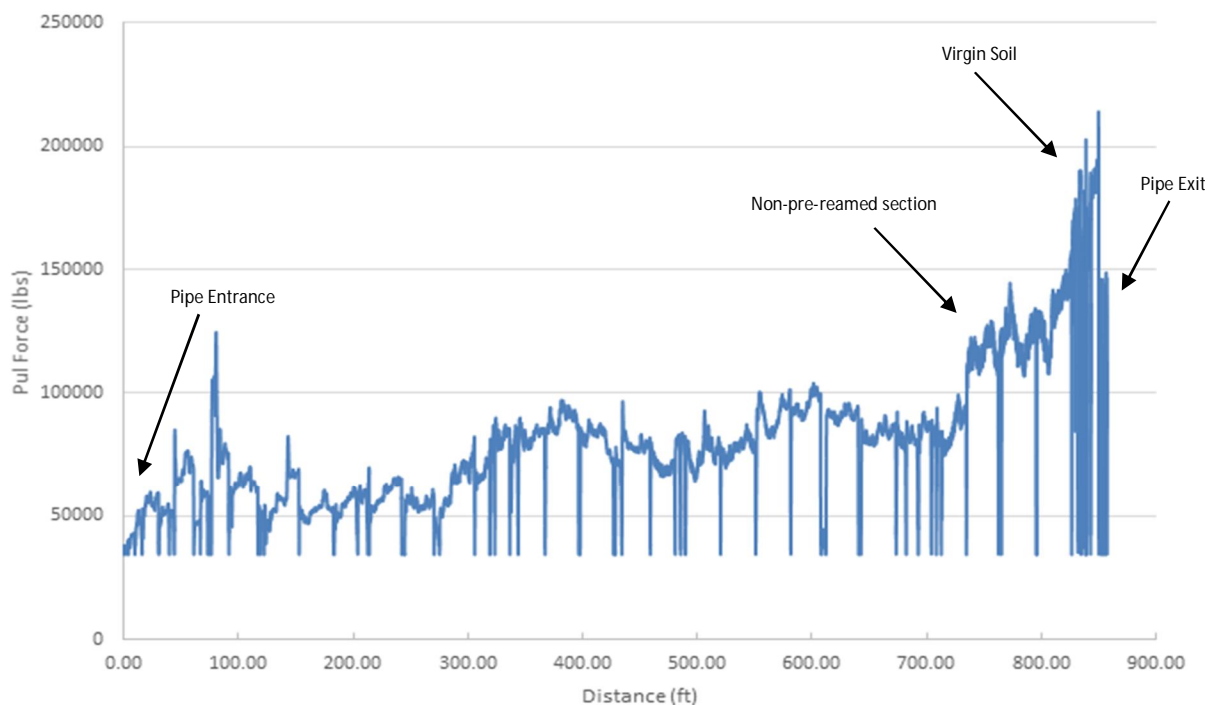

Figure 17: February 8, 2012 Pull Force vs Distance

The last 200 ft of this pull was not pre-reamed with the 42″ (1066 mm) reamer, but was instead pre-reamed using only the 24″ (610 mm) reamer. The reamer was pulled at approximately the same rate throughout the entire pull, so the force jumped up once the 24″ pre-reamed section was reached. This can be seen in Figure 17 at the 830 ft distance mark as the pull force increases and continues to increase dramatically. In the case of this pull, the data is not complete. There is an additional 3 drill rods worth of data missing. This data was not collected due to a mechanical problem with the drill rig and an extended delay with pull back. The very last rod recorded and the rods that were not recorded were not pre-reamed with either of the 42″ or 24″ reamer. Instead their bore path was pre-reamed using only the drill rod having an 8.5″ (215 mm) diameter. Figure 18 is the low resolution pull force data and Figure 19 is the low resolution rotational force.

