Construction of Horizontal Wells in Municipal Solid Waste Using A Directional Drill

by

Pei-Yi Joy Ho

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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.

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Abstract

Horizontal directional drilling (HDD) has been employed in many situations including cable lines under rivers and rehabilitation of pipelines under buildings and busy traffic. Within the context of a municipal landfill site, a by-product of organic waste (leachate) accumulates within an established landfill. Leachate is a liquid produced from the wastes placed inside landfills and rain that percolates through the wastes and reacts with the products of decomposition. This thesis investigates the effectiveness of employing HDD techniques to extract leachate in the municipal landfill application.

There are two primary objectives of this research:

- Identify key parameters that influence horizontal well installations in landfill applications; and,
- Examine the efficiency and effectiveness of employing a carrier case to protect the product pipe.

Employing HDD techniques in landfill applications provide several challenges, including unknown waste material density, unknown waste material hardness, and unknown drilling operation and waste material interaction. There are limited documented studies or research related to HDD techniques in landfill applications. In addition, conventional HDD studies cannot be directly applied in this research as the drilling medium parameters are virtually unknown.

This research incorporated a trial site to gather field data related to the primary objectives described above. The trial site is located at the Region of Waterloo Landfill site located on Erb Street in Waterloo, Ontario. The installations took place at the Original Landfill Area (OLA). The OLA is currently inactive and capped. The vertical wells, originally installed to control the leachate, have degraded resulting in the landfill gas collection system to work inefficiently. The field installation of two horizontal wells (in opposing directions) were put in practice not to replace vertical wells, but to assist in capturing and collecting leachate. The installations were monitored and key parameters were recorded.

In addition to understanding key parameters in an HDD process, the efficiency and effectiveness of using a carrier case, during the installation to protect the product pipe, was investigated. Carrier pipe material candidates included HDPE and steel. In both trials, an HDPE product pipe was within the carrier pipe to protect the product pipe from damage. A section of each carrier pipe (one HDPE and one steel) was equipped with sensors, including internal load bolt, pressure transducers, strain gauges, displacement transducers, and thermocouples, to monitor elastic and plastic deformations the carrier pipe during installation. Due to the geometry of the steel carrier pipe, only limited sensors were installed. A data acquisition system was designed and installed within the product pipe to record the sensor readings.

The results indicate that drill rig torque is essential when drilling through municipal landfill waste. Strain and displacement data from both HDPE and steel carrier pipes indicate the approximate location of hard objects within the landfill. Fluid pressure data suggest the pressure within the landfill was lower than expected.

Based on the findings within this research, coupled with similar studies in the US and UK, it is recommended that all landfill HDD installations employ maxi-HDD rig to have sufficient torque during installation. Furthermore, modification of the reamer and a cover for the swivel is recommended in future installations to prevent in-situ objects interfering with the drilling operation.

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Chapter 1: Introduction

1.1 General

Prior to the 1980's, most Municipal Solid Waste (MSW) Landfills were constructed without a Leachate Collection System (McBean 1995). Due to low permeability of daily cover material, leachate mounding was generated from water infiltration and waste degradation inside the landfill cells. Biofouling of Leachate Collection System (LCS) has also been observed to cause leachate mounding in landfills constructed post 1980's. Leachate mounding can increase the potential for contaminants to migrate off the property and reduce the volume of landfill methane gas production. As leachate head elevates inside the landfill, gas wells capacity is reduced and thus extracts less biogas. The reduction in landfill gas production can have significant economic impacts for MSW facilities with Landfill Gas (LFS) Recovery System, such as the Regional Municipality of Waterloo Landfill (RMWL) that produces and sells electricity (Region of Waterloo 2005).

The construction and pumping of vertical wells placed within the MSW is a common technique used to reduce leachate mounding. However, vertical wells have been found to have high operational and maintenance costs and a short functional life due to biofouling and the corrosive nature of the leachate (Region of Waterloo 2005). Although horizontal well may encounter similar problem, one horizontal well covers more area than one vertical well, comparatively. In addition, the use of gravity wells can reduce the need of pumps to extract leachate.

The main purpose of this thesis is to investigate the use of the directional drilling technique for the construction of two gravity drainage wells that can be used to reduce leachate mounding and increase landfill gas production.

1.2 Horizontal Directional Drilling (HDD) in MSW Landfills

In North America, the use of directional drilling for the construction of horizontal wells installed in landfills have been reported, to date, in only four published studies (City of Superior 2005, Cox 2002, Friend & McDonnell 1996). In the United Kingdom, only one paper discusses the construction of a well in MSW using a directional drill (Cox et al 2001). Thus, the use of directional drilling technique for the construction of gravity wells in MSW is relatively new and unique.

1.3 Research Goals and Objectives

The main goals of this research are to:

1) better understand the behaviour of the drill rig and down hole tools behaviour during drilling in MSW.
2) better understand well construction and behaviour during installation in MSW.
3) increase the probability of successful gravity well installations in MSW.

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

- Development of a monitoring system to monitor the drill rig and the well behaviour during installation.
- Development of a directional drilled well construction and performance monitoring program.
- Identification of well construction obstacles and barriers.
- Determine drill rig and well performance during and after installation.
- Determine key parameters that will increase the probability of a successful well installation in MSW.

To fully understand of the behaviour of drilling equipment and well construction, a real time monitoring system was developed. Data was recorded and downloaded daily and analyzed.

1.4 Thesis Outline

Chapter 2 of the thesis provides background information on the design and construction of MSW landfills and specific RMWL site data. Chapter 3 provides a description of the directional drilling process for the construction of utility pipelines and environmental wells. Chapter 4 provides a review of the published literature with respect to the construction of wells in or under MSW using a directional drill. The development of the field monitoring program for two well installations is discussed in Chapter 5. Chapter 6 details the construction of the two wells while Chapter 7 presents field results. Analysis of field results is presented in Chapter 8. Conclusions and recommendations for future work are presented in Chapter 9.

Chapter 2: MSW Landfill Background

2.1 Current Landfill Design and Components

Each day, MSW is placed and compacted in a cell. Daily cover material is placed on top of the waste for odour control. The compacted waste and the daily cover material make up a cell (McBean 1995). Leachate is produced from the decomposing of the waste and poses a danger to the surrounding groundwater system. To prevent the build up of leachate within the landfill, a Leachate Collection System (LCS) is constructed on top of the cell liner. The LCS collects the leachate and transports it to a treatment facility prior to discharge. Underneath a cell is a low hydraulic conductivity barrier system refers to as a liner. The function of a liner is to contain leachate within the cell and to minimize groundwater contamination. Figure 2-1 shows the configuration of a typical modern landfill.

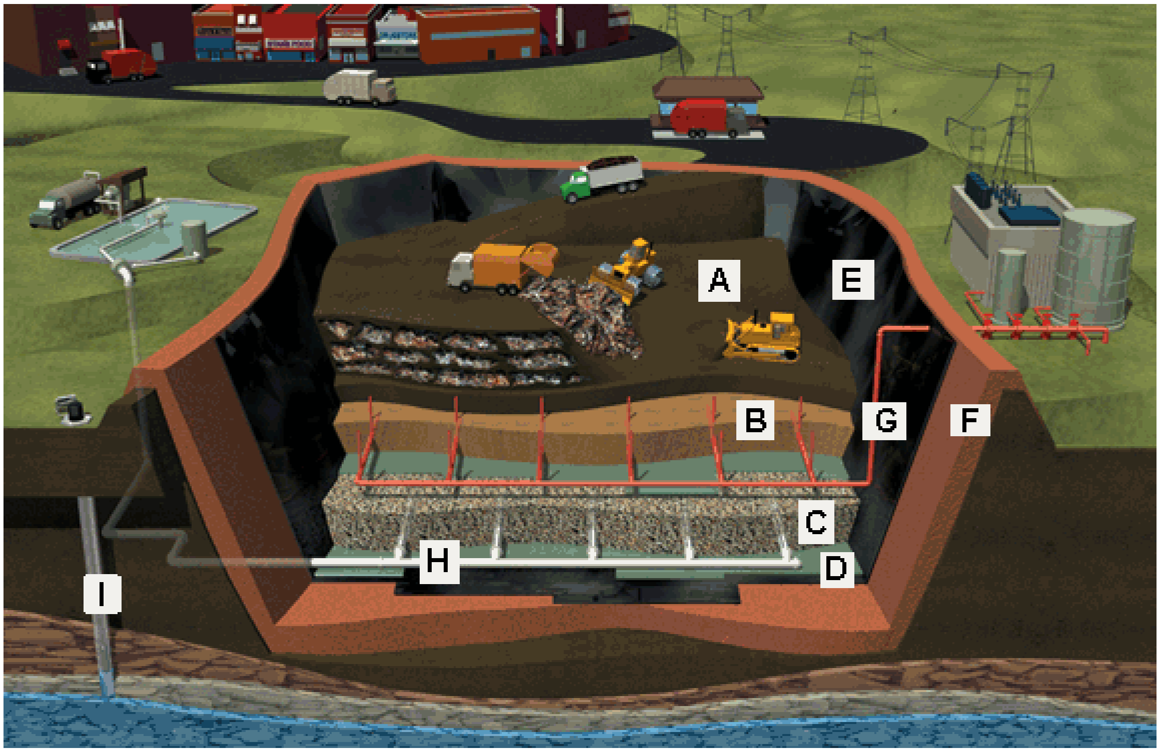


Figure 2-1: Configuration of a Typical Modern Landfill (Bluewater Recycling 2005).

The layer underneath the haulers and compactors is the cell where MSW is placed and compacted (A). A daily cover is placed on top of the MSW for odour control. Beneath the MSW is a fine material layer (B). This layer is used to confine MSW and filter the leachate.

Below the fine material is a coarser granular layer (C). The function of this layer is to collect leachate and transport it into the LCS (H). In between layers B and C is a fabric liner (D) that prevents particles from penetrating downward. Below the LCS is the impermeable liner system. This system typically consists of two layers (E and F). The lower system (F) typically consists of compacted clay with a maximum hydraulic conductivity of $1x10^{-7}$ cm/s. On top of the clay barrier, a high density polyethylene barrier is constructed (E). The LFG collection system (G) is typically installed in the waste or a fine filter material (Bluewater Recycling 2005). During decomposition of waste, methane and other combustible gases are produced. In some landfills, landfill gas (LFG) collection systems are constructed during waste placement. The collected gas is transported to a co-generation facility that generates electricity to be sold to the local utility provider.

2.2 Regional Municipality of Waterloo Landfill (RMWL)

MSW landfills built before 1980's, such as Regional Municipality of Waterloo Landfill, typically did not sort MSW prior to placement. Consequently, waste including hazardous materials and mixed waste were placed into the landfill. Most pre-1980's landfills were also not constructed with a LCS. In addition, biofouling and/or sediment fouling has resulted in many LCS not functioning as designed. To reduce leachate levels in landfills, vertical wells are a common remedy (Region of Waterloo 2005).

The Regional Municipality of Waterloo Landfill (RMWL) is located on Erb Street in Waterloo, Ontario, Canada. The RMWL consists of three major cells: the Original Landfill Area (OLA), the North Expansion Area (NEA), and the South Expansion Area (SEA). Figure 2-3 shows the location of each cell. The OLA was constructed in the 1970's and the NEA was constructed in the Fall of 2002 and is to be decommissioned in 2006-2007. The SEA cell was constructed in 2006 and commenced operation in the Fall of 2006.

Figure 2-2: Waterloo Landfill Site (Region of Waterloo 2001)

The main focus of this research is the Original Landfill Area, which was the former Kitchener landfill site managed by the City of Kitchener. In 1973, the ownership and operation of the landfill was transferred to the Regional Municipality of Waterloo (RMW). In the fall of 2002, the OLA was considered filled and decommissioned (Region of Waterloo 2005). Waste in the OLA was not sorted. Thus, it contains mixed waste consisting of metals, wood, appliances, automobiles, industrial and organic waste, fibrous material, and concrete.

2.3 Leachate Collection System

The Leachate Collection System (LCS) consists of the following (Region of Waterloo 2005):

1. A perforated toe drain collector along the northern, eastern, southern, and western extents of the OLA.
2. A network of collection pipes and french drains installed at the landfill base in the west central and south-western portions of the OLA.
3. A network of vertical extraction wells: fourteen dual-phase (water/gas) and seven dedicated wells.
4. Three pumping stations and associated forcemains.

2.4 Leachate Problems

Leachate mounding has been observed in the RMWL along with a reduction in gas production and recovery. Water quality testing of the off site wells have shown an increase in vinyl chloride of 5 to 15 micrograms per litre (µg/L). The Ontario Drinking Water limit Standard for vinyl chloride is 2 µg/L. Leachate mounding in the OLA has been attributed as the reason for the increase in vinyl chloride concentrations. Vertical leachate extraction wells were constructed and pumped to reduce leachate head in the OLA. Due to silting and biofouling, these wells did not perform as designed. In 2004, most of the vertical extraction wells were not functional. The RMW installed seven additional dedicated vertical extraction wells in the upper section of the OLA, but were shut down. In 2004, a work plan was prepared by the RMW to develop strategies for leachate extraction.

2.5 Horizontal Wells

The construction of two horizontal leachate/gas collection wells using a horizontal directional drill (HDD) was recommended as a pilot project. These wells would be designed as gravity wells to eliminate the need for pumps. It was recommended that the well would be constructed by drilling from the top of the OLA down through the MSW and exiting the OLA. The well would then be pulled back through the toe berm until it exited at the top of the OLA. Leachate collected from the well will be connected to the french drain at the base of the landfill.

Chapter 3: Horizontal Directional Drilling

3.1 Development and Process

Specific drilling technique and equipment have not been developed for drilling in MSW. As a result, the process of drilling technique in MSW is similar to conventional directional drilling.

The process for the installation of a pipeline using a horizontal directional drill can be divided into three drilling stages: pilot bore, pre-ream, and pipe pullback. The pilot bore process starts by pushing a slant faced bit into the ground at an angle typically between 5 to 15 degrees (HDD Consortium 2001). Steering is maintained by controlling the orientation of the slant face while pushing the head into the ground. Drilling fluid is pumped through the drill rods and drill head to aid in ground cutting, to remove cutting from the bore path, to support the bore, and to cool the drill head. The bore path is formed and cleaned by rotating the drill head in the formation and moving it back and forth in the fluid fill bore path. The size of the pilot bore is typically 100 to 150 mm in diameter. The depth and orientation of the slant faced bit is determined using a walkover and/or a wireline locating system. The pilot bore is completed when the drill head exits the ground surface.

The pre-ream stage consists of removing the slant faced bit and installing a bore reaming device. The reaming device is then pulled back through the pilot bore path. To aid the reaming process, drilling fluid is pumped through the drill rods and the reamer. For larger diameter pipe installations, the bore may be reamed multiple times for the pipe installation.

The pipe pullback stage consists of connecting the pipe to the reamer using a swivel. The function of the swivel is to prevent the pipe from rotating during pullback through the bore path. Pullback is completed when the pipe exits the ground at the drill rig. For small diameter bores, the pre-ream stage may not be used. Figure 3-1 illustrates the three drilling stages of a typical HDD process.

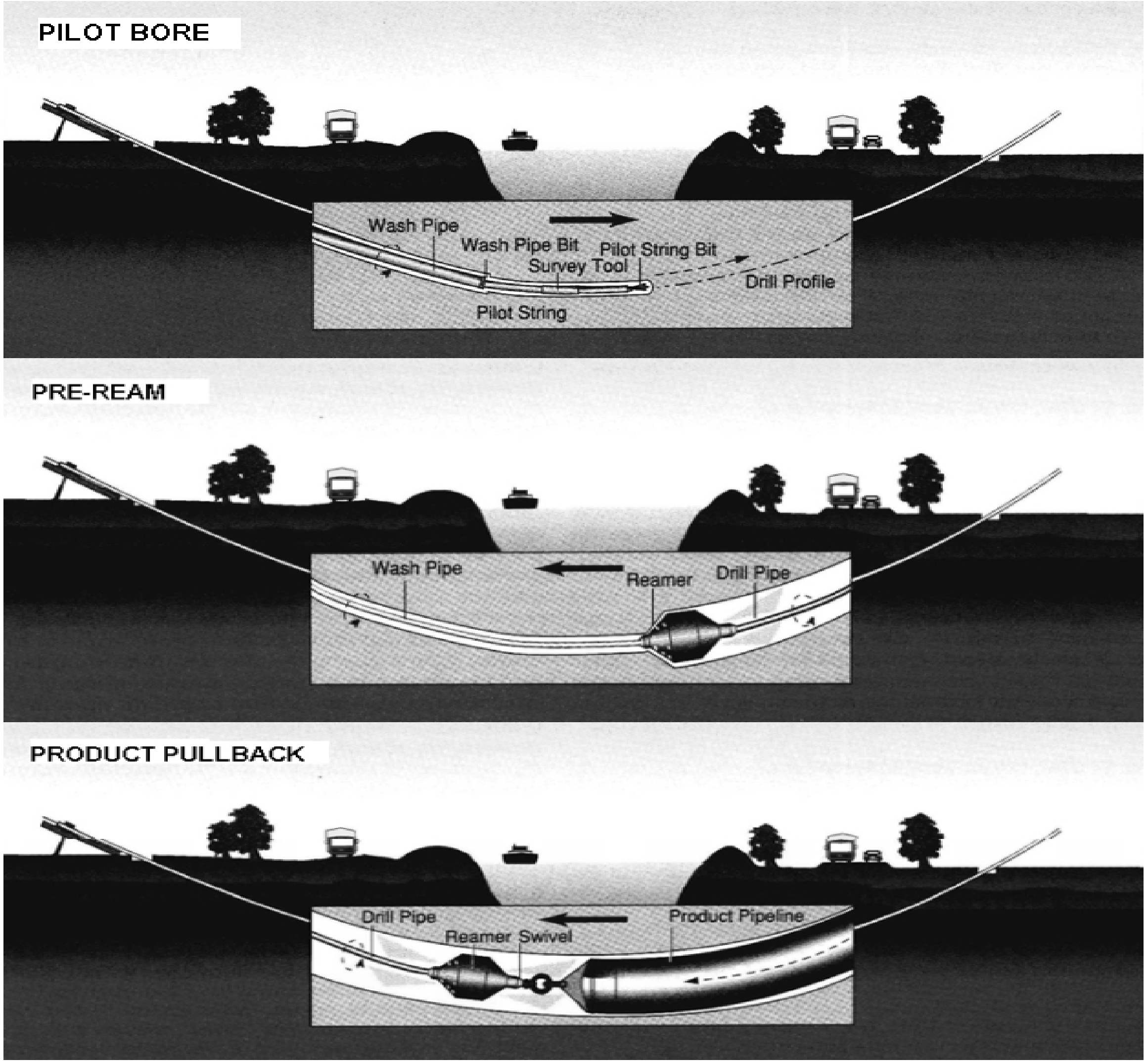


Figure 3-1: HDD process pilot bore, pre-ream and product pullback (HDD Consortium 2001).

3.2 Equipment

The main drilling equipment in a directional drilling construction is the drill rig. A typical HDD drill rig (Figure 3-2) consists of tracks that support and provide mobility to the rig, a rack and pinion carriage travel system to push, pull, and rotate drill rods and drill bits. Table 3-1 shows typical specifications for Mini, Midi, and Maxi drill rigs.

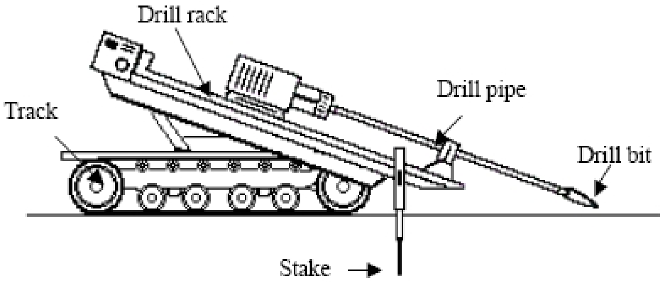


Figure 3-2: HDD Drill Rig Schematic (HDD Consortium 2001)

Table 3-1: Characteristics of Drill Rigs (HDD Consortium 2001)

	Mini-HDD Rig	Midi-HDD Rig	Maxi-HDD Rig
Thrust/Pullback	< 178 kN (<40,000 lb)	178 kN – 445 kN (40,000-100,000 lb)	> 445 kN (>100,000 lb)
Maximum Torque	54,23 kNm (<40,000 ft-lb)	54,23 kNm – 271 kNm (40,000-200,000 ft-lb)	> 271 kNm (>200,000 ft-lb)
Rotational Speed	>130 rpm	90-210 rpm	<210 rpm
Carriage Speed	> 30.5 m/min (>100 ft/min)	27.4 m/min – 30.5 m/min (90-100 ft/min)	< 27.4 m/min (<90 ft/min)
Carriage Drive	Chain, cylinder or rack & pinion	Chain or rack & pinion	Rack pinion with & without cable assist
Drill Pipe Length	1.52 m – 4.57 m (5-15 ft)	3.05 m – 9.14 m (10-30 ft)	9.14 m – 12.2 m (30-40 ft)
Drilling Distance	≤ 213 m (≤ 700 ft)	≤ 610 m (≤ 2,000 ft)	≤ 1829 m (≤ 6,000 ft)
Power Source	< 150 hp	150-250 hp	<250 hp
Mud Pump	0.283 m^3/s (<75 gpm)	0.189 m^3/s – 0.757 m^3/s (50-200 gpm)	0.757 m^3/s (>200 gpm)

Mini-HDD rigs (Figure 3-3) are regularly used to install cable utility and small diameter pipelines in congested urban areas. Midi-HDD rigs (Figure 3-4) are typically used to install conduits and pipelines up to 400 mm (16 inches) in diameter and drilling distance to a maximum of 600 m (2000 ft). Maxi-HDD rigs (Figure 3-5) are mainly used to for large diameter pipelines and/or long bores. Separate mounted trailers for drilling fluid system, carriage, and other support equipments are required for midi and maxi rigs.


Figure 3-3: Mini-HDD Rig (The Charles Machine Works, Inc. 2001)


Figure 3-4: Midi-HDD Rig (Vermeer Manufacturing Company 2004)


Figure 3-5: Maxi-HDD Rig (HDD Consortium 2001)

To complete a bore and product installation, downhole tools, such as drill pipes, drill bits, and reamers must be attached to the drill rig. Drill pipes are commonly made of steel; however, there are manufacturers that produce aluminum and titanium drill pipes. The main function of the drill pipes is to transfer thrust/pullback and torque from the drill rig to the drill bit or the reamer. The cavity in the drill pipes is used to transport drilling fluid down to the drill head.

Drill bits are made to steer and excavate ground formations at the face of the bore. Drill bits are designed to have a slanted face so that directional changes in the bore path can be made. Traditional drill bits work well in soft to medium clay and loose to dense sands. Figure 3-6 and 3-7 shows typical and modified drill bits.

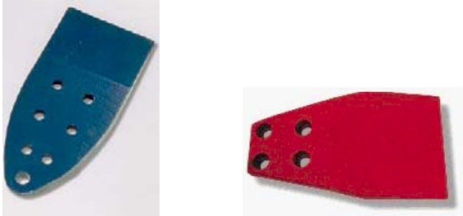


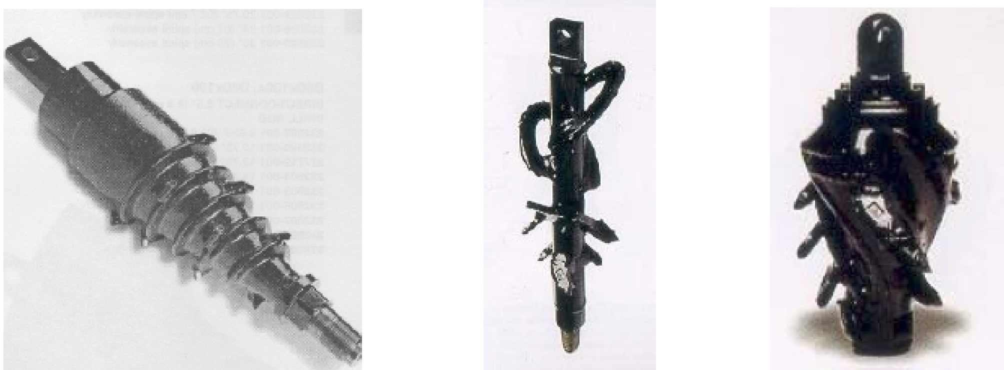
Figure 3-6: Traditional Slanted Face Drill Bits (HDD Consortium 2001)

Figure 3-7: Modified Slanted Face Drill Bits (HDD Consortium 2001)

To establish a straight bore, the drill bit is constantly rotated while the drill rig applies thrust to the drill bit slant face. If a steer correction is required, the slanted face is placed in the desired orientation and thrust is applied. The ground formation reaction then moves the drill bit. To steer upwards, the slanted face needs to face downwards. Similarly for steering left and right, the face of the drill bit needs to be placed opposite to the desired direction.

The equipment used to enlarge the pilot bore is the reamer. This device is connected to the drill string after the removal of the drill head. The reamer is pulled back towards the drill rig while under constant rotation. The purpose of the reamer is to enlarge the pilot bore to a sufficient diameter to accept the product pipe. Reamer selection is based on the soil conditions, bore size, and drill fluid pump capacity. The diameter of the reamer should be

1.2 to 1.5 times the outside diameter (OD) of the product pipe or 300 mm (12-inch) larger than the product pipe. Figure 3-8 shows reamers commonly used in the industry.



a) Compaction Reamer b) Mixing Reamer c) All Purpose Reamer

Figure 3-8: Back-reamer (HDD Consortium 2001)

To make space for the pipe, the volume of pipe to be installed must be equivalent to or greater than the volume of soil cuttings removed from the bore path. Drilling fluid is used to stabilize the bore and to aid in cutting removal from the bore path.

To track the bore path location, walk-over and wireline tracking system are employed. A walkover tracking system consists of three components: a transmitter (sonde) that is installed in the drill head, a hand-held receiver on ground surface to receive data from the sonde, and an optional remote monitor. The sonde is located in the drill head where it continuously emits an electromagnetic signal at a predetermined frequency. Figure 3-9 shows the location of the sonde within the drill head assembly.

Figure 3-9: Sonde location inside the Drill Head (HDD Consortium 2001).

Sonde pitch, roll, temperature, and battery strength are monitored at the surface using a receiver. In ground and above ground electromagnetic interference can distort the Sonde field, resulting in false readings. The accuracy of the receiver is typically within ± 2 to 5% of depth provided there is no field interference. A complete tracking system unit is shown in Figure 3-10.

Figure 3-10: Tracking System Unit (HDD Consortium 2001).

A wireline (also called non-walkover) system can be utilized when walkover is not possible or the depth of the bore is greater than 10m (30 ft) and/or when magnetic interference is expected. The system consists of a survey probe or instrument called “a steering tool” mounted in a non-magnetic drill collar or drill pipe section located behind a bent sub, mud motor and drill bit (HDD Consortium 2001). The combination of these components is called the Bottom Hole Assembly (BHA), as shown in Figure 3-11.

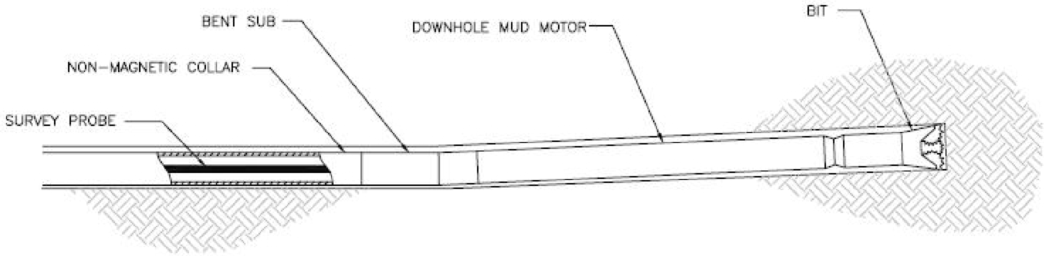


Figure 3-11: Bottom Hole Assembly Wireline Tracking System (HDD Consortium 2001)

Periodic readings of the probe inclination and azimuth are taken during pilot bore drilling to ensure that the drill path corresponds to the drill plan. The horizontal and vertical co-ordinates of the probe leading edge are determined by comparing current readings with previous readings. Typically readings are taken at a constant drilled distance relative to the entry point coordinates (Hair and Associates, et. al., 1995). The signal from the probe is transmitted through a wire, placed in the drill stem cavity, to the drill rig operator.

3.3 Drill Fluid Role and Functions

The use of proper drill fluids is a critical component in ensuring a successful HDD project. Drill fluid is a carrier fluid consisting mainly of water and some additives (bentonite, polymers, surfactants or wetting agents). The fluid is design to:

1. Support and stabilize the bore.
2. Transport formation cuttings to the surface.
3. Reduce friction between the product pipe and the bore wall.
4. Cool the sonde during drilling
5. Aid drill and reamer cutting

The composition of the drill fluid will depend on the formation composition and the properties required. Ground conditions can vary throughout the bore path and thus, drilling fluid additives are required. The drill fluid is pump into bore path and enters the bore via the drill bit or reamer. Drill fluid and formation cuttings mix to form a flowable slurry mixture that can be easily displaced by the product pipe. Biodegradable drill fluid is typically used for the construction of environmental wells (Katzman 1997).

3.4 Environmental Well Construction

The reported use and growth of HDD for the construction of horizontal wells has been slow compare to other industries. Due to project sensitivity, confidentiality and requirements by the site owners, very few well projects are reported or discussed in the literature. Details on well installation using a directional drill are discussed in the following sections.

The primary HDD configurations are the double drilled wells (also called the continuous wells) and the blind wells. Double drilled wells extend from the surface entry point to an exit point at some distance, similar to those of a typical HDD installation. On the other hand, blind wells terminate within the ground. In a continuous well configuration, the well bore path starts where the drill bit enters the ground to where the drill bit exits from the ground surface. Washover pipes or special reaming and cutting tools are employed to enlarge the bore path to the design diameter (Katzman 1997). For well installations, screen and casing materials are pulled into the bore path from the drill bit exit point. The well screen must have sufficient tensile strength to resist pull forces applied to the well. The well screen may also be placed inside a carrier casing that is pulled through the bore path. Once installed, the carrier casing is pulled out of the bore leaving the well in place. In a blind well installation, the borehole terminates at some pre-determined subsurface point. This type of well is usually used to reach a contaminated zone beneath a building or other obstructions. During the blind well construction, bore collapse is more likely to occur since it is left unprotected between drilling and reaming and between reaming and casing installation (Miller 1996). The well must be pushed in the cased or uncased bored.

The main design function for an environmental well is to allow flow into the well. As a result, drill fluids required to install the well must be removed or degraded once the well is in operation. Thus, biodegradable or degradable drilling fluids are commonly used.

Materials used for HDD wells include polyethylene (PE), Polyvinyl Chloride (PVC), and steel/stainless steel. Design factors that need to be considered in the choice of well screen and casing materials include tensile strength, flexibility, and material compatibility with ground and environmental conditions. The benefits of Polyethylene (PE) are light-weight, corrosion-resistance, flexibility, and the ability to fuse lengths together to form leak-tight joints. Disadvantages of PE are its low tensile strength, creeps under load, and its high thermal expansion coefficient. PE can be used as a well screen or carrier casing. For installations with high expected tensile pull loads, steel or stainless steel is the preferred pipe material.

Chapter 4: Literature Review

4.1 Previous Work in Landfills

Successful HDD installations in landfills have been reported in the United States and United Kingdom. This chapter reviews the published literature with respect to case studies on the use of a directional drill for the construction of horizontal wells installed in municipal solid waste. The main focus of this chapter is to illustrate difficulties encountered during constructions with drilling equipment and solutions achieved.

4.2 Livingston Landfill, Illinois, USA (Cox et al 2000; Friend & McDonnell 1996)

Livingston Landfill is located near Pontiac, Illinois, which is north of Interstate 55 and west of Illinois Route 23. The site was originally called the Pontiac Landfill, but more recently has been called the Livingston County Landfill. Landfill construction began in 1979 and became operational in the mid-1980's. Typical of landfills constructed during this period, it did not have an engineered liner or a leachate collection system.

In 1996 and 1999, three horizontal wells were constructed within the waste with a variety of waste composition to lower leachate levels within the 26 m high waste pile. Details of each constructed horizontal well are provided in following sections.

In March 1996, construction of the first well began. Construction consisted of pulling back a high density polyethylene perforated pipe through a 170-m long bore path. For this installation, no carrier casing was used. The location of the pilot bore was tracked during drilling using an AccuNav wireless tracking system developed by the Electronic Power Research Institute (EPRI). Biodegradable drill fluid was applied during all drilling stages and the pipe installation. Some drilling fluid returns were observed but no waste cuttings were observed in the slurry. A 200-mm diameter fluted reamer was used for enlarging the bore.

Two attempts were required to pull back the pipe. The first attempt consisted of pulling back a 150-mm diameter HDPE perforated pipe. During well pullback, the well screen failed.

The second attempt consisted of pulling back a 100-mm diameter HDPE perforated pipe. This installation was successful. Drilling and well installation took approximately 30 days to complete.

The second and third wells were installed in April 1999. These installations were mostly in the waste of a new section of the landfill. The length of each bore path was approximately 400 m. The second well also took two attempts to complete without a carrier casing. The first attempt employed a perforated HDPE pipe whereas the second attempt used a perforated steel pipe. Similarly to the first well, the well screen diameter was 100 mm. The tracking system used for these installations was the TruTracker wireline system. Biodegradable drill fluid additives were used and no drill fluid returns were observed after 60 m of drilling. The same 200-mm diameter fluted reamer used for the first well was also used for enlarging the bore path. During the second well installation, difficulties with the drill rig were encountered. The time required to complete the second well was approximately seven months. Changes made to the construction of the third well reduced construction time to several days.

4.2.1 Drill Rig Capacity

The drill rig used for the first well installation was the mini-HDD rig with 107 kN of pullback. Because the first well was completed with a mini-rig and within a reasonable timeline, the construction of the second well was attempted using the mini-rig. Difficulties encountered showed that a larger rig was required. Five drill rigs ranging from 267 kN to 2,224 kN capacity were employed in succession to complete the installation. With the aid of a 2,224 kN rig, the second well was completed. The third well was completed within several days. No data on the performance of the wells was reported.

4.3 City of Superior Landfill (City of Superior 2005)

The City of Superior in Wisconsin also demonstrated the benefits of horizontal wells utilizing HDD technique in landfills. Similar to Livingston Landfill, the City of Superior Landfill did not have a leachate control system. High leachate levels within the landfill resulted in leachate contaminated ground water being measured off site. Consequently, the City was required to lower its leachate level within the landfill. The construction and the operation of vertical wells failed to collect leachate. As a result, the Department of Engineering decided to perform a pilot study using the SchumaFlow process to install HDD wells.

The SchumaFlow process was developed in Germany and is a patented process. The process uses a carrier casing to protect the leachate collection well screen from tensile stress, smearing, and intrusion of drill spoils during installation. Well construction began in September 1996 and consisted of drilling a 365 m long bore through old MSW. Biodegradable drill fluid was used and no fluid returns were observed after 12 m of drilling. For the well installation, the bore path was reamed using a 400-mm diameter barrel reamer. The carrier casing, a 250-mm diameter HDPE pipe with a 100-mm diameter HDPE well screen installed in the pipe, was installed using a 300-mm diameter reamer. Once the carrier casing was installed, the well screen was held in place while the carrier casing was pulled out. Well construction and installation took four days. Although some obstructions were encountered during drilling, the overall process was considered a success. To date, the collection system is operating as designed.

4.3.1 Drill Rig Capacity

The drill rig used for the leachate collection well at the Superior Landfill was a midi-HDD rig with 311 kN of pullback. Compared with the Livingston Landfill, the well installation process went smoothly without any major delays in construction.

4.4 Rainham Landfill (Cox et al 2000)

At the Rainham landfill located in Essex, UK, a pilot project was conducted to investigate the feasibility of constructing a leachate control system using HDD horizontal wells. Prior to the well installations, a series of site investigation boreholes were drilled into the waste to characterize the waste and to provide some indication of potential problems. Two field trials were carried out: a 100 m long continuous well and three 250 m long wells blind wells.

Figure 4-1: HDD Horizontal Well Construction at the Rainham Landfill (Cox et al 2000)

The construction of the continuous well began in March 1999. Pilot bore drilling went through MSW place in the 1990's and in the mid 1970's. The bore path length was approximately 100 m. The tracking system used was a walkover guidance system that had a maximum operating depth of 10 m. After the pilot bore was completed, the bore was enlarged through two pre-reams. The first pre-reaming consisted of using a 100-mm diameter cutting reamer combined with a 150-mm diameter compaction reamer. The second pre-ream used the same assembly as the first pre-ream with the addition of a 250 mm diameter compaction reamer. Polymer based drilling fluids were used during all drilling stages. No slurry returns was observed at the ground surface. The drill plan called for a 150-mm diameter low carbon well screen to be pulled back to the entry point without a carrier casing. Pullback was stopped 25 m into the bore due to insufficient drill pullback capacity. The well screen was removed from the bore path and inspected. The authors reported that the integrity of the waste had caused the bore to collapse which resulted in difficulties for the well screen to advance through the bore. This construction method was abandoned.

A second field trial was carried out using a better tracking system, a larger drill rig, and the overwashing technique with a casing, to prevent the collapse of borehole. Three 250 m blind wells were constructed. Using the TruTracker wireline system the pilot bore path was maintain and located. The insertion of a 150-mm diameter steel overwashing casing was successfully achieved. Biodegradable drill fluid or water was pumped into the annulus between the overwashing casing and the drill string to ensure the inside of the casing remained free of cuttings. Drill pipes were removed when the pilot bore path was completed and a 114 mm diameter stainless steel well screen, (Figure 4-3) was pushed into the overwash casing. The casing was removed once the well screen was installed.

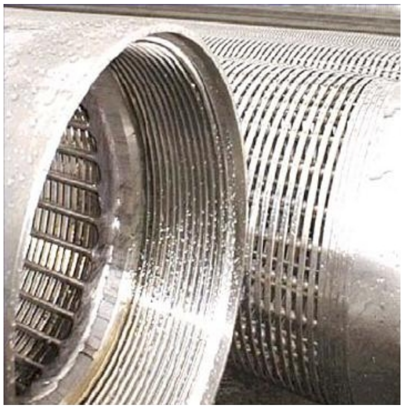


Figure 4-2: Stainless Steel Well Screen for the 2nd Field Trial (Cox et al 2000)

4.4.1 Drill Rig Capacity

The drill rig used for the first trial was the mini-HDD rig with 120 kN of pullback. The second trial employed a maxi-HDD rig with a minimum of 800 kN of pullback. The maxi rig also had significantly greater torque capacity that made waste cutting easier.

4.5 Summary

Based in a review of the three case studies, the following conclusions can be drawn:

1. The pullback capacity of the drill rig is a critical component for a successful HDD well installation. A maxi-HDD rig is the preferred drill rig size.
2. Biodegradable drilling fluid was used and very little drill slurry returned to the surface.
3. Drill slurry returns had no waste cuttings.
4. HDD technique can be used to successfully install horizontal wells in MSW.
5. Stainless steel wells screens and the use of a carrier casing are recommended.

Chapter 5 - Development of A Field Monitoring Program

5.1 Introduction

The purpose of this Chapter is to describe the monitoring program developed and implemented. The overall design of a field monitoring program is to collect data as drilling proceeds. Real-time data acquisition is the ultimate goal for this program so that any doubtful data attained can be related back to the well installation. Preliminary parameters for the monitoring program are determined based on literature reviews and the description of parameters monitored during the field tests is included in this Chapter.

The design of horizontal leachate collection wells using the HDD technique in MSW is currently not well documented and/or established. Although successful installations have been reported, there is limited data published to date to validate design assumptions. To understand both HDD equipment and pipe performance during a leachate collection well installation in MSW, a field program was developed to monitor the drill rig performance, the drill fluid behaviour, and the pipe performance.

5.2 Drill Rig Performance

A HDD drill operator advances, retracts and rotates the drill rods using machine hydraulics. Throughout the pilot bore, the pre-ream, and the well installation, the operator monitors hydraulic pressure gauges to determine the drill rig performance. For this research project, the drill rig hydraulic lines were modified so that Sensotec 13,790 kPa (2000-psi) pressure transducers, Figure 5-1, would record pressure gauge readings. Each pressure transducer was connected to a Lakewood Model R-X Ultra data acquisition system (DAQ), Figure 5-2, so that recorded pressure readings are provided at five second intervals. The data logger was downloaded daily to a notebook computer.

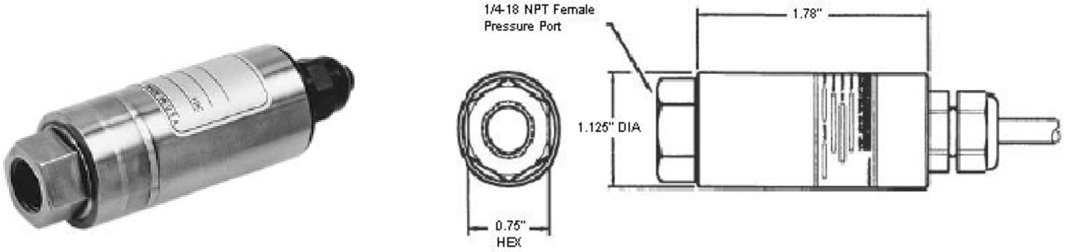


Figure 5-1: Schematic of a Drill Rig Installed Pressure Transducers (Honeywell Sensotec Inc)

Figure 5-2: Data Acquisition Unit used for Drill Rig Performance (Lakewood Systems Ltd.)

All pressure transducers were calibrated in the laboratory using the data logger and power supply used in the field. Calibration equations for each pressure sensor are provided below.