As shown in Figure 18, as the product pipe enters the unreamed section of the bore path the force required to pull the pipe increases to almost three times the amount needed to pull the pipe through the reamed section of the bore path. It should be noted that this force does not necessarily indicate the pressures from force felt by the product pipe. The force felt by the product pipe can only be accurately recorded with a force strain gauge located between the product pipe and the reamer as described in phase 2 of this research.
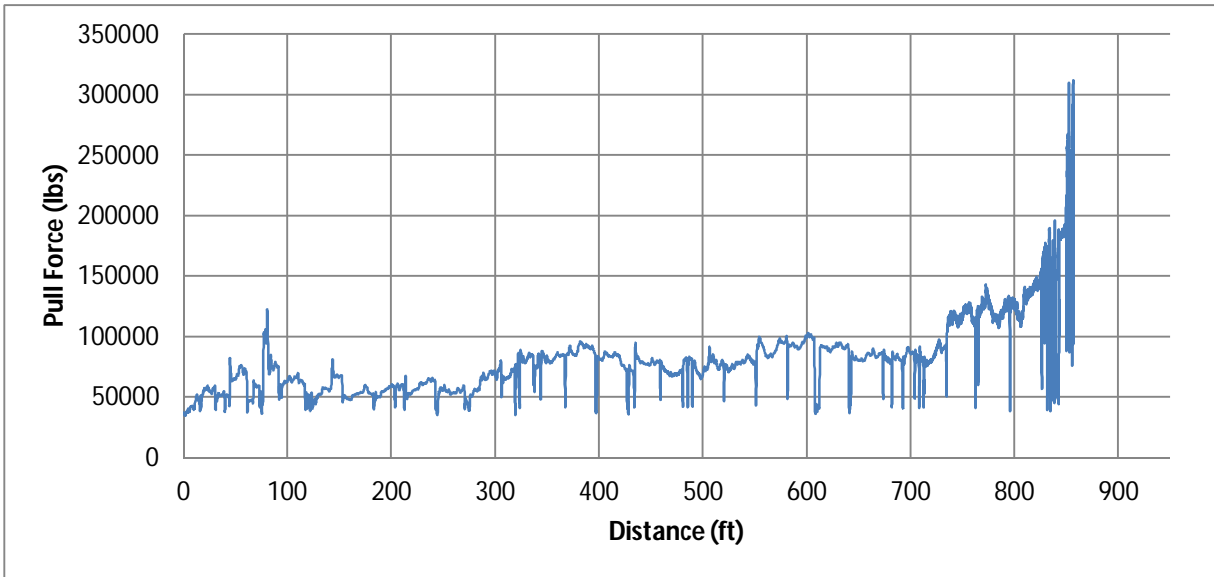
Figure 18: February 8, 2012 Low Resolution Pull Force vs Distance
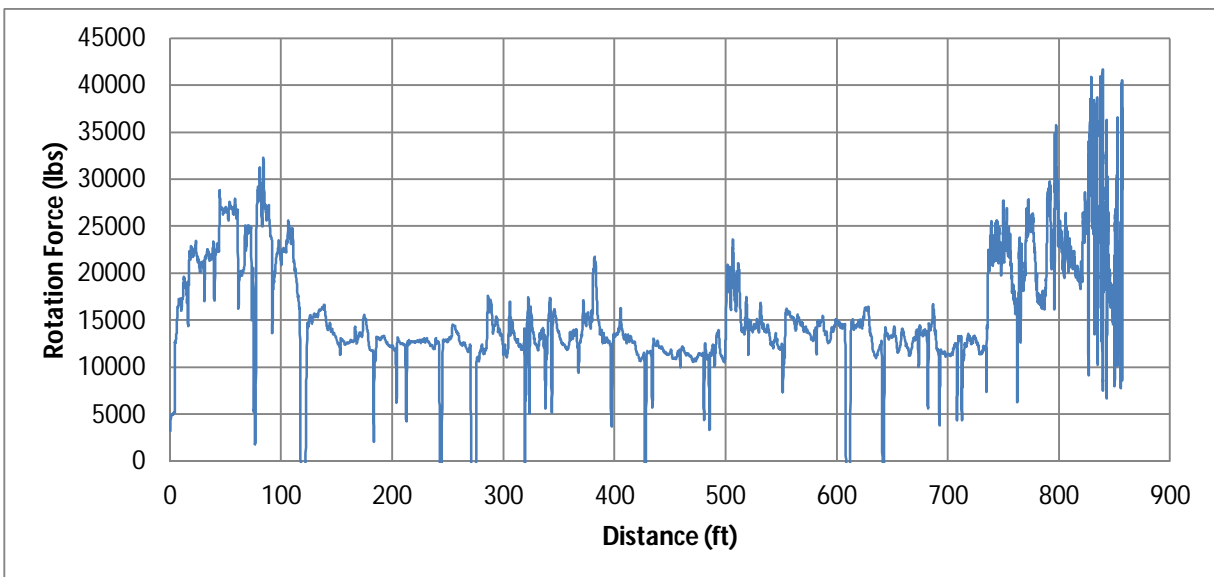
Figure 19: February 8, 2012 Low Resolution Rotational Force vs Distance

Chapter 5 - Challenges of In-the-hole Data Logging

Currently the most common wireless in ground system used in HDD installation is a sonde. A sonde is an electromagnetic transmitter that emits a signal which is picked up by a hand held receiver that is stationed above the sonde on the surface. The sonde is used to orient and locate the drilling head as the initial drill path is made. Most sondes are not equipped with any data transmitting devices. They are strictly used for orientation and location purposes. Unfortunately sondes are limited to certain depths and in cases of large scale HDD projects a sonde may not be applicable. The Sharewell TruTracker is a wire-line locating system that transmits location and orientation of the drill bit but is not limited to depths and project size.