S/N 746766: $y = 1853.739x - 86.454$ $R^2 = 0.999$ (5.1)

S/N 469763: $y = 1838.076x - 89.353$ $R^2 = 1.000$ (5.2)

where S/N is the Pressure transducer serial number
y is the pressure transducer reading in psi
x is the pressure sensor voltage readings recorded by the DAQ

5.3 Pipe Performance

To understand how the carrier casing performs during installation, through the bore path, and post installation, sensors were installed onto and into the pipe walls to record:

- Load applied to the pipe.
- Pipe wall strain.
- Pipe wall deflection.
- Fluid pressure on the pipe outer surface.

- Pipe interior temperature and fluid temperature adjacent to the pipe wall outer surface.

Two instrumented pipe sections (test sections) approximately 1.5 m in length, were modified in the University of Waterloo Soils Laboratory to accommodate data acquisition units and sensors. Sensors were installed in the HDPE pipe section for the East Well and also on the steel pipe section for the West Well.

The East Well test section, shown in Figure 5-3, consisted of the following parts:

- A load cell connecting to an eye bolt (load bolt) placed at the front of the test section.
- Quarter bridge strain gauges placed on the inside pipe wall.
- Displacement sensors placed on the inside of the pipe.
- Fluid pressure sensors installed in the pipe wall.
- Thermocouples placed on the inside of the pipe wall and in the pipe wall.
- Data loggers & batteries used to record sensor readings.

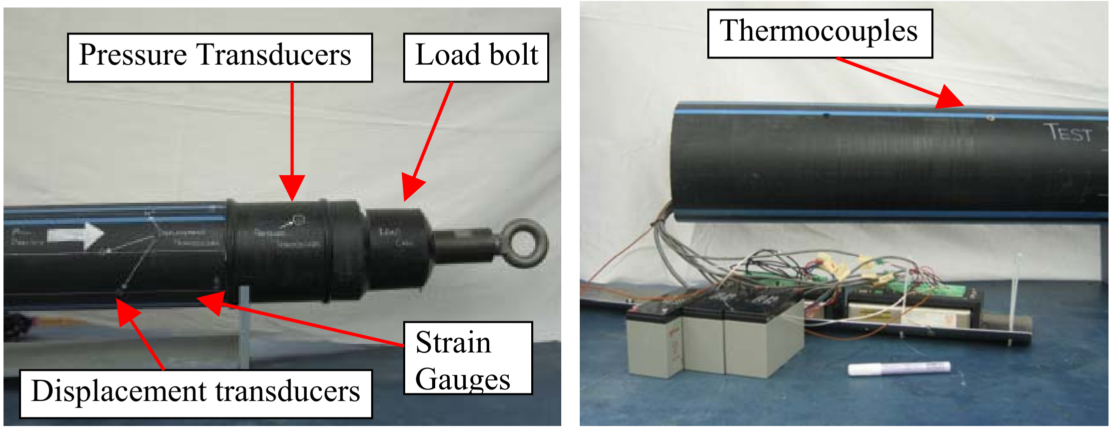


Figure 5-3: East well HDPE Test Section.

The West Well test section, shown in Figure 5-4 consisted of the following:

- Quarter bridge strain gauges placed on the inside pipe wall.
- Fluid pressure sensors installed in the pipe wall.
- Thermocouples placed on the inside of the pipe wall and in the pipe wall.
- Data loggers & batteries used to record sensor readings.

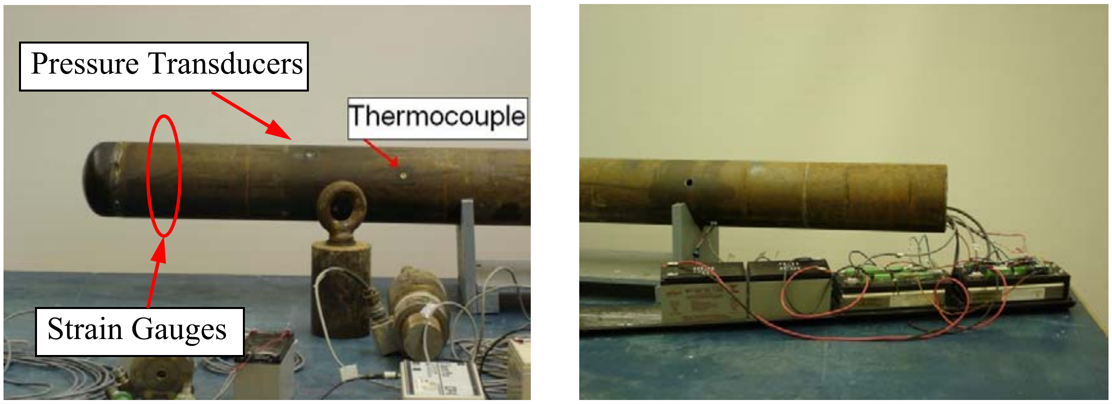


Figure 5-4: West Well Test Instrumented Steel Carrier Casing.

For both test sections, data loggers and batteries were mounted on a plastic tray that was placed and screwed to the pipe inner surface. Two access points were created and capped with brass plugs. Data logger and power wires were attached to the brass plug so that access to the data logger and the power supply could be obtained without the need to remove the equipment.

5.3.1 Pipe Pull Load

To measure the pipe pull load, a Strainsert SXS series hex head cap screw, also refers as load bolt was used. Figure 5-5 shows the load bolt used for both the East and West well installations.

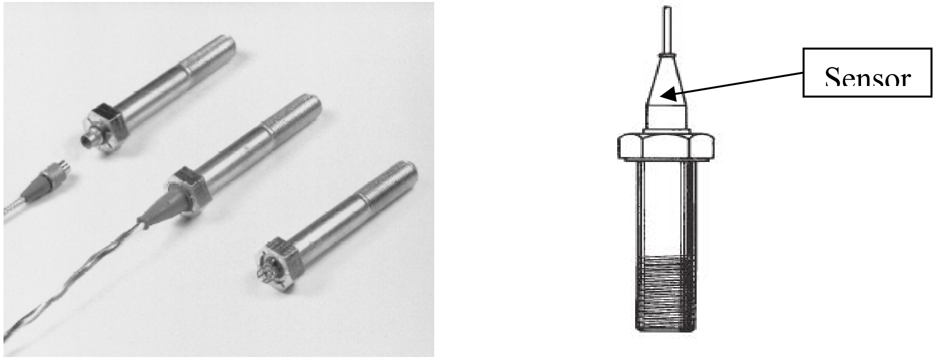


Figure 5-5: Strainsert Standard Internally gauged hex head cap screw

For the load bolt to work as design, a thread steel adapter was manufactured at the University of Waterloo machine shop to connect the load bolt to the reamer swivel. The load bolt was positioned through the adapter and placed inside the butt cap. An eye bolt on the outside of the butt cap was then threaded to the load bolt. The swivel connecting to the drill rig then could be hooked to the eye bolt. To connect the butt cap to the 200-mm (8-inch) Ductile Iron Pipe Size (DIPS) DR-11 HDPE carrier casing, a DIPS to IPS connector were fused onto the butt cap. The fused butt cap was then fused to a 1.5 m long section of the HDPE pipe to form a test section. Figure 5-6 shows the load bolt location inside the HDPE Iron Pipe Size (IPS) butt fusion cap.

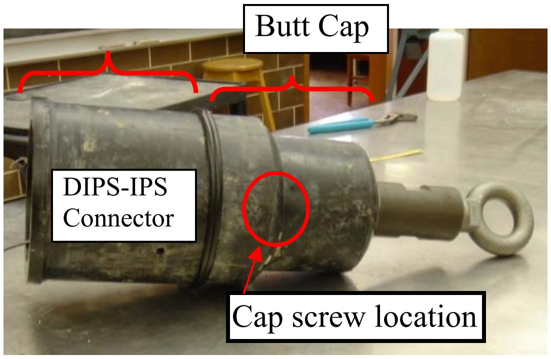


Figure 5-6: HDPE butt cap that contains load bolt connected to steel adapter.

A CR-10X Campbell data logger was used to monitor and record load bolt data. Figure 5-7 shows the schematic of the data logger with either twelve single-ended or six differential channels that can store 62,000 data points.

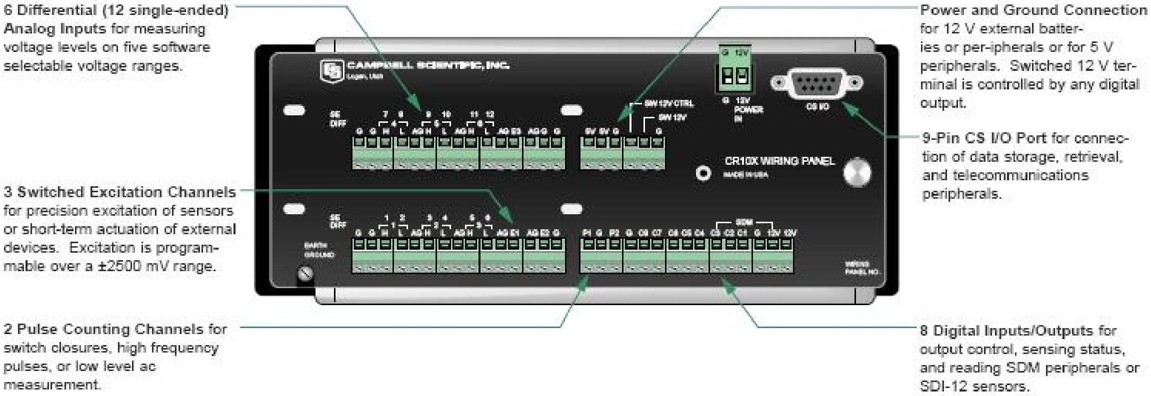


Figure 5-7: Data logger for Monitoring Pipe Performance (Campbell Scientific, Inc.)

Calibration of the load bolt for the HDPE test section was completed using the Campbell data logger on the full-scale load reading and the power supply to be used in the field (12volt batteries). Equation 5.3 presents the calibration equation used to convert sensor voltage to pull force.

$$y = 1767.79x - 94.5 \quad R^2 = 1.000 \tag{5.3}$$

where y is the load bolt load in lbs

x is the DAQ voltage reading in mV

R^2 is the coefficient of determination

5.3.2 Pipe Strain

Quarter bridge strain gauges were glued to the interior of the HDPE and steel test sections as shown in Figures 5-8 and 5-9, respectively. The configuration of these strain gauges is explained in Tables 5-1 and 5-2, respectively. For the East Well, longitudinal strain gauges were installed at 12, 4 and 8 o'clock positions relative to the pipe entrance into the ground and transverse strain gauges were installed at the 12 and 3 o'clock positions. For the West Well, four longitudinal and four transverse strain gauges were installed at 12, 3, 6, and 9 O'clock positions.

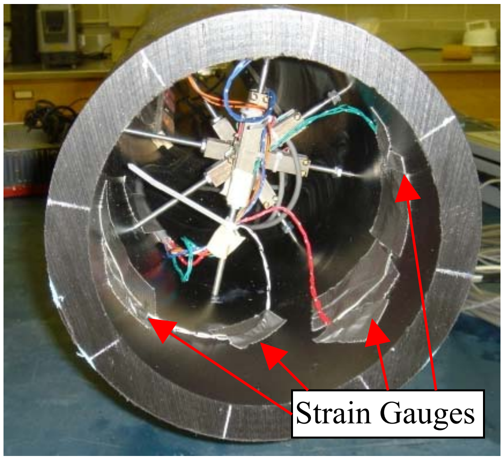


Figure 5-8: East Well HDPE Test Section Strain Gauge Locations.

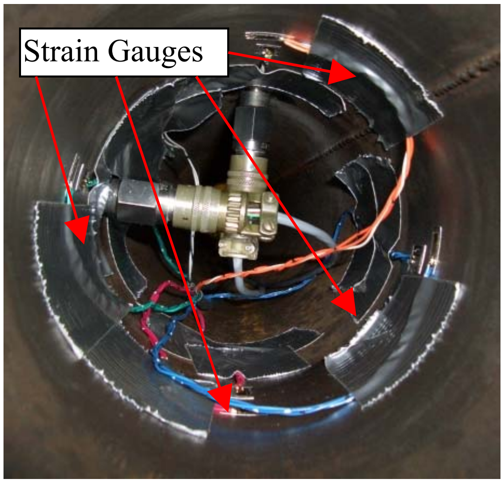


Figure 5-9: West Well Steel Test Section Strain Gauge Locations.

Table 5-1: East Well HDPE Test Section Strain Gauges Identification.

Sensor Type	Location (relative to pipe entry)	Gauge ID
Strain Gauge	12 o’clock transverse	T12
	3 o’clock transverse	T3
	12 o’clock longitudinal	L12
	4 o’clock longitudinal	L4
	8 o’clock longitudinal	L8

Table 5-2: West Well Strain Steel Test Section Strain Gauge Location and Colour Codes

Transversal Direction			Longitudinal Direction		
Orange/White	12 o’clock	T12	Black/White	12 o’clock	L12
Blue	3 o’clock	T3	Blue	3 o’clock	L3
Red	6 o’clock	T6	Red	6 o’clock	L6
Green	9 o’clock	T9	Green	9 o’clock	L9

To complete the strain gauge, bridge terminal input modules shown in Figure 5-10, were used to connect the strain gauges to the Campbell data loggers. Calibration curves were not developed. To convert voltage changes that were measured in the strain gauges to strain, Equation 5.4 was used. Equation 5.5 was used to convert strain to load to determine correlation between strains and pull load.

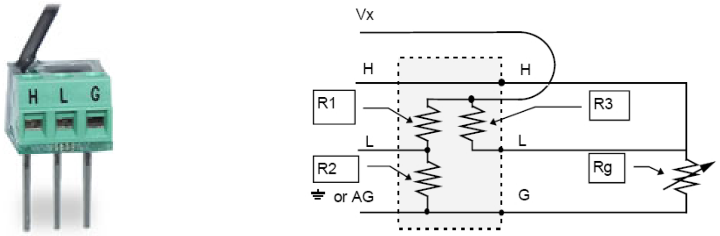


Figure 5-10: Strain Gauge Wiring Schematic (Campbell Scientific).

$$\mu\varepsilon = \frac{4\times10^{6}\left(\frac{V_d}{V_e}\right)}{GF\left[1-2\left(\frac{V_d}{V_e}\right)\right]} = \frac{1.4\times10^{6}V_d}{GF\left[1-0.8V_d\right]} \tag{5.4}$$

where V_d is the output voltage

V_e is the excitation voltage, which is 2.5V

GF is the gauge factor

$$p = \frac{E\times A\times\varepsilon}{10^{6}} \tag{5.5}$$

where p is the pipe load force, lb_f

A is the cross sectional area of the pipe, in^2

ε is the strain, in microstrain

E is the pipe material elastic modulus at 23˚C (73˚F)

The elastic modulus of 760 MPa (110,000 psi) was assumed for the HDPE pipe and 200,000 MPa (29,000,000 psi) was used for the steel pipe. It should be noted that the HDPE elastic modulus is temperature and load rate dependant.

5.3.3 Pipe Wall Deflection

A linear potentiometer (displacement transducer) was installed on the inside the pipe circumference to monitor carrier casing wall deflections during installation. The displacement transducer is shown below in Figure 5-11. For the East Well, four displacements were installed in the HDPE test section as shown in Figure 5-12. The position of the four displacement transducers are explained in Table 5-3.

Figure 5-11: Displacement Transducer used to monitor carrier casing wall deflections.

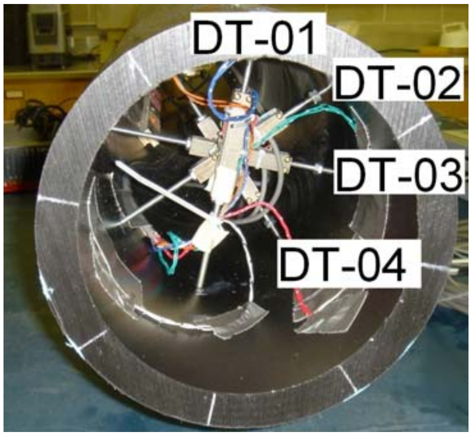


Figure 5-12: Displacement Transducer Locations inside HDPE Test Section.

Table 5-3: Displacement Sensors Identification for East Well HDPE Carrier Casing

Sensor	Location (relative to pipe entry)	ID
Displacement Transducer	0 degree	DT-01
	45 degree	DT-02
	90 degree	DT-03
	135 degree	DT-04

Transducers were placed at intervals of 45 degrees with DT-01 at the 12 to 6 O'clock position. All displacement transducers were connected to a Campbell CR-10X data logger. Using the data logger and the field power source, displacement transducers were calibrated. Calibrations equations for each of the transducers are listed below.

$$\text{DT-01: } y = 0.0136x - 2.4681 \qquad R^2 = 0.997 \tag{5.6}$$

$$\text{DT-02: } y = 0.0136x - 3.2277 \qquad R^2 = 0.995 \tag{5.7}$$

$$\text{DT-03: } y = 0.0135x - 2.0171 \qquad R^2 = 0.985 \tag{5.8}$$

$$\text{DT-04: } y = 0.0139x - 2.2066 \qquad R^2 = 0.998 \tag{5.9}$$

where DT represents a displacement transducer number
y is pipe wall deflection in millimetre
x is the transducer voltage reading in mV
R^2 is the coefficient of determination

Displacement transducers were not installed in the West Well test section due to high wall stiffness of the steel test section.

5.3.4 Bore Annular Space Fluid Pressure

Two pressure transducers were installed on the inside of the test sections so that the pressure sensor was flush with the outside pipe wall. For this field program, 517 kPa (75 psi) Sensotec Model A-105, Figure 5-13, pressure transducers were used.

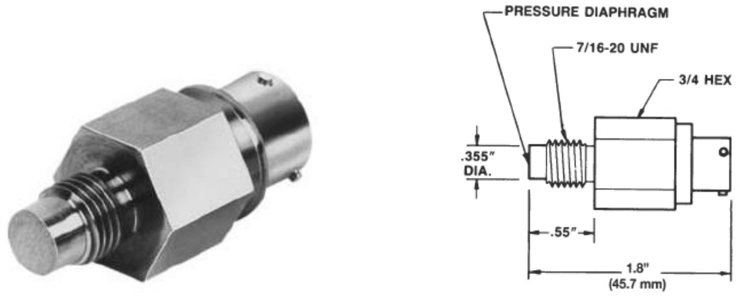


Figure 5-13: Schematic of a 517kPa (75 psi) Pressure Transducer (Honeywell Sensotec).

For the East Well, the HDPE test section had two pressure transducers installed inside the butt fusion cap as shown in Figure 5-14. The transducers were located at 12 o’clock and 9 o’clock positions relative to the pipe entry orientation. Transducers were denoted as PT-01 and PT-02. For the West Well, pressure sensors were installed in the steel test section at the 12 and 9 o’clock positions as shown in Figure 5-15.

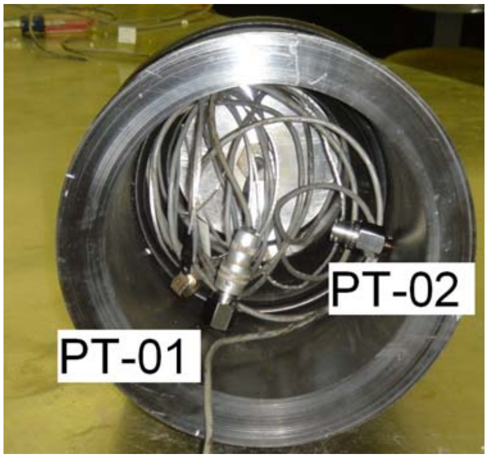


Figure 5-14: East Well HDPE carrier casing Pressure Transducers location.

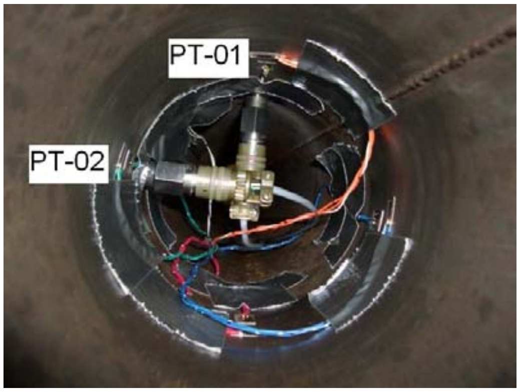


Figure 5-15: Pressure transducer location in the West Well 125-mm Steel Carrier casing.

Pressure sensors were connected to a Campbell CR-10X data logger. Using the data logger and the field power source, pressure transducers were calibrated at the University of Waterloo. Calibrations equations for each transducer are presented in Equations 5.10 and 5.11.

$$\text{PT-01: } y = 17.740x - 0.238 \quad \text{(S/N 956054)} \qquad R^2 = 0.999 \tag{5.10}$$

$$\text{PT-02: } y = 17.745x + 0.668 \quad \text{(S/N 960081)} \qquad R^2 = 0.999 \tag{5.11}$$

where PT represents pressure transducer

y is the pressure sensor pressure in psi

x is the pressure sensor voltage in mV

S/N is the serial number

R^2 is the coefficient of determination

5.3.5 Temperature

Two thermocouples were installed both on and in the test sections. One thermocouple was placed on the inside to the pipe while the second thermocouple was placed into a hole drilled into the brass plug so that fluid temperatures adjacent to the outside of the pipe could be recorded. Both thermocouples were connected to the Campbell CR-10X data logger and the data was collected at two seconds intervals.

5.4 Carrier Casing Pullout Load

Construction equipment was used to pull the pipe out of the bore to remove the pipe when the carrier casing became stuck during installation on several occasions. The construction equipment pull force was recorded using a 333 kN (75,000 lbs) Sensotec Model RMV5S37-01 load cell. This external load cell was connected to the equipment via a choker or steel chain via adapters with eye bolts that were screwed on the ends of the load cell. Figure 5-16 shows the load cell with the eye bolt connector.

Figure 5-16: External Load Cell used to measure Pullout force applied to Carrier Casing.

The load cell was connected to a Lakewood Model R-X Ultra data acquisition system (DAQ), previously shown in Figure 5-2. A calibration of the load cell was not performed for this research. The following calibration equation using Lakewood DAQ was previously determined and used to convert load cell voltage to pull force.

$$y = 71908x - 309.2 \qquad R^2 = 0.9281 \tag{5.12}$$

where y is the applied load in lbs

x is the voltage load cell reading in Volts

5.5 Drill fluid Volume

To quantify the volume of drill fluid used during each drill stage, an ultrasonic Doppler Flowmeter Model HFM-5EM was installed onto the test section as shown in Figure 5-17.

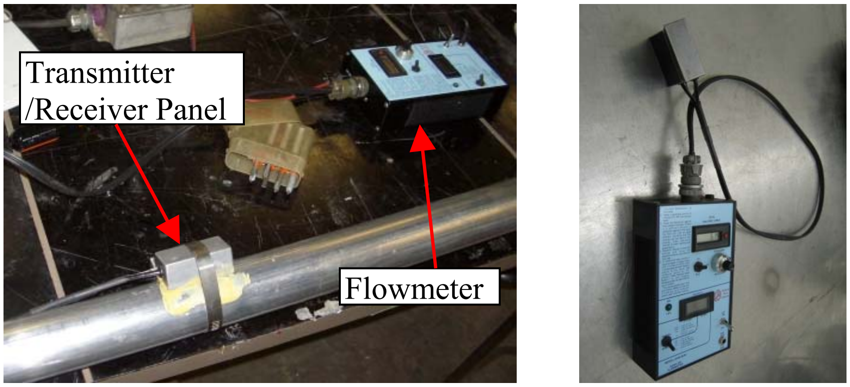


Figure 5-17: Doppler Ultrasonic Flowmeter

This device works as follows: a transmitter (XMIT) is mounted on a pipe and a receiver (RCV) is installed on the opposite side of the pipe. A signal is emitted from the transmitter and this signal collides and deflects off particles in the fluid stream. The movement of the ultrasonic signal is illustrated in Figure 5-18. The transmitted signal is received by the receiver and the velocity of the fluid is determined thereby the volumetric flow rate can be determined.

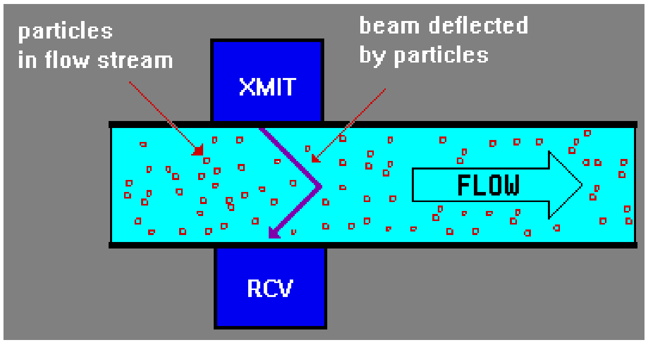


Figure 5-18: Schematic of Transmitter and Receiver Panel (US Department of Interior 2006)

A Hobo Micro Station data logger, shown in Figure 5-19, manufactured by Onset Computers, was used to record data obtained from the flowmeter, at two second intervals.

Figure 5-19: Data Acquisition Unit for Drill fluid Performance (Onset Computer Corp.)

Several weeks were spent in the laboratory attempting to calibrate the flow meters using water as the fluid. The best calibration obtained is presented in Equation 5.13.

$$y = 0.2696x - 0.9931 \quad R^2 = 0.5297 \qquad (5.13)$$

where y is the fluid velocity in ft/s

x is the sensor current reading in mA

R^2 is the coefficient of determination

The flow meter displayed velocity readings as low as 0.1 ft/s. This low sensitivity resulted in significant fluctuations of the velocity readings and the poor R^2 coefficient of determination.

Chapter 6 - Horizontal Well Construction

6.1 Introduction

Two HDD wells at the Waterloo Landfill site were approved to be installed in the OLA: one located on the east side of the landfill and one located on the west side of the landfill. This Chapter presents details on the construction of the two wells.

6.2 East Well Construction

The East Well started on July 12, 2005 at the southeast corner of the OLA Waterloo Landfill site. This well was completed on August 12, 2005. A total of four attempts were made to complete it.

6.2.1 Bore Path

The East Well was designed to be 213 m (700 ft) in length. Drilling was started at the top of the west side of the landfill and it proceeded on a downward slope with a minimum grade of 2% until it exited at the east toe of the landfill. The vertical elevation drop was 33 m (108 ft). Figure 6-1 shows the planned bore path and as constructed bore path for the East Well.

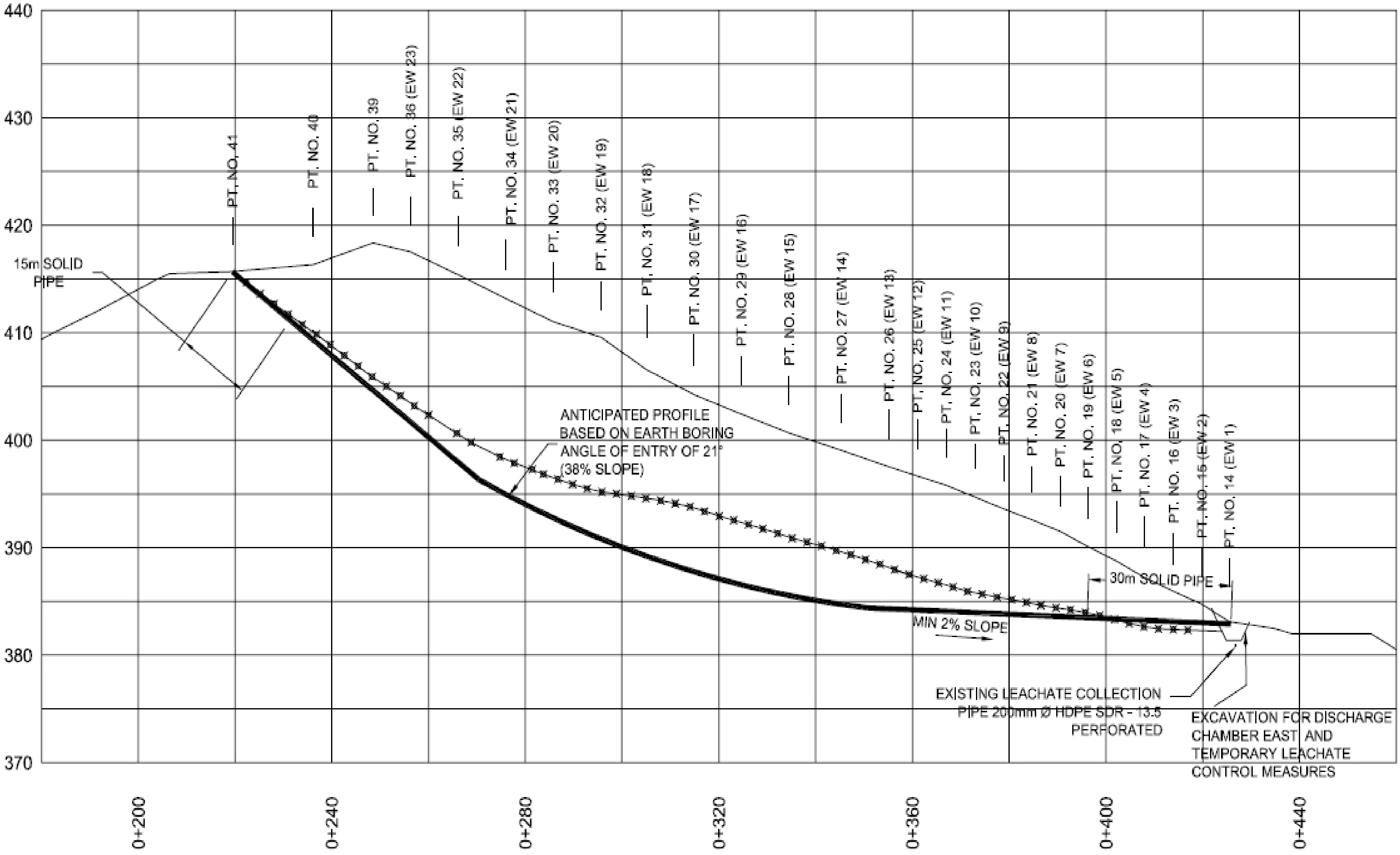


Figure 6-1: East Well Drill Plan and Actual Pilot Bore Path Profile.

The bore plan consisted of pulling a 200-mm (8 inch) DIPS DR-11 HDPE carrier casing with a 150-mm (6 inch) HDPE well screen placed inside. The bore path determined by the RMW consultant was surveyed and staked using a total station. During drilling of the pilot bore, obstacles were encountered. As a result, the drill head was deflected upwards. Thus, the constructed bore path, shown in Figure 6-1, is higher than the proposed bore path. The pilot bore exited the MSW as designed by drilling through the clay toe berm where the minimum, grade requirements were achieved. Prior to the drill head exiting from the bore, frac-out occurred approximately 3 to 5 m (10 to16 ft) before the drill head exited. A frac-out is caused when excessive drilling pressure results in drilling mud propagating vertically toward the surface. Because the cover around exit point was shallow, the excessive drilling pressure caused drilling fluid to escape to the ground surface.

6.2.2 Drill Rig Setup

A Robbins 4515TM-MSC drill rig operated by Earth Boring Inc. was used for the well construction. This rig is rated for 214 kN (48,000 lb) pullback and 7.1 kNm (5,200 ft-lbs) of torque. Earth Boring customized the drill rig to have 302 kN (68,000 lbs) pullback. Initially, the rig was setup on top of the covered waste pile. Following heavy rains, the ground anchoring the rig became unstable. To correct this problem, a gravel pad was constructed to set the rig on (Figure 6.2). The drill rig was set up to enter the ground at an angle of 21º (38% pitch).

Figure 6-2: The Addition of Gravel Platform for Drill Rig Stability

The drill rods had an outside diameter (OD) of 72.5 mm (2.5 inches) and an internal diameter (ID) of 25 mm (1 inch). The bore path was tracked using a DigiTrak Eclipse locating system that allowed the use of both wireline and walkover systems. An Eclipse EDRR sonde was connected via splice wires placed inside the drill rods to a receiver on the drill rig, shown in Figure 6-3.

Figure 6-3: The Combination of Wireline System and Walkover System.

During drilling stoppages, the wireline was connected to the receiver, information from the sonde was obtained. Continuous readings were not possible with the drill rig setup. Data collected from the sonde via the wireline included temperature, pitch, and orientation of the drill head. Depth data was obtained using the walker receiver. Due to the depth of the bore being greater than 10m and the potential for electromagnetic interference to occur, the use of the walkover system was limited.

6.2.2.1 Pilot Bore Construction

Pilot bore drilling started at an elevation of approximately 415 m (1362ft) using a 75 mm (3 inches) diameter hogs head drill bit as shown in Figure 6-4. Pilot bore drilling required fourteen working days to complete.

Figure 6-4: Drill Head used for the East Well installation

6.2.2.2 *Leachate Flow from Pilot Bore Exit*

The leachate mound at the Landfill suggested that the leachate elevation was at an elevation significantly greater than the pilot bore exit location. This high estimated leachate head led to the concern that large volume of leachate would be drained from the OLA when the pilot bore exited the toe berm. On-site pumps and vacuum extraction equipment were used to collect and discharge leachate to an adjacent manhole when the drill head broke through the berm. However, very little leachate was observed when drill head broke through. Figure 6-5 shows the condition of the bore after exit of the drill bit.

Figure 6-5: Breakthrough of pilot boring

During the drill head breakthrough, drill slurry and a limited amount of leachate flowed briefly from the bore. Using a rubber tire backhoe, a small leachate collection sump pit was dug. Leachate was observed to seep out of the bore and the amount increased briefly during precipitation periods. The pumping equipment was removed from the site after several days of leachate monitoring,

6.2.3 Carrier Casing and Well Installation

Following the completion of the pilot bore, the instrumented test section was fused onto the 200-mm (8 inch) HDPE DR-11 carrier casing and the 150-mm (6-inch) HDPE well screen was installed inside the carrier casing. Figure 6-6 shows the fusion of the test section onto the carrier casing.

Figure 6-6: Fusion of Instrumented Test Section onto the 200mm Carrier Casing.

During the pipe pullback, problems occurred in which the installation was stopped and re-started several times. A total of four attempts were made to install the HDPE carrier casing and well screen. Each attempt is described in the following sections.

6.2.3.1 Carrier Casing and Well Installation – 1st Attempt

The 200-mm HDPE carrier casing was connected to the Dub swivel that was connected to a 305 mm (12-inch) fluted reamer. Figure 6-7 shows the reamer entering into the bore at 10:00 a.m. on July 18, 2005.

Figure 6-7: The entering of the 305 mm Reamer into the Bore during Pullback

Carrier casing pullback proceeded until approximately 33.5 m (110 ft) of the casing entered into the bore (approximately 11:30 a.m.). At this point, the pipe stopped moving while drill rods were being removed. Drilling was stopped and the failure was inferred to be a drill rod breakage.

To retrieve the reamer and the pipe, several attempts were made to pull the carrier casing out of the bore using a rubber tired backhoe. These attempts were not successful and thus a CAT 235 excavator was brought to the site on July 29, 2005 to remove the pipe. Using a choker, as shown in Figure 6-8, the pipe was pulled out of the bore.

Figure 6-8: Pullout of Carrier Casing during 1st Pullback Attempt by Backhoe & Excavator

The pipe pullback rate was controlled so that drill rods could be pushed at the same rate as the reamer being pulled back. The pipe pullout load was recorded using the external load cell connected to the choke. Inspection of the equipment after the removal from the bore found that failure occurred where the drill rod threaded into the reamer. The reamer and swivel were also found to be wrapped with ropes, cables, and carpet fragments, forming a ball. A grinder was used to cut is material wrapped around the reamer. Figure 6-9 shows the condition of the reamer and swivel upon removal from the bore.

Figure 6-9: The Removal of Reamer after 1st Pullback Attempt (July 28, 2005)

Once the swivel was disconnected from the swivel, data were retrieved from the test section and downloaded. Once the reamer was cleaned of debris, it was taken off site to have the broken drill rod section removed.

An initial flush of leachate was observed during the pipe removal but it had quickly decreased to a trickle. To contain leachate, a vacuum extraction truck for long term control was used. In addition, the leachate collection sump was extended. Subsequently, it was observed that a significant increase in fluid (drilling fluid/leachate) flowed from the bore following removal of the reamer and the casing as shown in Figure 6-10. The fluid that entered the exit pit was permitted to infiltrate through the base of the pit back into the waste mound.

Figure 6-10: Leachate Flow after Pullout of 200-mm HDPE Pipe on July 18, 2005

6.2.3.2 Carrier Casing and Well Installation – 2nd Attempt

The second installation attempt consisted of re-installing the 200-mm (8-inch) HDPE carrier casing on August 23, 2005 at approximately 10:25 a.m. using the same reamer and swivel as the first attempt. Pullback proceeded without problem until approximately 36.5 m (120 ft) of the pipe entered into the bore when the carrier casing stopped moving while drill rods were pulled back (approximately 11:30 a.m.).

Figure 6-11: Leachate Flow during 2nd Pullback of 200-mm HDPE Casing

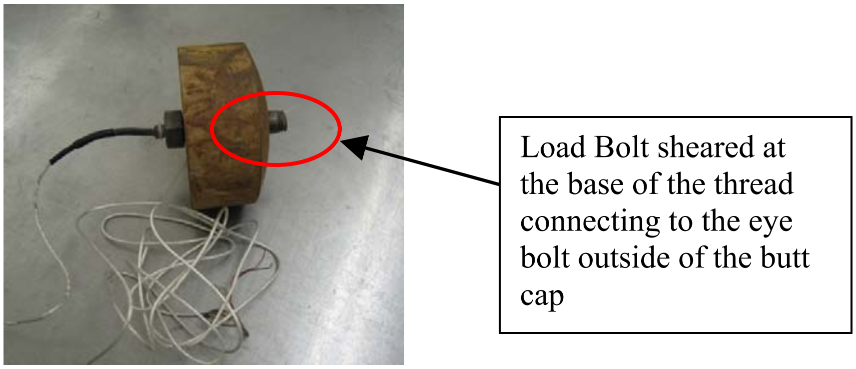
The CAT 235 excavator was used to pull the pipe out of the bore. When the pipe was removed from the bore, leachate mixed with drilling fluid flowed into the exit pit as shown in Figure 6-11. The pullout load was recorded using the load cell shown in Figure 6-12. As with the 1st Attempt, drill rods and the pipe pulling were co-ordinated so that they occurred together.

Figure 6-12: Load Cell Connected to the Excavator during 2nd Pullout of Carrier Casing.

Upon pipe exit, it was found that the carrier casing was no longer connected to the swivel and that the load bolt placed through the HDPE butt cap was not present. The steel adapter that connected the load bolt to the swivel was found to be intact. Figure 6-13 shows the condition of the carrier casing upon the removal from the bore.

Figure 6-13: Condition of Carrier Casing After 2nd Pullout.

The testing section containing data from the loggers was transported to the University of Waterloo for clean-up and to determine the cause of the failure. Inspection of the load bolt found that the load bolt failed at the base of the threads as shown in Figure 6-14.



Load Bolt sheared at the base of the thread connecting to the eye bolt outside of the butt cap

Figure 6-14: Load Bolt Shear Failure

The failure pattern on the bolt suggested that the bolt failed in shear and not tension. Upon exit from the bore, the reamer and swivel were found to be wrapped with rope, cable and a bicycle tire, as shown in Figure 6-15. The debris was observed to prevent the swivel from turning. Swivel failure was inferred to rotate and shear the load bolt.

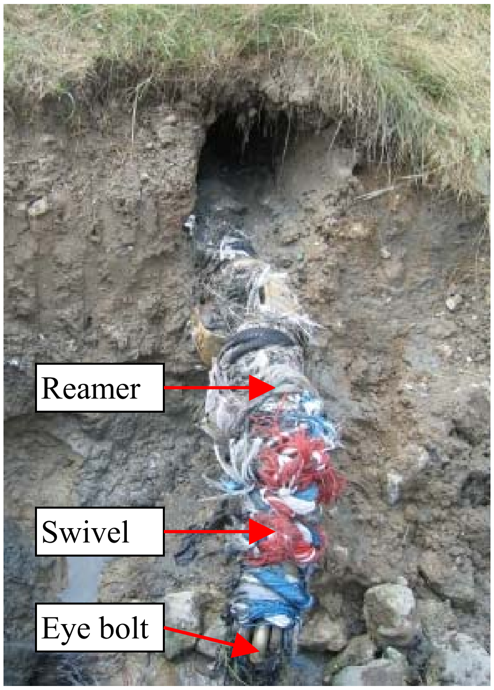


Figure 6-15: Reamer tangled with Garbage after 2nd Pullback Attempt

6.2.3.3 Carrier Casing and Well Installation – 3rd Attempt

The third pullback attempt involved re-installing the carrier casing without the test section. The installation started at 9:30 a.m. on August 4, 2005. Pullback proceeded without problems until approximately 11:00 a.m. when the casing could not be advanced. At this time, 41 m (135 ft) of pipe had entered into the bore. Pushing with the drill rig and pulling in the casing with the excavator dislodged the reamer/casing allowing pullback to resume for 14 m (45 ft) or until approximately 55 m (180 ft) of pipe had entered into the ground. At this point, approximately 12:10 p.m., the casing became stuck. Attempts to dislodge the reamer and the casing were made by pulling back the casing and at reversing the pull (pushing with the drill rig). Pullback was resumed after pulling back the casing approximately 1.5 m (5 ft). Pullback resumed for another 3.0 m (10 ft) when alternate drill rig pushing and pulling was completed to get by an obstacle for 1.5 m (5 ft). Following passing the obstacle, pullback proceeded for 16m (55 ft) (approximately 71.6 m of pipe entered the bore) when drill rig pressure gauges for pullback and rotational pressure readings were reaching maximum values and that the casing was about to become stuck. At this point, it was decided to withdraw the reamer and the casing from the bore so that it could be clean of debris. At this point, 72.1 m

(236 ft) of the pipe was installed. While attempting to pull back the casing, the choker severed the pipe, shown in Figure 6-16.