When this research was begun there was no such product that could safely be used with a Maxi-sized drill rig to transmit data from underground to the surface in real time. The Digitrak TensiTrak does do this, however it is only rated up to 100,000 lbs of pull force. Each of the described data gathers in this study have points where the pull force goes well above the 100,000 lbs limit. The worst thing that could potentially happen during a pipe installation is, if a piece of equipment between the reamer and the product pipe were to break and require a spot excavation to reattach the drilling rods.

5.1 Explored Data Transfer Methods

Two data transfer methods were explored in this research. The first method involved a combination of wireless transfer methods. Initially a Bluetooth transmitter would be installed in the data recording device which would use a short range wireless jump to get to the more powerful Phoenix Contact wireless transmission card, 2867076 RAD-ISM-900-TX, which has a range of more than two kilometers. This transmission card would move the signal to the surface which would then be relayed to the SoMat eDAQlite terminal. Unfortunately, the Phoenix contact system is unable to transmit through obstructions including soil and water. Since both these obstructions were going to be present during product installation, this method was obsolete, which forced a different model to be explored.

The second data transfer method involved using a wired connection to reach down to the swivel, either along the drill rods or along the product pipe, then by using a wireless Bluetooth connection to bridge the remaining distance to the data gathering unit. This involved a substantial amount of extra work to install this system which creates extra cost for the drilling company. A wired connection has a high chance of breakage which would be impractical, if not impossible, to repair if it breaks. Figure 20 presents a diagram of the explored data transfer methods.

Option 1: Wireless Data Transmitter in product pipe

Option 2: Bluetooth Jump to wired system
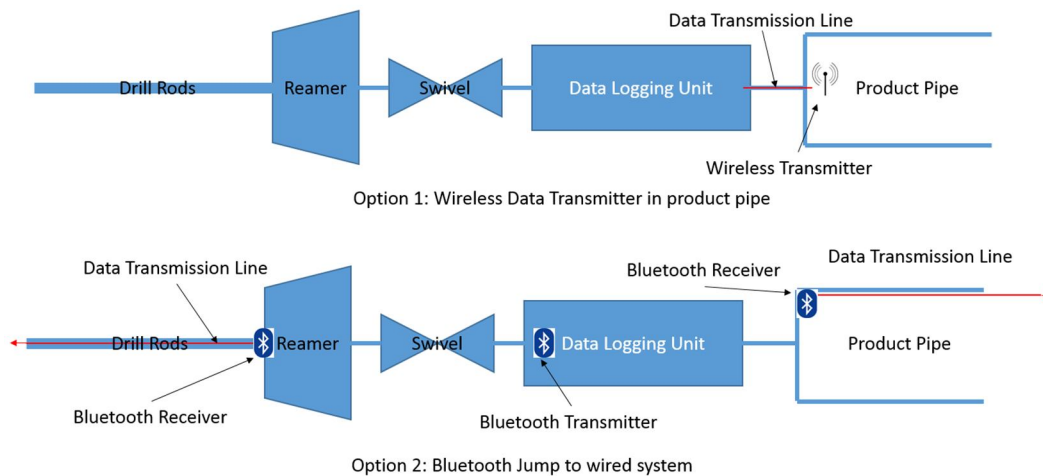
Figure 20: Explored data transfer options

5.2 Future Recommendations for Development

While a small scale commercial product is available, the first steps to develop a new Maxi-sized system would be to develop the various components required currently unavailable.

To begin, a control system that can monitor and maintain battery power to the system while it is in use and conserve the battery during rod change or downtime is a required component. The battery, which needs to be able to power all the components for a pre-determined length of time, must be housed within the unit. The control system should also be able to connect the various transducers to the transmitting device.

The next component is the data transmission system. This can either be a wireless, wired, or combination system. A wired or combination system would need to be specially modified for each individual installation and comes with the associated risks of breakage. A wireless system would need to be robust enough to transfer the signal through a range of depths, materials, and distances. The medium of transfer is also an important design aspect when dealing with underground wireless.

Finally, configuring the DAQ system is an important aspect and may change for individual installations. However, a standard configuration can be designed to make any modifications simple to adjust immediately prior to the installation pull.

With these components, if this product is developed it would be a powerful academic and QA/QC device which will assist installation contractors and suppliers with valuable data for future use. It can also be used to confirm or deny theoretical pull force models and improve upon current methods. Part 2 of this research compares how data collected for this research compares to current theoretical models.

Chapter 6 - Result Analysis and Model Comparison

There is a variety of literature, both published and not, that have endeavoured to compare various theoretical models for predicting pulling loads for HDD pipe installations. Some can be very complex and use numerical models to predict loads (Cheng & Polak, 2007). Others are somewhat simplified and account for different aspects of installation such as Duyvesten, 2009 and ASTM 1962-11. Each of these methods has been compared, analyzed, improved, and tested against each other and the ASTM standard. While all of these methods may be appropriate to give certain guidelines and estimates for the installation, they will never completely match the installed pull loads generated in the field.

With regards to the research completed for this thesis, none of the previously mentioned methods have been applied to Maxi-sized drill rigs. While in theory they should be able to encompass the larger forces and pulls, the comparison research and testing has not yet been completed.

6.1 BoreAid

The Terein Inc. program BoreAid is the most modern computing and design aid tool for HDD installations using PE and Steel pipes. It incorporates a number of design aspects into predicting install loads. However just like all design methodologies, it is limited to the user interface and certain assumptions. It does however have the most versatile interface which allows for adaptable reporting. BoreAid version 3.0 was used during this research, but an updated, more user-friendly, and 3D version of BoreAid is currently under development.

BoreAid uses four different methods for calculating installation loads. These methods are individually calculated and the user can determine which method they would like to use in their own design. The first method detailed by BoreAid uses the standard ASTM F1962 equations for PE pipe. These equations are somewhat detailed and represent most installations very well. It is very difficult to model changing ground conditions and complex bores using these equations, which are listed below as 1-7. Method 2 uses the Plastic Pipe Institute handbook (Chapter 12) which uses the same equations as ASTM 1962 with a slight modification. Instead of adding the pulling force increment Equation (7) after the force multiplications as recommended by the ASTM, it adds the pulling force increment Equation (7) into the force multiplications.

Method 3 and 4 are both drag models which include the direction of slurry return. Method 3 involves adding the drag friction forces to the force calculations as an addition component. The equation for this is designated below as Equation 8. Method 4 uses the same drag friction force, but for the final 2/3 of the pull, the slurry travels towards the pipe exit and the friction is subtracted from the pull force.

Table 4 details the parameters used in BoreAid which are based off the drill plan for the installation of the pipes for each installation. PO_{GPM} represents the rate at which the drilling mud is pumped into the bore path through the drill rods in gallons per minute. PV represents the plastic viscosity of the drilling fluid in centipoises. YP represents the yield point of the drilling fluid in lbs per 100 ft^2. The remaining values from Table 4 are described in section 6.2.

Table 4: Parameters for BoreAid Inputs

Parameter	June 22 Value	August 24 Value	December 15 Value	February 8 Value
PO_{GPM} (GPM)	140	180/260	260	260
PV (cP) *	30	30	30	30
YP (lbs/100 ft^2) *	100	100	100	100
D_{bore} (in)	24	42	42/24	42/24/8.5
D_{pipe} (in)	15.75	29.5	29.5	29.5
H (ft)	10	15	15	15
DR	18	11	11	11
V_a **	0.5	0.5	0.5	0.5
V_b **	0.4	0.4	0.4	0.4
γ_a	1.4	0.95	0.95	0.95
γ_m	1.5	1.5	1.5	1.5
α (°)	8	8	8	8
β (°)	13	13	10	10