Figure 6-16: Damages on the 200-mm and 150-mm HDPE pipe after 3rd Pullback Attempt.

The pipe and the reamer were withdrawn from the bore around 6:15 p.m. Unlike the previous pipe removals, no significant accumulation of debris was observed on the reamer or swivel. During the casing removal, a significant increase in black leachate flow out of the bore was observed. The sump pit was cleaned to provide additional capacity for leachate accumulation. Leachate flow reduced back to a trickle within a couple of hours.

6.2.3.4 Well Installation – 4th Attempt

Following a site meeting and discussion of available options, it was decided that the 100-mm (4-inch) OD HDPE pipe perforated well would be installed behind a 150-mm (6-inch) reamer.

Pullback of the HDPE well commenced at 11:00 a.m. on August 11, 2005. Pullback proceeded without any problems until approximately 1:00 p.m. when 146 m (480 ft) of the pipe was pulled back into the bore.

At this point, a discrepancy was noted between the length of drill rod removed from the bore and the length of HDPE pipe entering into the bore. Measurements of the HDPE pipe length installed during the removal of each drill rod (10 ft length) indicated that the length of the HDPE pipe pulled into the bore was progressively decreasing in length compared to the drilled length. This discrepancy in length led to the conclusion that the HDPE pipe was yielding in the bore. At this point, approximately 167 m of the 212 m (550 ft of the 695 ft) total length of well was installed. Pulling the HDPE well pipe out of the bore was not considered possible. Thus, it was decided to complete the pullback of the HDPE well pipe. With approximately 6 m (20 ft) of well pipe to install, the perforated HDPE pipe broke within the bore. Figure 6-17 shows the condition of the pipe when it came out of the bore.

Figure 6-17: Failure of 100-mm OD HDPE Well Pipe during 4th Attempt

A total of 23 m (76 ft) was pulled out from the bore at the entry point where the drill rig was sitting and a rubber tire backhoe was used to assisting pulling the pipe. Because the pipe was stretched, the location of the broken pipe was unclear. The HDPE pipe yielded through most of this length and had "necked" down to approximately 38 mm to 51 mm (1.5-inch to 2-inch) diameter as shown in Figure 6-18. It was also observed that the pipe had been crushed flat and kinked in several locations.

Figure 6-18: Reduced Diameter in 100-mm Perforated Pipe after Last Attempt

Stretched segments of the HDPE pipe were taken back to the University of Waterloo lab for inspection and analysis. After weighing and measuring the segmented pieces, it was found that the 23 m (76 ft) of HDPE well had strained approximately 223% or approximately 10 m.

Figure 6-19 illustrates the leachate flow from the bore and within the pipe at the pipe entrance location.

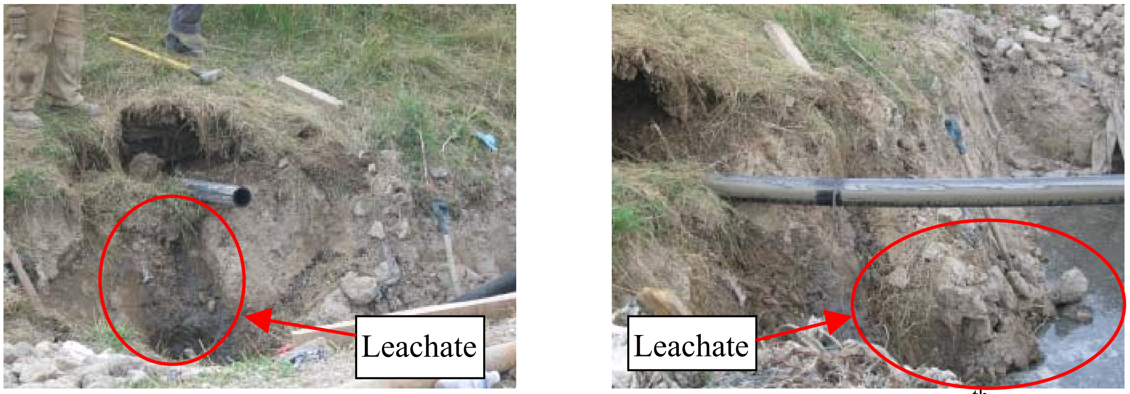


Figure 6-19: Leachate Flow during Pullout of 100-mm HDPE Pipe in the 4th Attempt

Leachate flow was observed coming out of the bore and within the 100-mm (4-inch) pipe from the perforated slots. Upon removing the pipe from the bore at the location of the drill rig, landfill gas was detected and it was emanating from the open bore. The volume of gas was significant enough that the bore had to be plugged.

6.3 West Well Construction

The construction of the West Well commenced on January 26, 2006 at the south west corner of the OLA. Due to the problems encountered in the construction of the East Well it was decided that the West Well construction would include:

1. Installing a 125-mm (5-inch) OD Steel Carrier Casing
2. Installing a 100-mm (4-inch) OD HDPE Perforated Pipe inside the steel carrier casing.
3. Using of a modified rounded reamer (150-mm OD) and a covered swivel.

6.3.1 Bore Path

The initial West Well design required the setting of the directional drill with an entrance angle in excess of 22º. This entrance angle was considered to be too steep. The location of the drill rig was moved down to the east slope so that the entry angle would be 12.18º. Figure 6-20 shows the design and the as constructed pilot bore location. The drill bit entered the ground at an elevation of 412 m (1,352 ft). The bore length was 275 m (900 ft) with an elevation drop of 35 m (115 ft) between the entrance and the exit point.

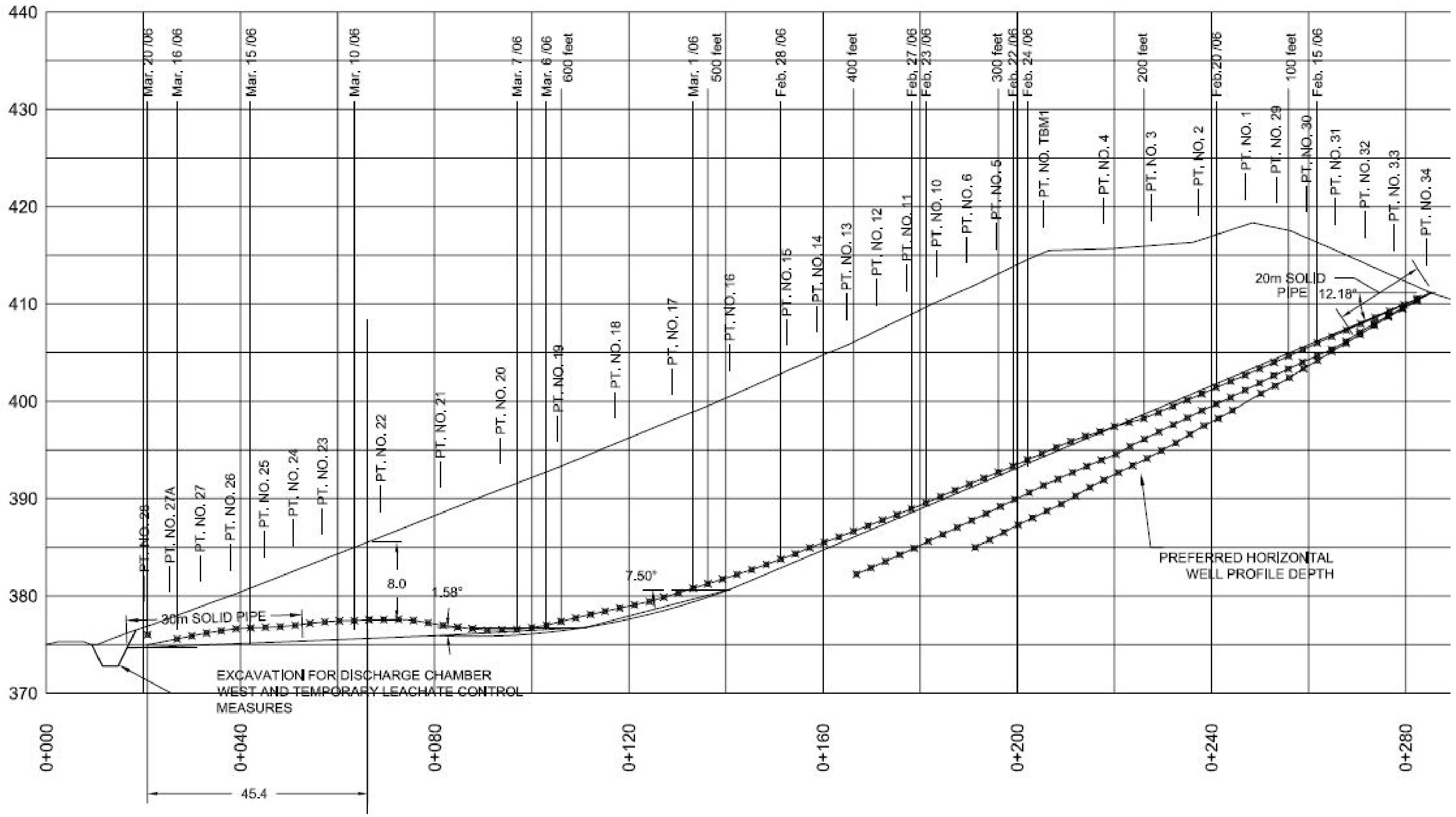


Figure 6-20: West Well Pilot Bore Profile.

6.3.2 Drill Rig Setup

The placement of drill rig on the side of the east slope required the construction of a gravel drill pad as shown in Figure 6-21. Concrete anchors were also installed into the waste to ensure that the drill rig had sufficient resistance to thrust and pull.

Figure 6-21: Drill Rig Sitting for West Well Installation

The DigiTrak wireline tracking system used for the East Well was also used for the West Well. To aid in the drill process, water with no additives was pumped through the drill rods.

6.3.2.1 Pilot Bore Construction

The Hogs head drill bit used for the construction of the East Well was also used for the West Well. Pilot bore drilling commenced on January 26, 2006 and was completed on July 19, 2006. Due to waste obstructions, the pilot bore was abandoned twice before it was successfully completed. The time to complete the bore was approximately eight weeks. Figure 6-22 shows the condition of the drill head upon exiting from the pilot bore.

Figure 6-22: Drill Head Breakthrough Condition Upon From West Well Pilot Bore

Unlike the East Well, the drill head broke through the ground without any waste wrapping around the drill head.

6.3.2.2 *Leachate Flow from Pilot Bore Exit*

No leachate flow was observed following pilot bore breakthrough. Figure 6-23 shows the breakthrough of drill bit.

Figure 6-23: West Well Pilot Bore Breakthrough

6.3.3 Carrier Casing and Well Installation

Following the completion of the pilot bore, a 150-mm (6-inch) rounded reamer, shown in Figure 6-24, was attached to the drill rods. This reamer was modified with a rounded surface and no cutting teeth. The main function of this reamer was to displace the waste.

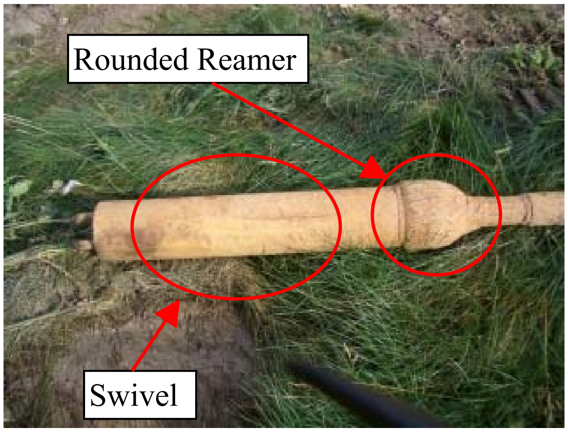


Figure 6-24: 125-mm Modified Reamer

6.3.3.1 Steel Carrier Casing Installation – 1st Attempt

Pullback of the steel casing commenced at approximately 10:15 a.m. on March 21, 2006. Pullback proceeded without problem for approximately 45 m (150 ft) when at 12:30 p.m. the drill rig rotational pressure increased dramatically. To lower the drill rig rotational pressure, the carrier casing was pushed back approximately 6 m (20 ft) then re-installed. During reinstallation, the rotational pressure was found to be dramatically high at the same location as before. After several attempts to pull the pipe past the obstruction point, the installation was abandoned. Using the drill rig with the aid of an excavator, the steel casing was removed from the bore. Limited leachate flow from the bore was observed.

6.3.3.2 Well Installation – 2nd Attempt

Following the failed attempt to install the 125-mm (5-inch) diameter steel pipe, Earth Boring proposed the following options for consideration:

1. Use a new 150,000 lbs maxi-HDD drill rig that would have sufficient pullback and torque to install the steel pipe.

2. Use a ramming tool to assist the directional drill with the pipe installation.

RMW decided to attempt to install the 100-mm (4-inch) OD HDPE well without a carrier casing. This option was same as the one used in the 100-mm pipe installation in the East Well. The goal was to pull the pipe as far as possible.

The Installation of the 100-mm (4 inch) HDPE well commenced on July 19, 2006 and the pipe was pulled back approximately 91 m (300 ft) when a popping was “felt” by the drill rig operator. Subsequently, the 100-mm well screen stopped advancing when drill rods were pulled back. It was found that the HDPE pipe had ruptured just past the pipe connector adapter. Figure 6-25 shows the broken perforated well pipe.

Figure 6-25: The Broken 100-mm Pipe after the Second Pullback Attempt for West Well

The 91 m (300 ft) pipe remained inside the bore to serve as a leachate collection well while the excess pipe was cut off. The entry point where the drill rig was sitting was plugged and was covered by clay material to prevent landfill gas escaping.

Chapter 7 - Instrumentation Results

7.1 Introduction

This Chapter presents data collected from the field monitoring system: drill rig hydraulics, drilling fluid volumes, pipe load, pipe strain, pipe deflection, bore fluid pressure, and pipe and annular space temperature.

7.2 East Well Construction Data

Three attempts were made to install the 200-mm (8-inch) diameter HDPE carrier casing and one attempt was made to install the 100-mm (4-inch) diameter HDPE well. Details on the carrier casing and the well installation are presented in Chapter 6. Instrumentation results recorded during pilot bore drilling and for each installation attempt are presented in this Chapter.

Due to misplacement of the pressure transducers fittings, the East well drill rig rotational and pullback hydraulic pressure were not monitored during pilot bore drilling. Following the Campbell data logger setup and testing in the laboratory with the internal load bolt, one of the data logger setup was changed from single to double precision. This change resulted in the data logger memory reaching capacity within approximately four hours. New data would then overwrite the oldest data points. Since the pipe installation exceeded four hours, only strain data in the first well installation attempt was completely recorded and stored. Drill rig hydraulics and carrier casing pullout load were measured and recorded in other data acquisition units.

7.2.1 Pilot Bore Drilling Fluid Volume

Drilling fluid flow was recorded daily using the Doppler flow monitor and the Hobo data logger. Figure 7-1 shows a typical record of drill fluid flow rate during pilot bore drilling on July 13, 2005. Drill fluid flow monitoring showed that between 2,460 L to 3,785 L (650 gal to 1,000 gal) of drilling fluid were used daily during pilot bore construction. The total volume of drilling fluid used to drill the pilot bore was estimated at 45,430 L (12,000 gal).

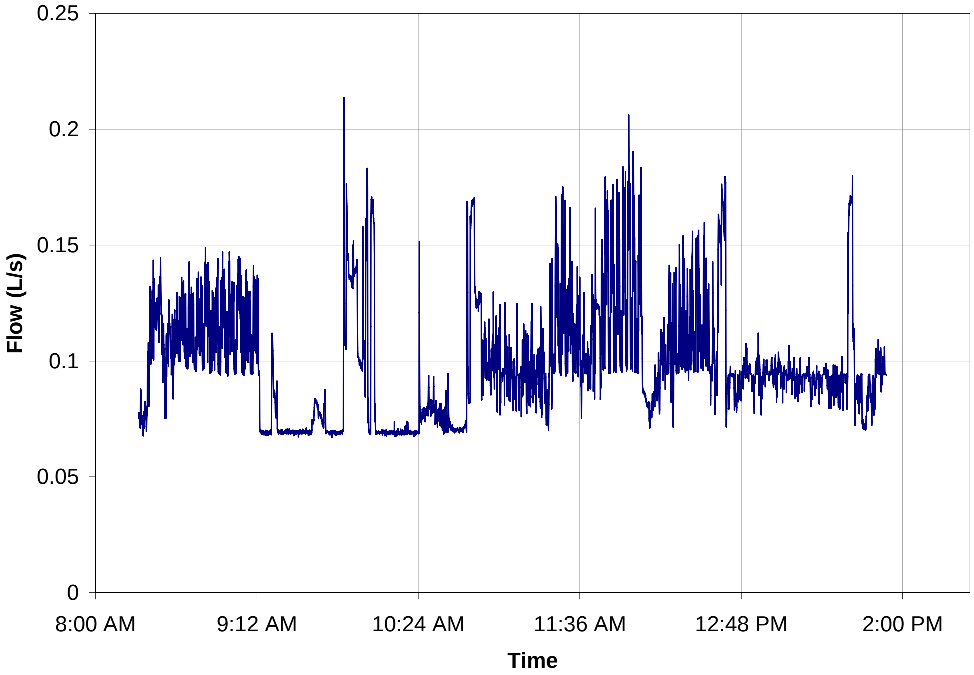


Figure 7-1: Drilling Fluid Flow Recorded during Pilot Bore on July 13, 2005.

Figure 7-1 shows that the minimum drilling fluid flow rate was 0.07 L/s and this minimum flow rate was recorded when the drill rig operator stopped pumping drill fluid so a drill rod length could be added or removed. The measurement of flow, when no drill fluid was pumped, resulted in questioning the accuracy of the flow monitored device. To verify the flow meter, daily volumetric measurements were taken from the drill fluid reservoir before and after drilling operations; specifically the fluid height was recorded. Differences of more than 400 L (100 gal) per drilling day were found between the flow monitor and the volumes determined from manual tank readings.

7.2.2 HDPE Carrier Casing Installation – 1st Installation Attempt

The first attempt consisted of installing the 200-mm (8-inch) HDPE carrier pipe with the 150-mm (6-inch) perforated pipe inserted into the carrier casing. After installing 33.5 m (110 ft), the casing stopped advancing during a drill rod pullback. Upon removal of the casing and the reamer from the bore, it was found that drill rod failure occurred at the reamer-drill rod connection.

7.2.2.1 Drill Rig Hydraulic Pressures – 1st Installation Attempt

Casing pullback started on July 28, 2005 at 9:50 a.m. and ended at 11:25 a.m. when the drill rod failed. The Lakewood data logger used to record drill rig hydraulic pressure transducer readings was set to record a maximum pressure of 31,715 kPa (4,600 psi). Thus, rotational and pullback pressures over 31,700 kPa were not captured. Figure 7-2 shows drill rig rotational hydraulic pressure during the carrier casing installation. This figure shows rotational pressures fluctuated between 3,450 and 31,715 kPa (500 and 4,600 psi) with the low pressure being recorded when drilling was stopped to remove drill rods. Peak and low pressure readings were presumed to be due to stopping and starting the drilling operation to remove drill rods.

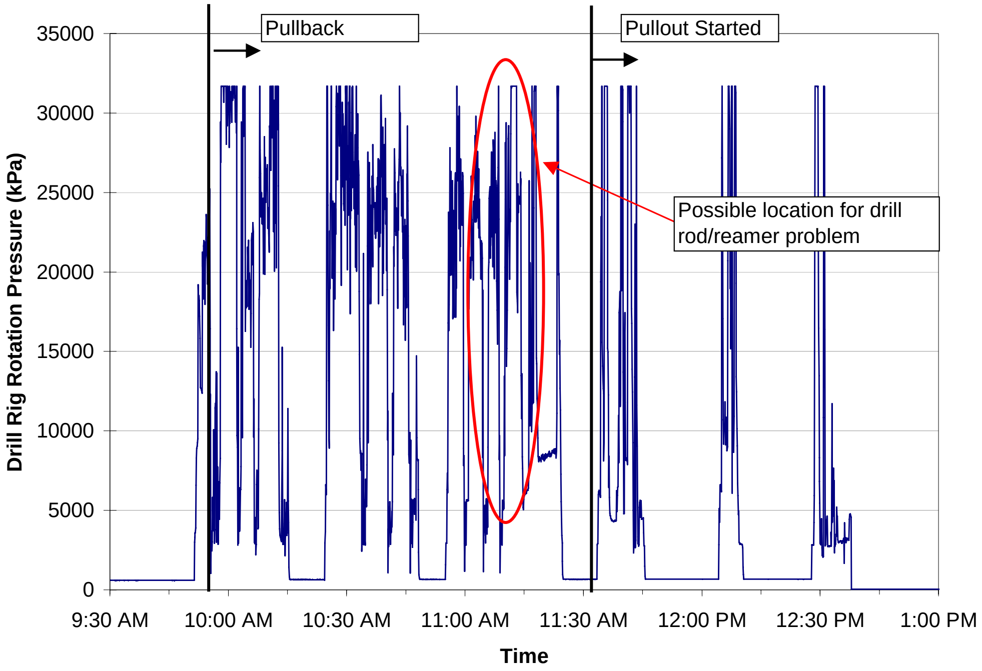


Figure 7-2: Drill Rig's Rotational Pressures during 200-mm HDPE Installation (July 28, 2005)

Eleven drill rods were removed from the bore. More detailed readings on the rotational hydraulic pressure for drill rods 9, 10, and 11 pullback are shown in Figure 7-3.