* Harbin 2003 from Duyvestyn 2009 – Sandy lean clay

** Raclavsky 2008 - Typical for sandy clay

6.2 ASTM F1962 and Friction Drag Equations

ASTM F1962 is the standard for HDD design installations in North America. Figure 21 describes a general HDD bore path. Point A is the end of the bore where the installed pipe first enters the bore as it is pulled back. Point B is where the pipe ceases its descent and is set at grade, this is not always 0% grade as depicted. Point C is where the pipe installation is complete and where the initial bore first reached the installation depth. Point D is the location of the drill rig and where the installed pipe will exit the bore. The following equations estimate the pull force felt by the installed pipe at each of these locations.
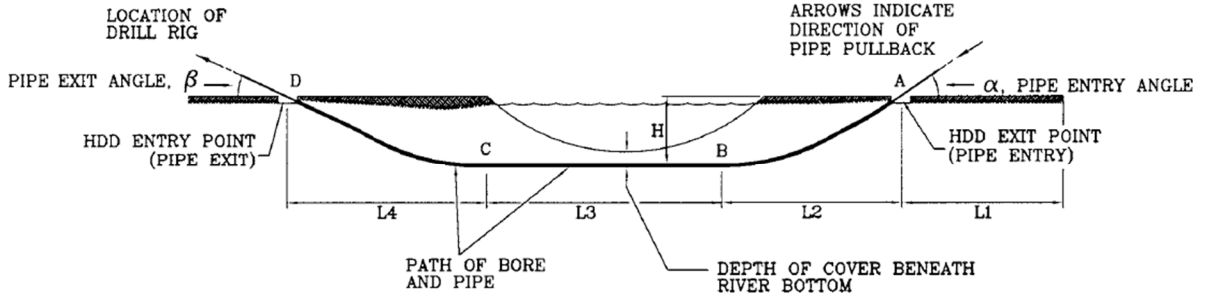
Figure 21: ASTM F1962 Equation Model

$$T_A = \exp(v_a \alpha)\,(v_a w_a (L_1 + L_2 + L_3 + L_4)) \tag{1}$$

$$T_B = \exp(v_b \alpha)\,(T_A + v_b |w_b| L_2 + w_b H - v_a w_a L_2 \exp(v_a \alpha)) \tag{2}$$

$$T_C = T_B + v_b |w_b| L_3 - \exp(v_b \alpha)(v_a w_a L_3 \exp(v_a \alpha)) \tag{3}$$

$$T_D = \exp(v_b \beta)(T_C + v_b |w_b| L_4 - w_b H - \exp(v_b \alpha)(v_a w_a L_4 \exp(v_a \alpha)) \tag{4}$$

$$w_a = \pi D^2 \frac{DR - 1}{DR^2} \rho_w \gamma_a \tag{5}$$

$$w_b = \frac{\pi D^2}{4} \rho_w (\gamma_b - \gamma_w (1 - \frac{2}{DR})^2) w_a \tag{6}$$

$$\Delta T = \Delta P \frac{\pi}{8} (D_{hole}^2 - D^2) \tag{7}$$

$$F_d = 12 \pi D \mu_{mud} L \tag{8}$$

where
T_A = pull force on pipe at point A, lbf (N),
T_B = pull force on pipe at point B, lbf (N),
T_C = pull force on pipe at point C, lbf (N),
T_D = pull force on pipe at point D, lbf (N),
L_1 = additional length of pipe required for handling and thermal contraction, ft (m),
L_2 = horizontal distance to achieve desired depth, ft (m),
L_3 = additional distance traversed at desired depth, ft (m),
L_4 = horizontal distance to rise to surface, ft (m),
H = depth of bore hole from ground surface, ft (m), $\exp(X) = e_x$, where e = natural logarithm base (e = 2.71828),
v_a = coefficient of friction applicable at the surface before the pipe enters bore hole,
v_b = coefficient of friction applicable within the lubricated bore hole or after the (wet) pipe exits,
w_a = weight of empty pipe, lbf/ft (N/m),
w_b = net upward buoyant force on pipe in bore hole, lbf/ft (N/m),
α = bore hole angle at pipe entry (or HDD exit, at side opposite drill rig), rad, and
β = bore hole angle at pipe exit (or HDD entry, at same side as drill rig), rad.
γ_a = specific gravity of pipe material (for example, 0.955 for PE),
ρ_w = weight density of water times length unit conversion factor, lbf/in.$_3$ (N/mm$_3$), and
D = outside diameter of pipe, in. (mm).
γ_b = specific gravity of mud slurry
γ_w = specific gravity of water
ΔT = pulling force increment, lbf (N),
ΔP = hydrokinetic pressure, psi (kPa × 10$_{-3}$), and
D_{hole} = backreamed hole diameter, in. (mm).