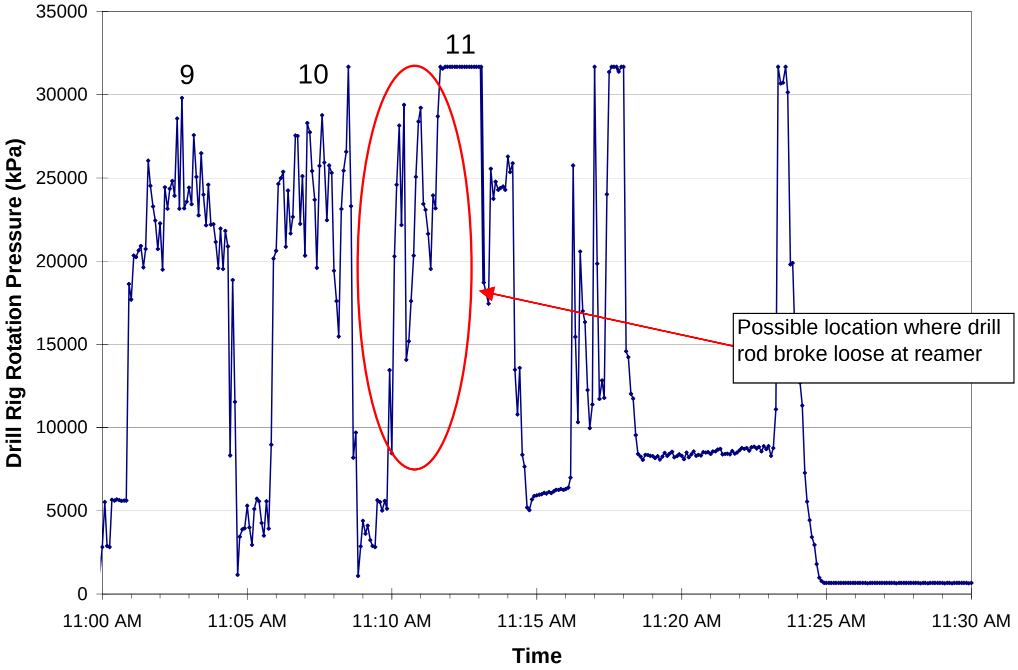


Figure 7-3: Drill Rig's Rotational Hydraulic Pressures for Drill Rods 9 to 11 on July 28, 2005.

Figure 7-3 shows drill rods 9 and 10 had rotational pressures between 20,685 and 27,580 kPa (3,000 and 4,000 psi) and that the rotational pressure for drill rod 10 was higher than for rod 9. For rod 11, the rotational pressure suddenly reached its maximum value of 31,715 kPa (4,600 psi) then rapidly decreased to approximately 17,926 kPa (2,600 psi). The decrease in rotational pressure is likely to be the moment of failure of the drill rod.

Drill rig pullback hydraulic pressures are shown in Figure 7-4. The maximum pullback pressure of 29,648 kPa (4,300 psi) was observed at 11:09 a.m. when 33.5 m of casing was installed. Peak and low pressure readings were inferred to be due to stopping and starting the drilling operation to remove a drill rod.

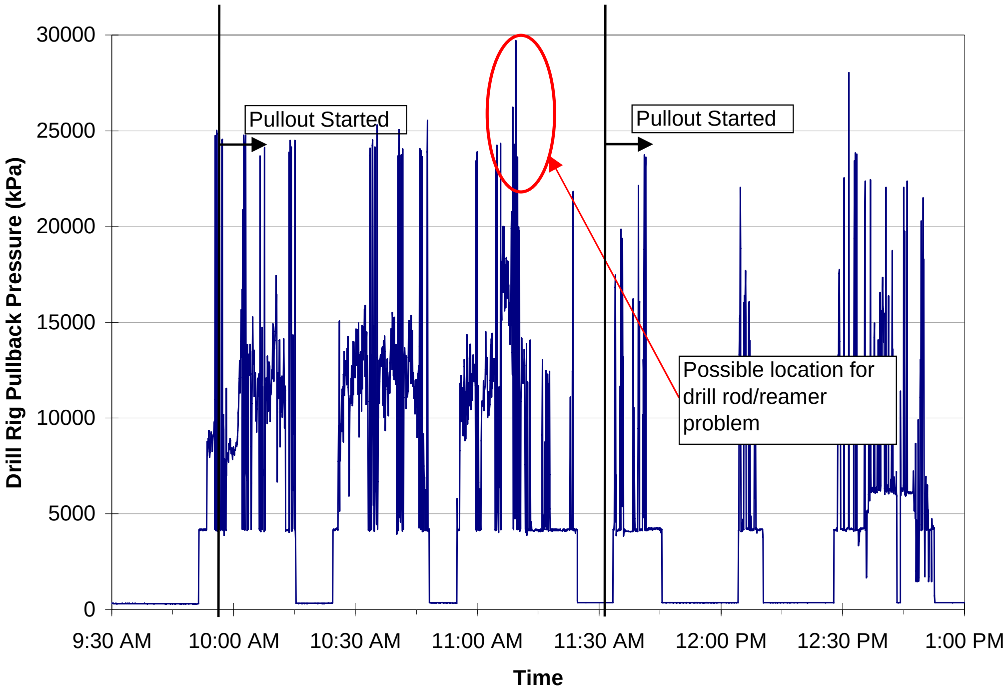


Figure 7-4: Drill Rig's Pullback Pressures During 200-mm HDPE Installation (July 28, 2005)

Drill rig pullback hydraulic pressures for drill rods 9, 10 and 11 are shown in Figure 7-5. This figure shows drill rod 9 had pullback pressures between 10,342 and 13,790 kPa (1,500 and 2,000 psi) while drill rod 10 had pullback pressures between 15,858 and 20,685 kPa (2,300 and 3,000 psi). For drill rod 11, large pressure fluctuations were observed between 4,136 and 29,650 kPa (600 and 4,300 psi). The largest pullback pressure was recorded near the moment of failure of the drill rod.

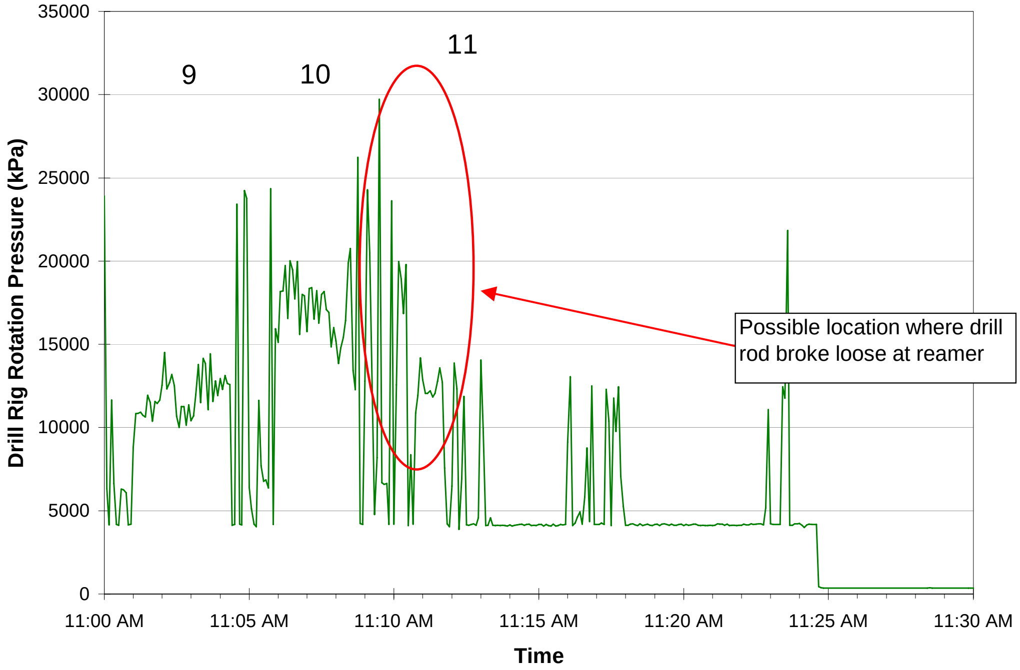


Figure 7-5: Drill Rig Pullback Hydraulic Pressures for Drill Rods 9 to 11 on July 28, 2005.

7.2.2.2 Drilling Fluid Volume - 1st Installation Attempt

Drilling fluid was constantly pumped into the bore to aid reamer cutting and casing installation. Due to the poor performance of the Doppler flow monitor, this flow meter was abandoned. The volume of drill fluid was determined by recording the height of the drill fluid in the drill fluid tanks. The volume of drill fluid used to install the carrier casing a distance of 33.5 m (110 ft) was 5,300 L (1,400 gal).

7.2.2.3 HDPE Carrier Casing Pipe Strain - 1st Installation Attempt

Figure 7-6 shows HDPE carrier casing pipe longitudinal and transverse strain recorded during the first pullback attempt. When the casing entered the bore at 9:50 a.m., the top of the casing was aligned at one o’clock position.

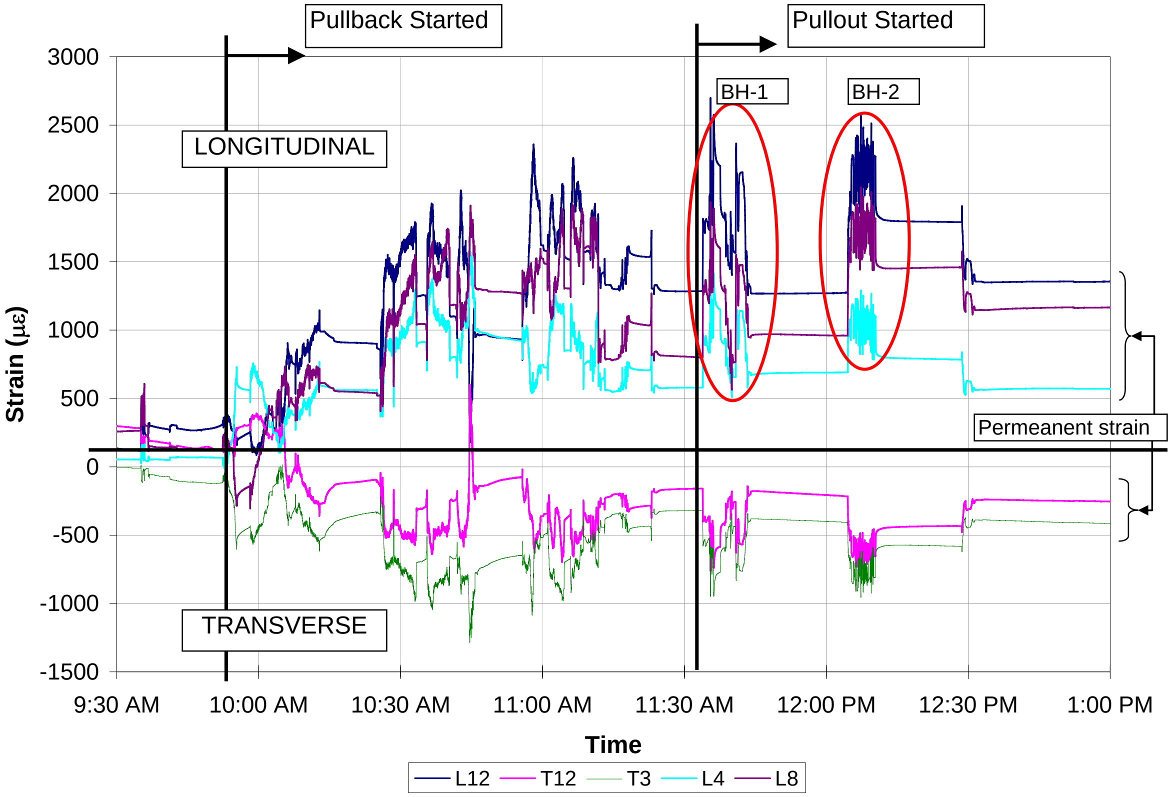


Figure 7-6: Strain Data on 200-mm HDPE Pipe (July 28, 2005)

From approximately 9:50 a.m. to 10:15 a.m., all longitudinal strain gauges showed a linear increase in tensile strain from 300 to 1,000 με. This is assumed to be due to friction on the HDPE pipe as the pipe moved through the clay berm. At approximately 10:25 a.m., the longitudinal stress of the pipe increased significantly to between 1,500 and 2,000 με. This is inferred to be approximately in the area where the pipe exited the berm and entered into the MSW. During drill rod removal at the drill rig, pipe strain reduced to between 600 and 1,200 με. Peak longitudinal strains between 1,800 and 2,400 με occurred around 11:00 a.m. just before drill rod failure occurred. Strain peaks and lows were inferred to be due to stopping and starting of the drilling operation to remove a drill rod.

In addition, Figure 7-6 also shows that the two transverse strain gauges recorded compressive strains (negative strain). Thus, as the casing was installed into the bore path, the pipe diameter decreased. Initially, the transverse strain gauges showed compressive strains less than 100 με. From 9:50 a.m. to 10:30 a.m., these strains increased linearly from 250 to 500 με and from 500 to 1,000 με. From 10:30 a.m. to 11:00 a.m., the transverse strains were found to remain relatively constant. At 11:00 a.m. just before drill rod failure, the transverse strains decreased to 150 and to 350 με.

The removal of the casing with a Rubber tire backhoe began at approximately 11:30 a.m. During the initial attempt to remove the HDPE pipe with the backhoe (BH-1), the longitudinal strains increased sharply to 2,500 – 2,600 με then decreased to 2,100 – 2,400 με. At the moment the operation was halted to change the location of backhoe, the longitudinal strains relaxed to 600 – 800 με. After repositioning the backhoe, load was applied to the casing increasing the longitudinal strain to 2,500 με (BH-2). This load was insufficient to mobilize the casing from the bore.

The compressive strains in the transverse direction increased to 700 - 1,000 με during the initial attempt using the backhoe (BH-1). During removal of the load the transverse pipe strains decreased to 200 and 400 με. During the second pull out attempt (BH-2), the transverse compressive strains increased to 700 – 1,000 με then relaxed to 250 – 400 με (approximately 12:30 p.m.).

7.2.2.4 HDPE Carrier Casing Pullout Load – 1st Installation Attempt

On July 29, 2006, a CAT 235 excavator was brought to the site to pull the carrier casing out of the bore. Figure 7-7 shows the external load cell response during pipe pull out.

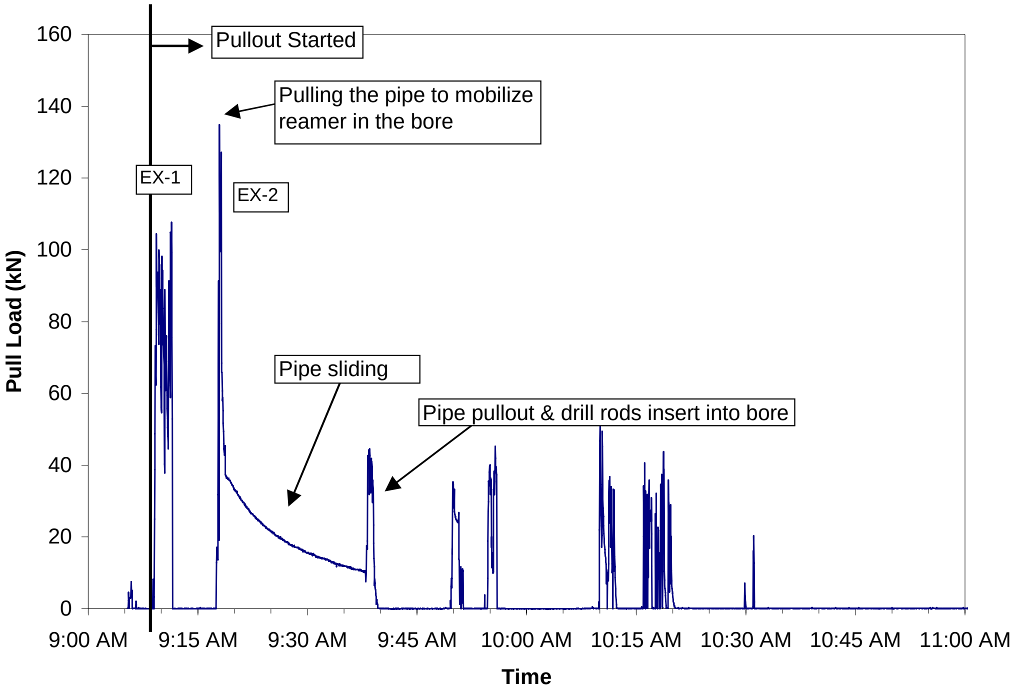


Figure 7-7: External Load Cell Pullout load Applied to HDPE Carrier Casing (July 29, 2005).

The initial attempt (EX-1) had the excavator sitting close the pipe entrance area. The excavator applied a maximum pull force of approximately 111 kN (25,000 lb). This force was not sufficient to mobilize the casing out of the bore. The excavator was relocated to extend the boom of the excavator reach and the pulling distance. During the second attempt (EX-2), the excavator applied a maximum pull force of 138 kN (31,000 lb) to the pipe. This force was sufficient to mobilize the pipe out of the bore. Once mobilized, the pull force rapidly decreased to 35.6 kN (8,000 lb) then gradually decreased to 8.90 kN (2,000 lb). To mobilize the pipe after each drill rod removal, pull out loads between 35.6 kN and 53.4 kN (8,000 lb and 12,000 lb) were required. Figure 7-8 shows the response of the internal load bolt, mounted inside the head of the HDPE carrier casing, during pipe pull out with the excavator.

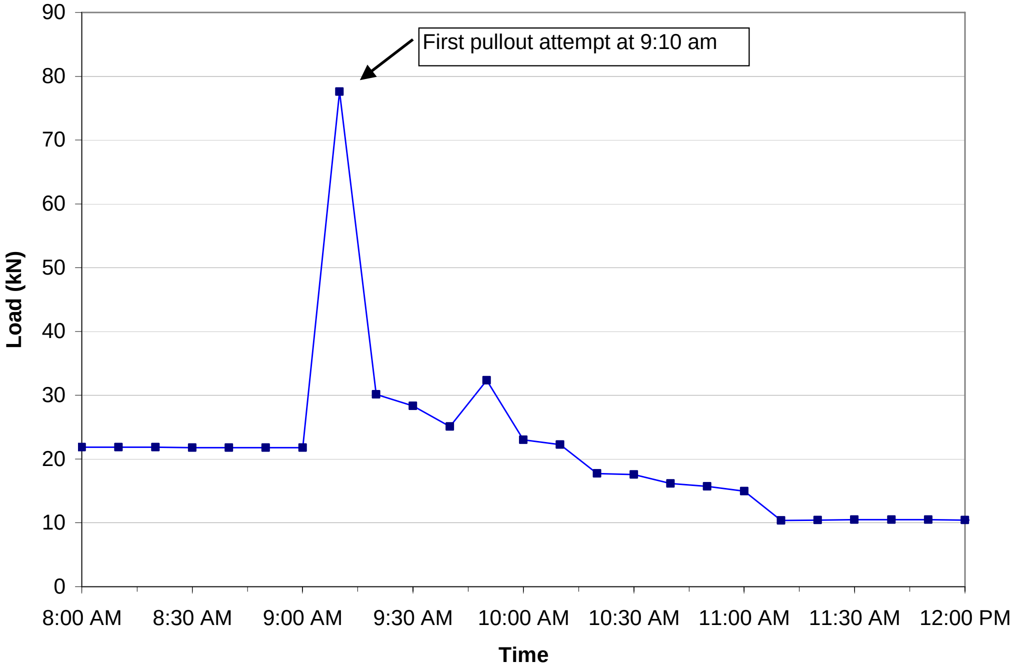


Figure 7-8: HDPE Carrier Casing Internal Load Bolt Pullout During Pullout (July 29, 2005).

The internal load bolt data logger was set to record load bolt readings at ten minute intervals after 18 hours from start up. This was done to preserve data logger memory and to prevent data being over written and lost. Since data in Figure 7-8 is recorded at ten minute intervals, peak loads applied by the excavator were most likely missed. The maximum load approximately 77.8 kN (17,500 lb) was recorded during the first pull out attempt (EX-1).

7.2.3 HDPE Carrier Casing Installation – 2nd Installation Attempt

Prior to re-installation, the HDPE test section, containing the sensors, was re-fused to the carrier casing with reprogrammed data loggers. The carrier casing was re-installed using the same equipment used for the 1st attempt. The pipe stopped advancing during removal of drill rod 12. This occurred at approximately 11:06 a.m. after 36.5 m (120 ft) of pipe was installed. The test section was pulled out of the bore using the CAT 235 Excavator. Upon pipe and reamer removal, it was found that the internal load bolt failed. Data retrieved from the loggers is presented in the following sections.