F_d = Friction Drag caused by slurry flow, lbf
μ_{mud} = Fluid Drag coefficient, psi (0.05 to 0.025)

6.3 Model Comparisons

The following figures describe the actual recorded pull load data with the corresponding calculated data using all four BoreAid methods. Table 5 summarizes all the compared model data and actual installation data.
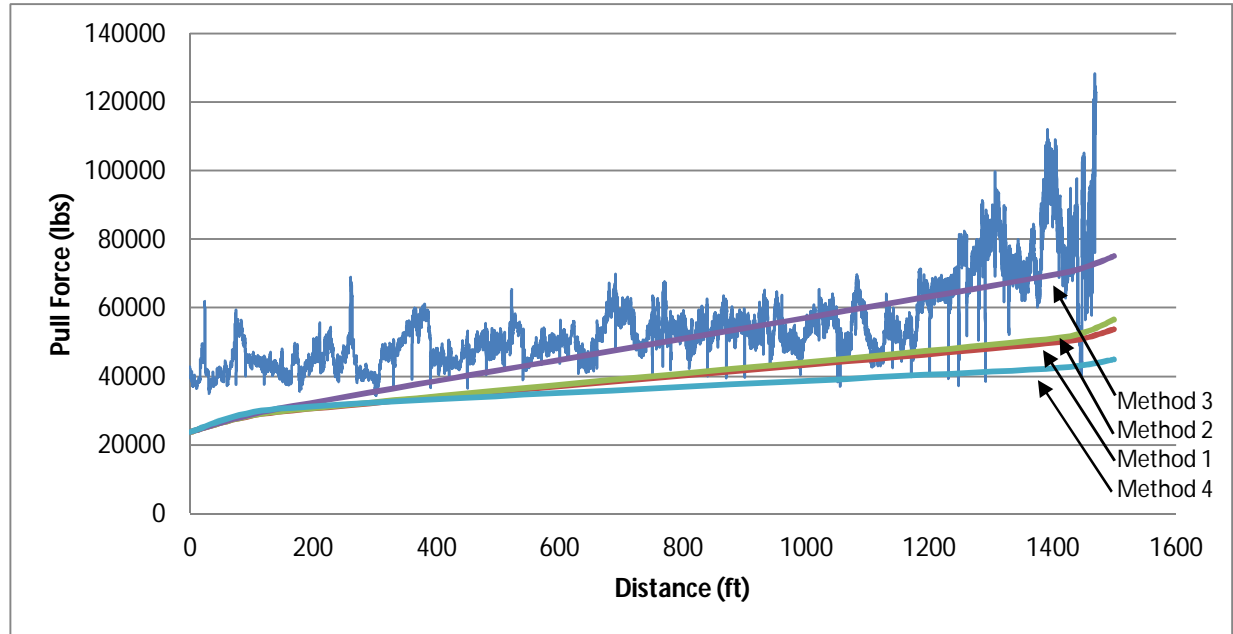
Figure 22: June 22 Low Resolution Data with Comparison Methods from BoreAid