7.2.3.1 *Drill Rig Hydraulic Pressures – 2nd Installation Attempt*

Drill rigs rotational and pullback hydraulic pressures data were recorded using pressure sensors connected to the Lakewood data loggers. Figure 7-9 shows drill rig hydraulic rotational pressures during the casing 2nd pullback attempt.

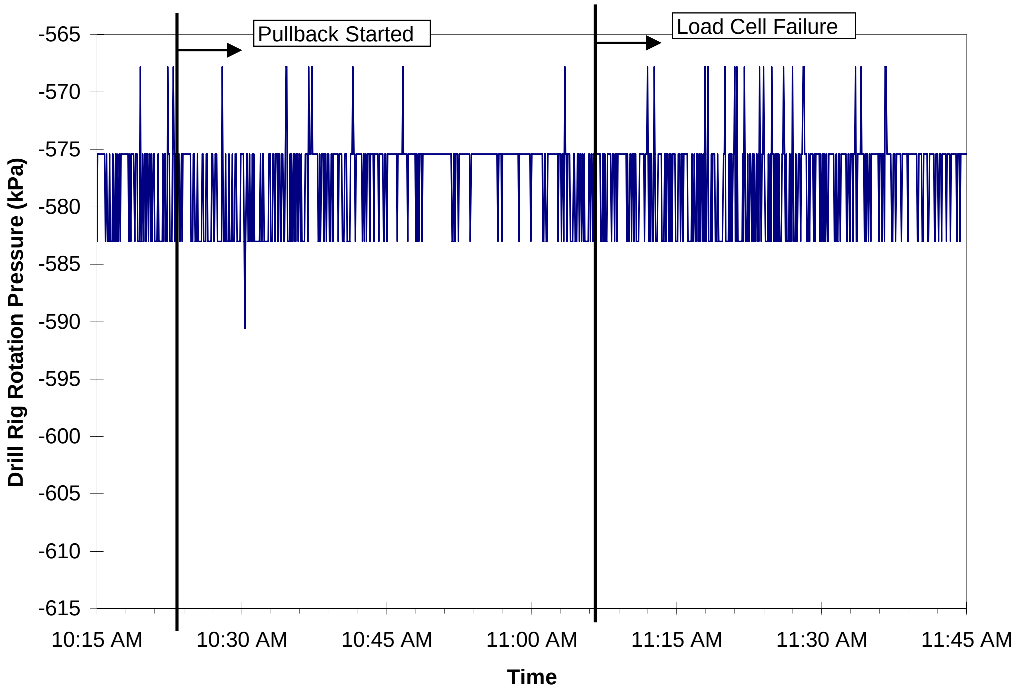


Figure 7-9: Drill Rig Rotational Pressure During 2nd Installation (August 3, 2005).

The figure shows that the drill rig rotational hydraulic pressure transducer was not operating properly. Inspection of the data logger and the transducer found that the transducer connection to the data logger was not properly connected. Figure 7-10 shows the drill rig pullback hydraulic pressure.

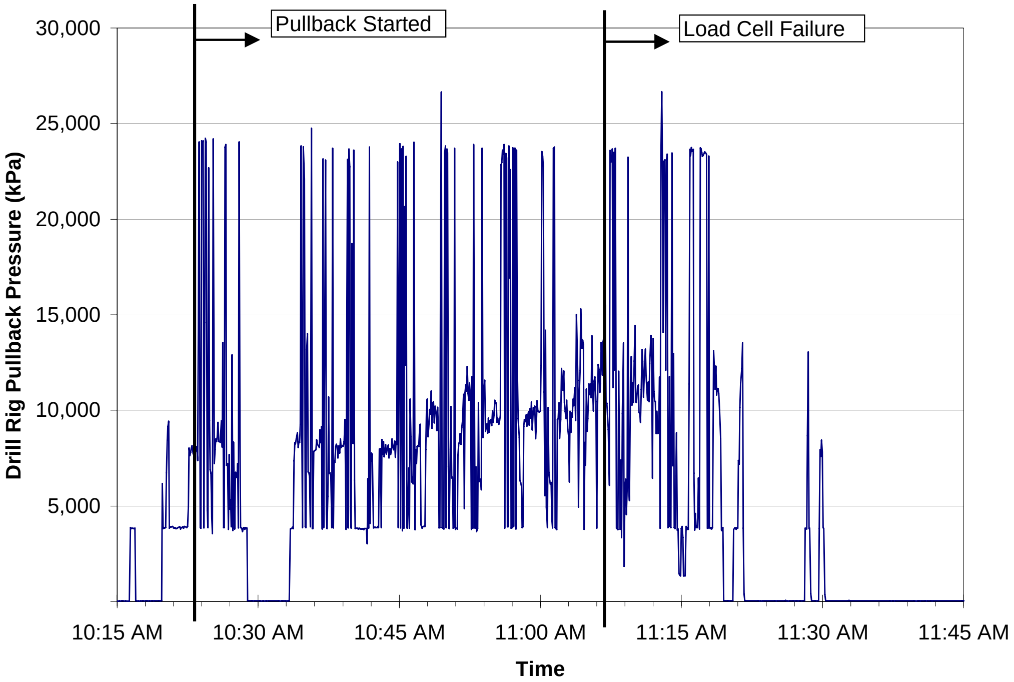


Figure 7-10: Drill Rig Pullback Pressure During 2nd Installation (August 3, 2005)

This figure shows that pullback pressures in the order of 24,100 kPa (3,500 psi) were required to mobilize the pipe at the start of each drill rod. During drill pullback of the first few drill rods (up to 10:45 a.m.), pullback pressures were approximately 8,275 kPa (1,200 psi). Drill back of subsequent rods showed an increase in pullback pressure to 13,790 kPa (2000 psi) when failure of the internal load bolt failed.

7.2.3.2 Drill Fluid Volume – 2nd Installation Attempt

The volume of drilling fluid used for the 2nd installation was estimated to be 5,300 L (1,400 gal).

7.2.3.3 HDPE Carrier Casing Pull Load – 2nd Installation Attempt

The carrier pipe pullback force recorded by the internal load bolt is shown in Figure 7-11.

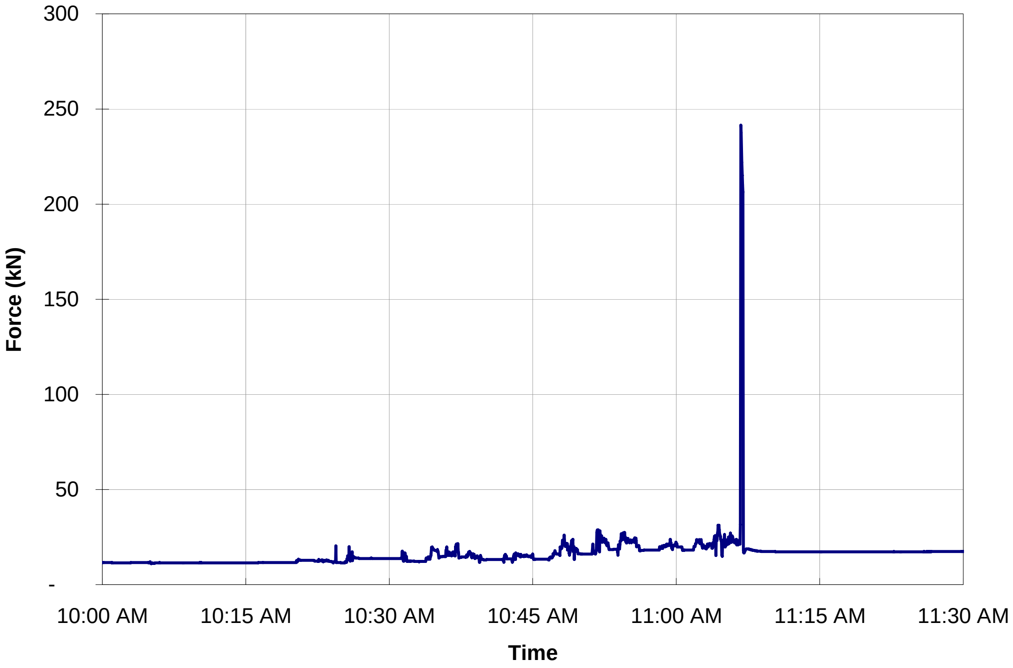


Figure 7-11: Internal Load Bolt Pullback Force on HDPE Carrier Casing (August 3, 2005).

The load bolt was calibrated and pre-loaded to 8.9 kN (2,000 lb). Thus, loads less than the pre-load were not recorded. Figure 7-11 shows an initial pull force on the pipe of 14.2 kN (3,200 lb) that gradually increased to 32.4 kN (7,300 lb) just prior to load bolt failure. At around 11:06 a.m., the pull force increased rapidly, within five seconds, to 242 kN (54,300 lb). At peak load, the load bolt failed and the force recorded by the load bolt decreased to 17.8 kN (4,000 lb). The data after load bolt failure confirmed the load bolt remained operational. Load peaks were inferred to be due to stopping and starting the drilling operation to remove a drill rod.

7.2.3.4 HDPE Carrier Casing Pipe Strain – 2nd Installation Attempt

Figure 7-12 shows transverse strains recorded during casing pullback and Figure 7-13 shows longitudinal strains during casing pullback. The strain gauges continued to record data after load bolt failure. However, the change in strains differed in longitudinal and transverse directions and thus it was inferred that waste might have collapsed onto the casing. Figure 7-12 shows the response of the transverse strain gauges. Both gauges show a linear decrease in strain, compression of the pipe wall, during installation. Prior to failure of the load bolt, the transverse strains had reached a steady state of approximately -400 to -600 με. Rapid changes in strains observed were inferred to be due to stopping and starting the drilling operation to remove a drill rod. Following the load bolt failure, the transverse pipe strain was between -200 με and -400 με. Upon pipe removal from the bore, the pipe strain increased which was an indication of pipe diameter increase.

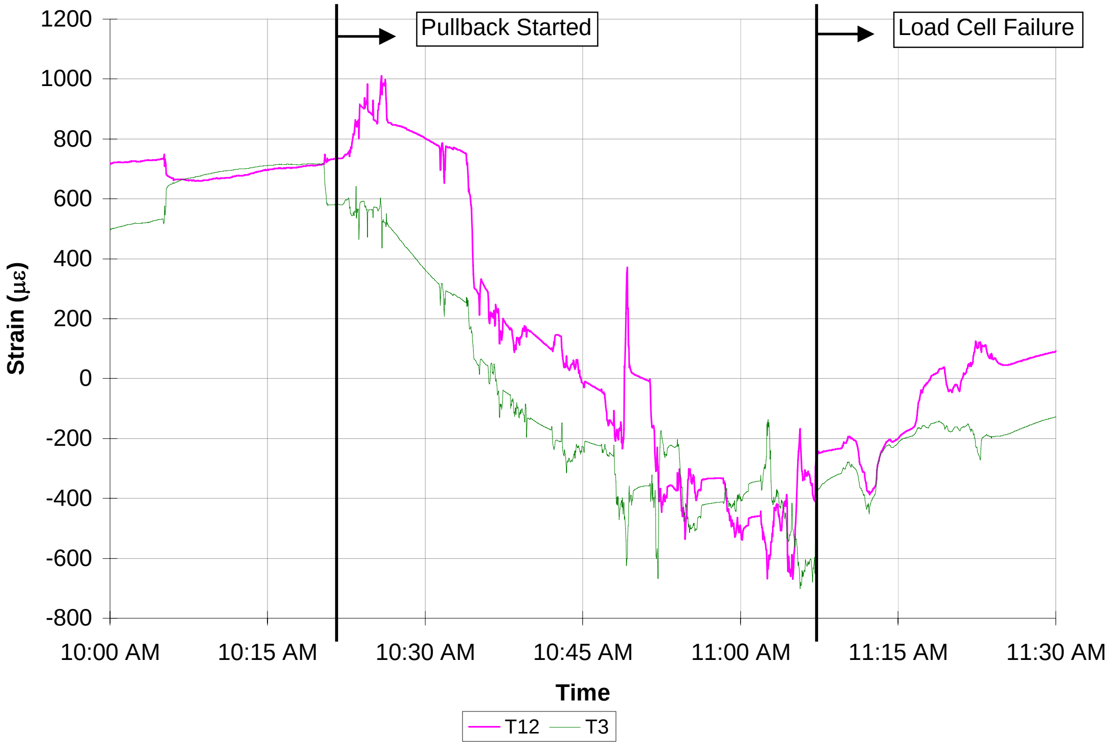


Figure 7-12: Transverse Carrier Casing Strains during 2nd Installation (August 3, 2005).

Figure 7-13 shows that the strain trends for the longitudinal gauges L4 and the L8 gauges response were similar. Both gauges showed a linear decrease from 300 με to 0 με between 10:20 a.m. and 10:50 a.m. and a linear increase from 0 με to 400 – 500 με until the load bolt failed. Gauge L12 showed an opposite trend to L4 and L8. This would indicate that the casing was bending through the bore path during installation. Rapid changes in strain observed were inferred to be due to stopping and starting the drilling operation to remove a drill rod.

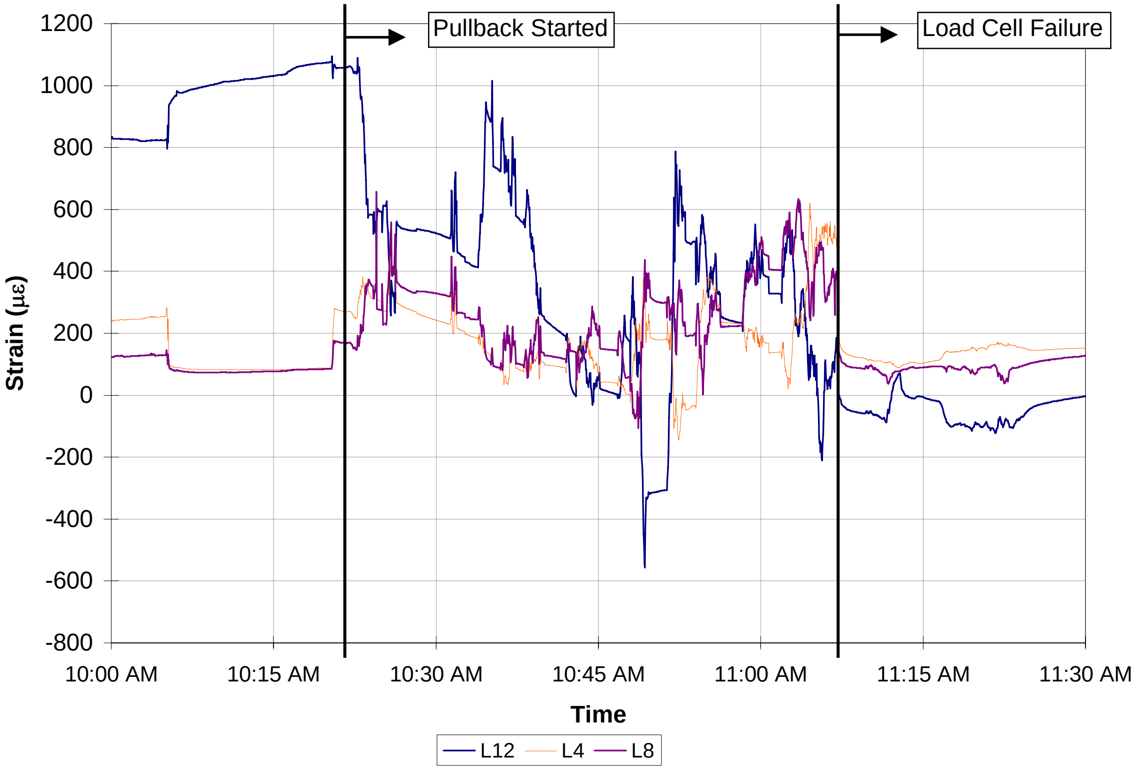


Figure 7-13: Longitudinal Carrier Casing Strains during 2nd Installation (August 3, 2005).

7.2.3.5 HDPE Carrier Casing Pipe Deflection – 2nd Installation Attempt

Figure 7-14 shows the casing wall deflection during the second installation attempt. Wall displacements were recorded in millimetres with positive displacement representing an increase in pipe diameter.

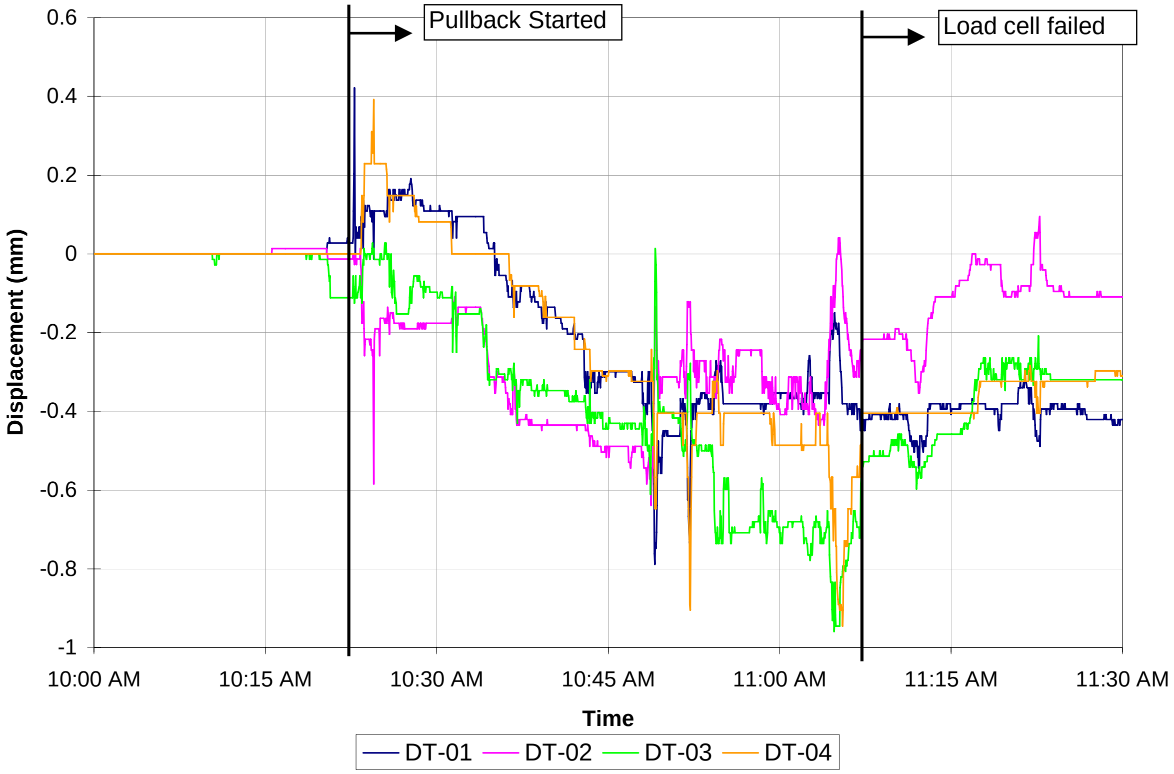


Figure 7-14: Displacement Data on 200-mm Casing during 2nd Installation (August 3, 2005).

Figure 7-14 illustrates all sensors experienced a similar response. From the start of the installation to approximately 10:50 a.m., all four displacement transducers decreased linearly. Between 10:50 a.m. and 11:04 a.m., DT-01, DT-02, and DT-04 yielded constant data trend (steady state) of 0.24 to 0.5 mm pipe diameter reduction. DT-03, however, exhibited a greater diameter reduction of 0.7 mm. Just prior to the load bolt failure, DT-01 and DT-02 showed the pipe wall moved outwards by approximately 0.1 to 0.3 mm while DT-03 and DT-04 showed a decrease in pipe diameter by approximately 0.2 to 0.4 mm. This indicates that the casing was squeezed or deflected by an obstacle in the bore path.

7.2.3.6 Bore Annular Space Fluid Pressure – 2nd Installation Attempt

Figure 7-15 shows the bore annular space fluid pressures recorded during the carrier casing installation.