Figure 22 describes the June 22nd pipe installation with the BoreAid models overlaid. While all of the methods do not correctly model the initial pull forces, they do follow the same trend of the data. Method 3 is able to approximate the final pull force required to complete the installation however it cannot account for the large spikes in the final section of the installation.
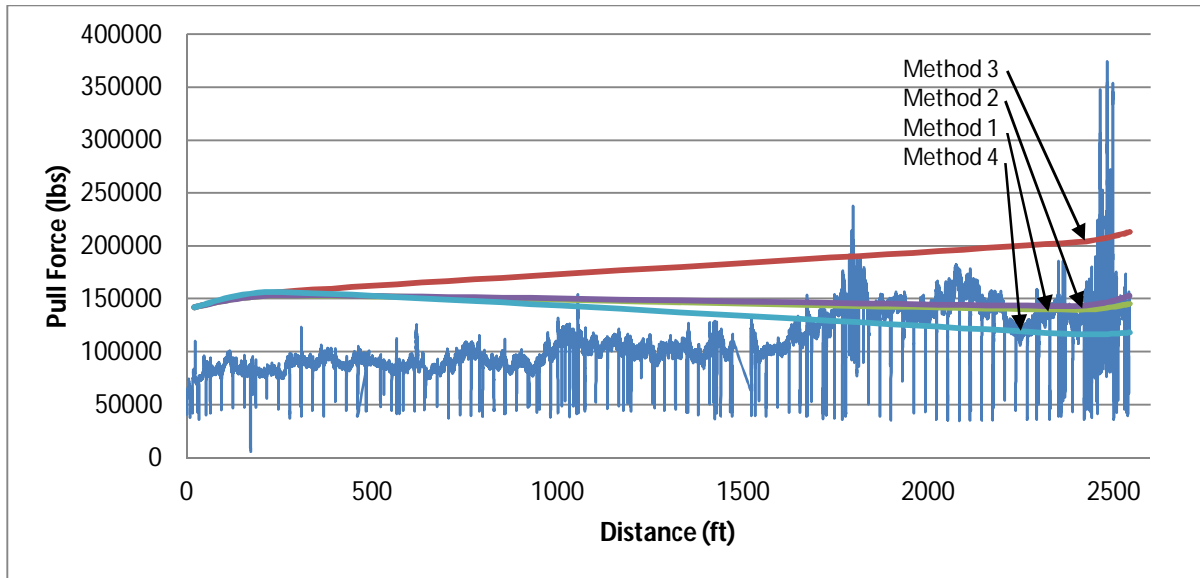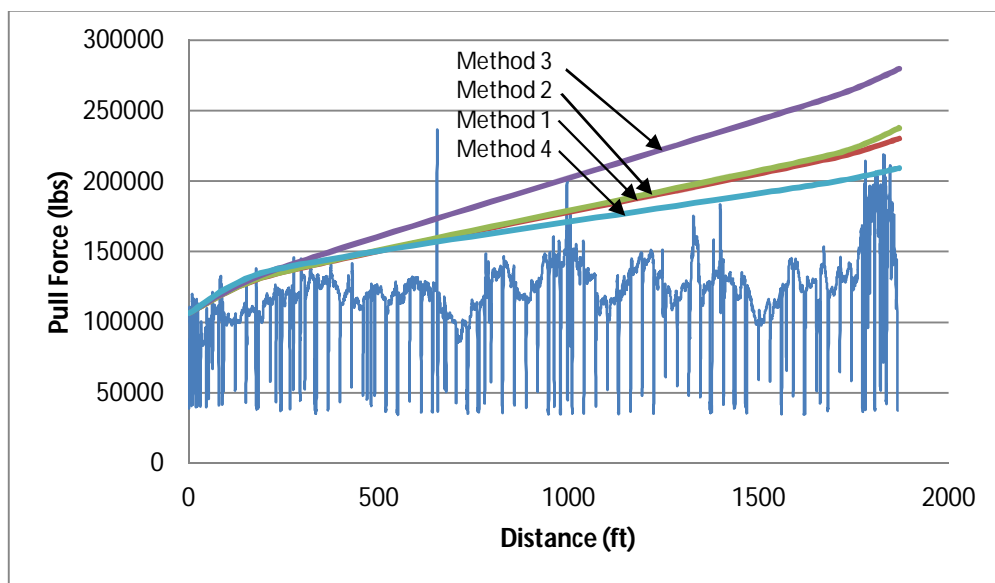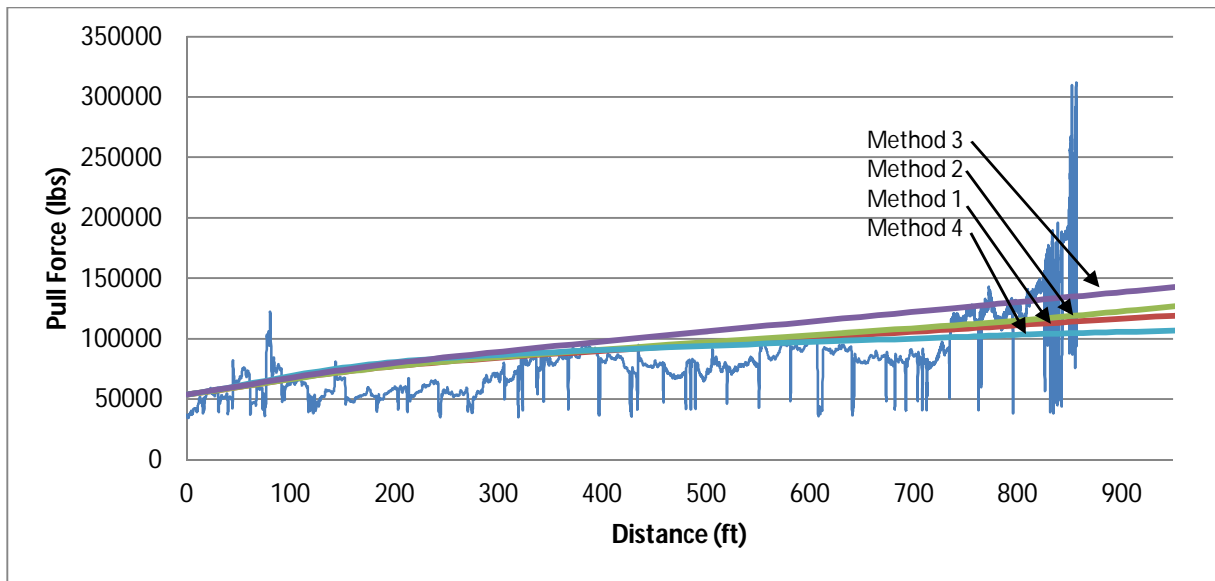
Figure 23: August 24 Low Resolution Data with Comparison Methods from BoreAid

Figure 23 describes the August 24th pipe installation with the BoreAid models overlaid. In a similar but opposite situation to the June installation, the models overestimate the initial pull force required but do follow the general trend of the data. It is interesting to note that Methods 1, 2, and 4 all decrease from their initial overestimation and almost exactly line up with the final length of pipe installation. Again none of the methods are able to account for the major or minor spikes during the installation. In this case methods 1 and 2 are able to model the pull loads the most accurate.

Figure 24: December 15 Low Resolution Data with Comparison Methods from BoreAid

Figure 24 describes the December 15th pipe installation with the BoreAid models overlaid. All of the methods estimate an initial pull force that is very close to the actual initial pull load. In this case the different modelling methods overestimate the trend of the data. However, other than two major spikes, each of the methods overestimate the pull forces in all cases. In the end, Method 4 is able to very closely estimate the final installation loads.

Figure 25: February 8 Low Resolution Data with Comparison Methods from BoreAid

Figure 25 describes the February 8th pipe installation with the BoreAid models overlaid. As with the December installation the estimating methods accurately predict the initial loads. The difference is that the models each follow the trend of the data closely. Other than the major spike at the end of the pull it seems like these any of these methods approximated the pull forces accurately. The spike at the end of the installation was caused by the soil not being pre-reamed, the estimating methods are not designed to take that into account.

In each case the calculated models are able to follow the general trend of the actual recorded data. The moderate dips and spikes involved with changing ground conditions and driller control cannot easily be modelled.

Table 5: Installation Load Comparison Prediction vs Actual

Installation Date	Peak Pull Force (lbs)				
	Method 1	Method 2	Method 3	Method 4	Actual Recorded
June 22	53800	56640	75160	45010	127219.3
August 24	153400	153500	213400	156600	374676.9
December 15	230500	238000	280000	209500	236507.4
February 8	119400	126900	142900	107000	311647.2

6.4 Discussion

Each of the models used in BoreAid are good representations of the general trend of the gathered data. In three of the four models the predicted loads are greater than the actual pull loads, which from a design perspective is conservative and beneficial to a design engineer. In the case where the predicted loads are less than the actual loads, this can be accommodated for by adding a factor of safety to the pipe design, which is standard design practice. Additionally, BoreAid is not setup explicitly to design with PVC pipe, and could also explain part of the reason the predicted models have a load slightly less than the actuals. However, since the recorded data was taken from the surface, the actual pull force felt on the product pipe itself will be less than that shown in the earlier figures. This only improves the safety factor on the models.

In each case the models are simplified and only work with four points as described by ASTM 1962. Since the distance between each of these points is so large, the models cannot account for local peaks and valleys. As shown in Figure 6, each individual rod pullback has its own trend. This is partially controlled by the drill operator but is also greatly affected by the ground conditions. It is impossible for a model to account for all the small peaks and valleys. These local spikes, regardless if they are caused by driller control or ground conditions, can peak the pipe into the limits of its pullback threshold, which is undesirable.

The prediction methods are a helpful tool for design and require detailed geotechnical research. The models should always be followed with data logging during installation. The benefits from QA/QC during installation can assist drillers with a more detailed output than the simple analog gauge. It can also assist with installation issues after installation to determine if or where problems may have occurred.

Chapter 7 – Conclusions and Recommendations

Real time data acquisition is without a doubt a very important tool to assist with Horizontal Directional Drilling installations. The current tools for data logging from the surface can be adapted and improved to provide a better interface for the operators and technicians to work with. In-the-hole real time data loggers do exist and function for small scale drilling installations however maxi-sized drill rigs do not yet have data loggers sized appropriately. Most models and design comparisons have been completed using smaller scale drill rigs. As HDD installations become more commonplace, larger installations will become more and more common. The large scale rigs will be operating at higher loads with larger pulls, and so having a powerful QA/QC system will improve and protect these installations.

As recommended earlier, the real time data acquisition from in the hole will allow for better model comparisons and the recorded data will better reflect the forces felt by the product pipe. Future research and testing will aid in the development in such products and improve HDD installations.

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