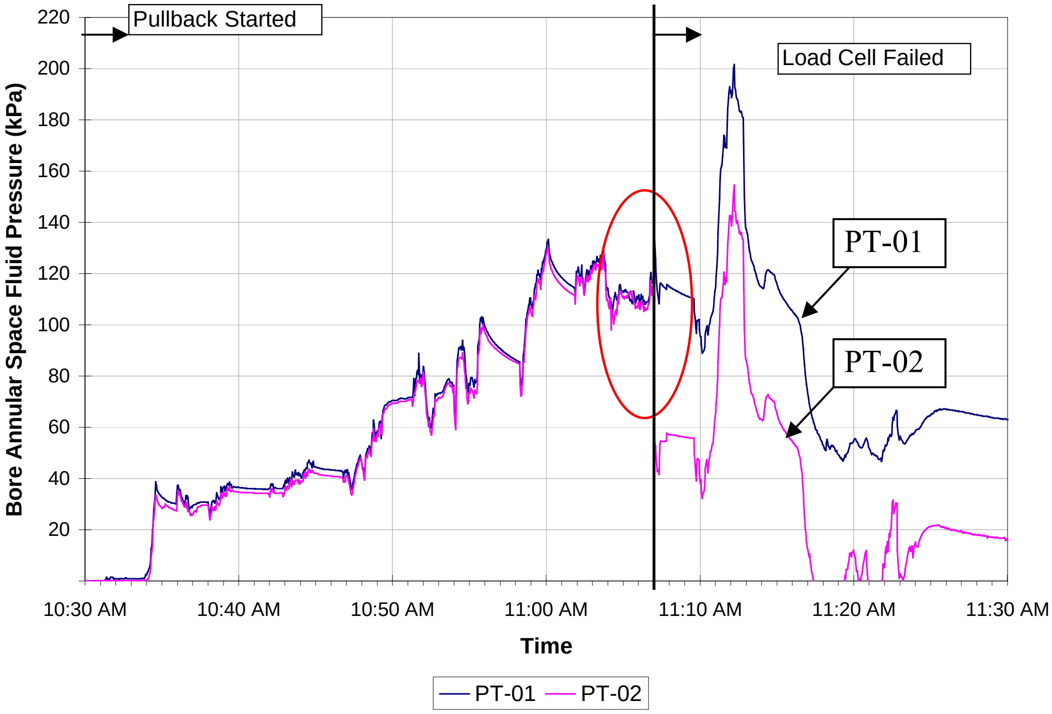


Figure 7-15: Annular Space Fluid Pressure during 2nd Installation (August 3, 2005).

Figure 7-15 shows that PT-01 and PT-02 have similar trends until 11:07 a.m., when the load bolt failed and an offset occurred between the pressure transducers. At 10:34 a.m., both pressures increased to approximately 34.5 kPa (5 psi). The pressures remained constant at 34.5 – 48.3 kPa (5-7 psi) until approximately 10:48 a.m. From 10:48 a.m. to 11:04 a.m., the pressures increased linearly from 48.3 kPa (7 psi) to approximately 124 kPa (18 psi). Soon after the increase, the pressures fluctuated between 96.5 and 110 kPa (14 and 16 psi) until the load bolt failed at 11:07 a.m. PT-01 continued to experience higher pressures while PT-02 had undergone a pressure drop. However, the trend of both transducers was similar: PT-01 had reached 206 kPa (30 psi) and PT-02 measured 152 kPa (22 psi).

7.2.3.7 Casing Interior & Annular Space Temperature – 2nd Installation Attempt

Pipe material and annular space fluid temperatures were determined using thermocouples placed inside the HDPE pipe and through the pipe wall. Temperature readings during the carrier casing installation are shown in Figure 7-16.

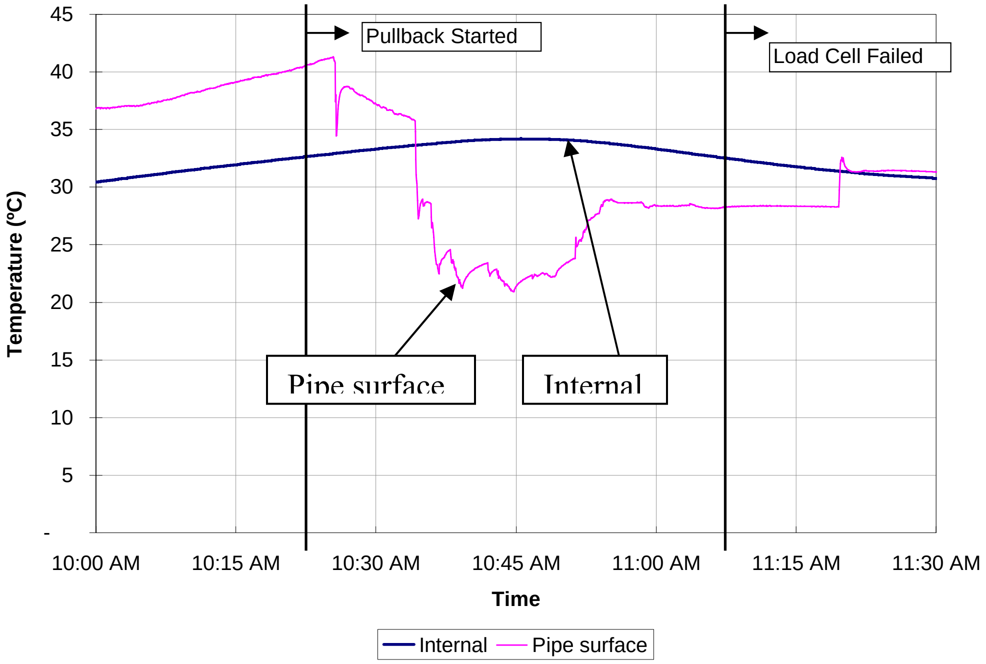


Figure 7-16: HDPE Carrier Casing Temperature during 2nd Installation (August 3, 2005).

Figure 7-16 shows that pipe internal temperature increased from 30 to 34.8 °C at 10:45 a.m. then returned to 30°C when the pipe was removed from the bore. The bore annular space temperature reduced from 40°C shortly after installation to 35°C. The bore annular space temperature then decreased to 22°C at 10:45 a.m. It then increased to 29°C where it remained constant until the pipe was removed from the bore. Upon pipe removal from the bore, both thermocouples recorded similar temperatures. This confirmed that both sensors were working correctly. The pumping of high volumes of drilling fluid is inferred to be the reason for the decrease in external temperature.

7.2.3.8 HDPE Carrier Casing Pullout Load – 2nd Installation Attempt

The external load cell was not connected to the excavator during casing pullout. Little force was required to mobilize the pipe out of the bore.

7.2.4 HDPE Carrier Casing Installation – 3rd Installation Attempt

The third attempt of the pullback commenced on August 4, 2005. Pipe performance monitoring could not be performed due to the load bolt failure. Drill rig rotational and pullback hydraulic pressures were recorded during carrier casing installation.

7.2.4.1 Drill Rig Hydraulic Pressures – 3rd Installation Attempt

Due to the loose connection between the transducer and the rotational hydraulic pressure line no rotational pressure data was obtained. However, drill rig pullback pressure readings during the carrier casing installation were still captured and are presented in Figure 7-17.

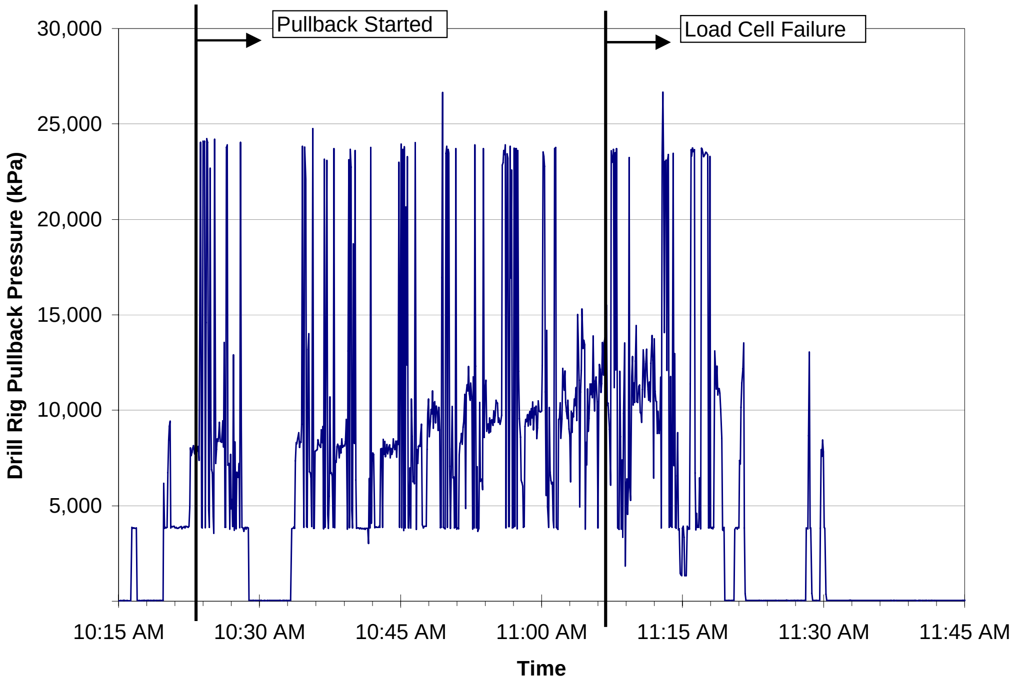


Figure 7-17: Drill Rig's Pullback Pressures during 2nd Installation (August 3, 2005).

Figure 7-17 shows maximum pullback pressures in the range of 24,130 kPa (3,500 psi). Peak and low pressures were inferred to be due to drilling stops and starts required to remove drill rods.

7.2.4.2 HDPE Carrier Casing Pullout Load – 3rd Installation Attempt

Due to high drill rig rotational pressure, the carrier pipe could not be advanced beyond 67 m (220 ft). The force required to pull the carrier casing out was recorded using the external load cell and the Lakewood data logger. Figure 7-18 shows the pullout load applied to the pipe with the CAT 235 excavator.

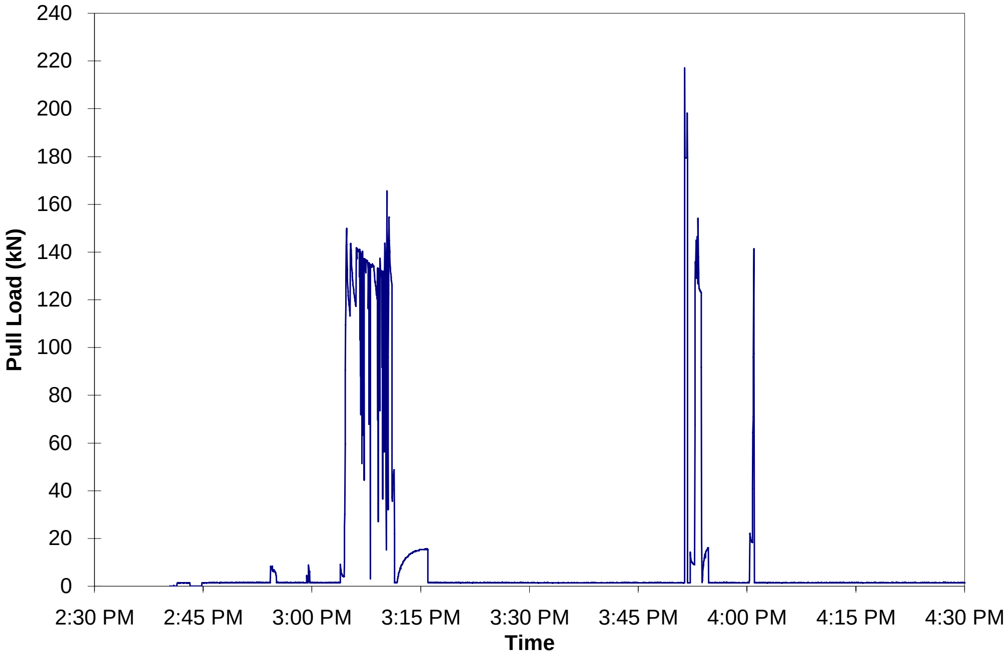


Figure 7-18: Carrier Casing Pullout Load recorded on August 04, 2005.

Two pullout attempts were made to pull out the pipe out of the bore. During the first attempt (3:05 p.m.), a pull force of 133 to 165 kN (30,000 to 37,000 lbs) was applied to the pipe. This force resulted in the choker wrapped around the pipe to cut through the carrier and well casing. The second attempt was made after the moving location of the excavator, a pull load of nearly 218 kN (49,000 lb) was applied to the pipe at approximately 3:51 p.m. to mobilize the pipe out of the bore.

7.2.5 100-mm HDPE Well Pipe Installation

The Region of Waterloo and its Consultant decided to pull back 100-mm (4-inch) DR-11 HDPE well pipe with 6.1 m (20 ft) of solid DR 11 pipe fused to the front of the well. The well section had 3.2 mm (1/8-inch) holes drilled with 152 mm (6-inch) centres and 90 degree offsets. Due to the small pipe size and the short time frame, quantifying the well performance during installation with sensors was not possible. Thus, only the drill rig hydraulics and drilling fluid volume were recorded during pullback. Drill rig rotational hydraulic pressures are shown in Figures 7-19.

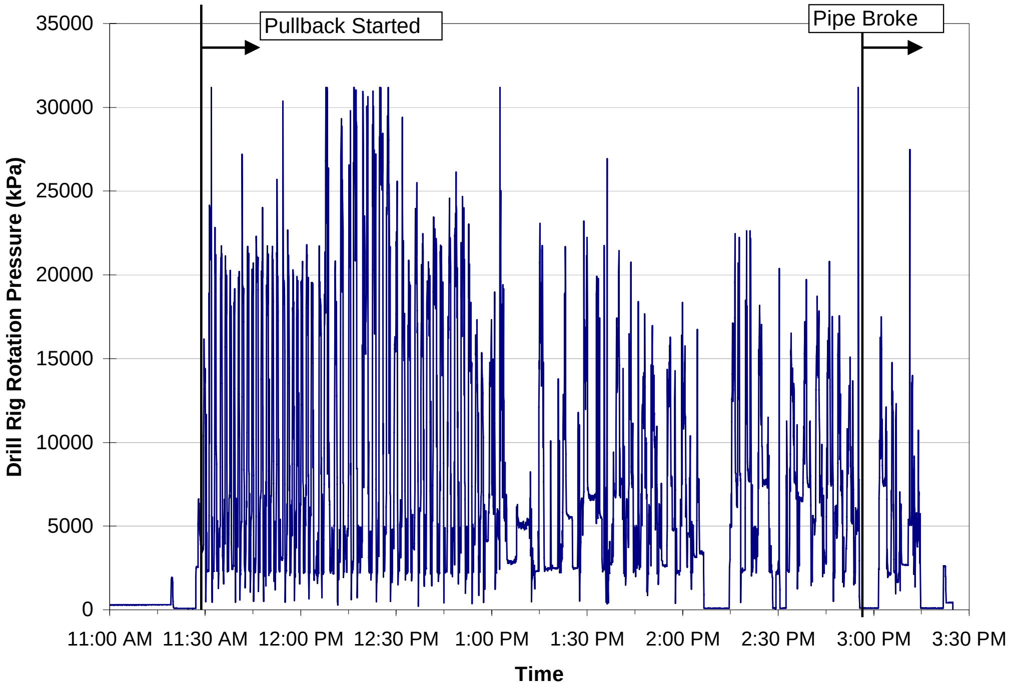


Figure 7-19: Drill Rig's Rotational Pressures for HDPE Well Installation (August 11, 2005)

The rotational pressures were consistently under 20,685 kPa (3,000 psi). However, higher rotational pressures of 31,000 kPa (4,500 psi) were measured from 12:10 p.m. to 12:30 p.m. After 1:00 p.m., drilling slowed down and the rotational pressures reduced to less than 24,132 kPa (3,500 psi). This was due to the lack of resistance from the drill rig to pull back the pipe. As a result, the rig was tied to the rubber tire backhoe and drilling was delayed as a result of manually installing drill to the drill carriage. Drill rig pullback hydraulic pressures are shown in Figure 7-20.

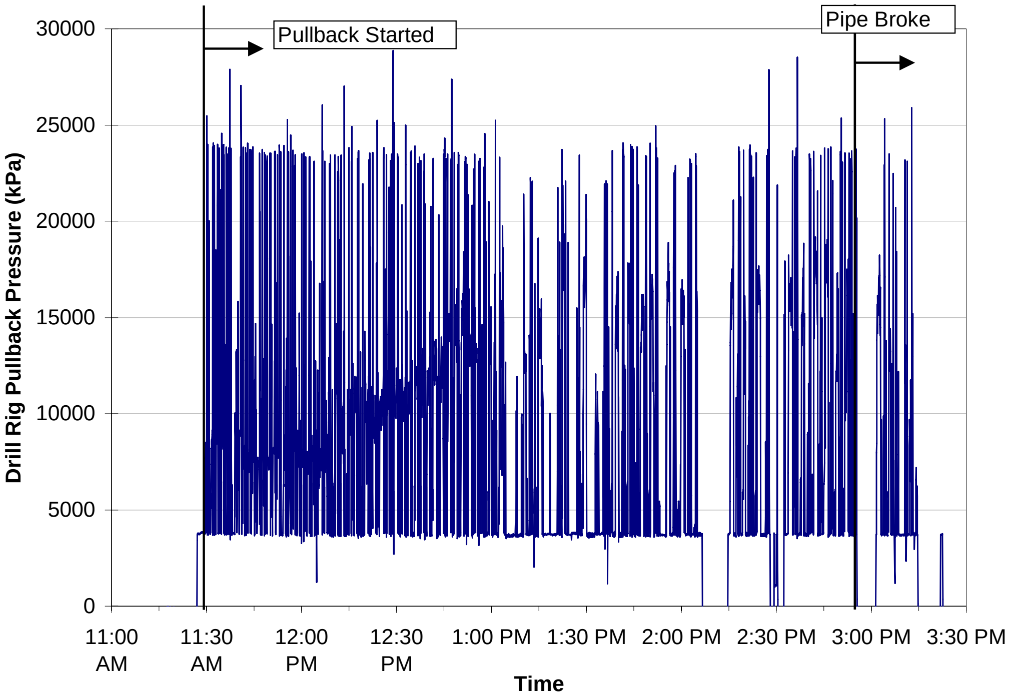


Figure 7-20: Drill Rig's Pullback Pressures for HDPE Well Installation on August 11, 2005.

The pullback pressure remained at 24,100 kPa (3,500 psi) throughout the well installation process. Pressure spikes and dips occurred during drill stoppage and restarts required to remove drill rods. The drill rig was able to install 198 m (650 ft) of the 100-mm (4-inch) diameter HDPE pipe until the pipe stretched and broke.

The total volume of the drilling fluid used for this pullback attempt was approximately 9,465 L (25,000 gal). The 100-mm (4-inch) diameter product pipe had failed during the pullback resulting in only partial retrieval of the product pipe. Figure 7-21 and Figure 7-22 show the pullout load recorded using the external load cell connected to backhoe and excavator.

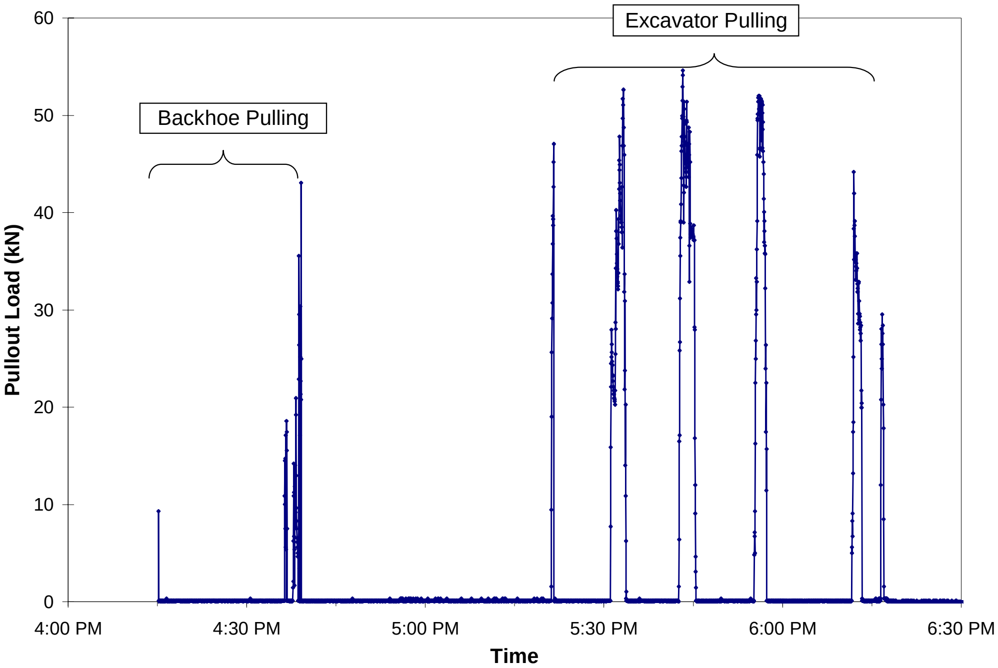


Figure 7-21: Pullout Load of 100-mm HDPE Pipe (August 11, 2005)

The initial pulling load was measured at 8.90 kN (2,000 lb) by the rubber tire backhoe at 4:30 p.m. The load immediately decreased to less than 1 kN (<30 lb) and remained constant. At approximately 4:38 p.m., the load increased to 18.7 kN (4,200 lb) and to 43.1 kN (9,700 lb). Due to insufficient pull capacity of the backhoe the excavator was used. The first attempt by the excavator applied 48.9 kN (11,000 lb) to the pipe. Due to the hot ambient temperature, the pipe became very elastic and stretched back into the bore. Many attempts were carried out before the pullout attempts were stopped. Peak applied loads for each attempt were: 52.5 kN (11,800 lb), 54.7 kN (12,300 lb), 52.0 kN (11,700 lb), 44.2 kN (9,930 lb), and 29.5 kN (6,640 lb).

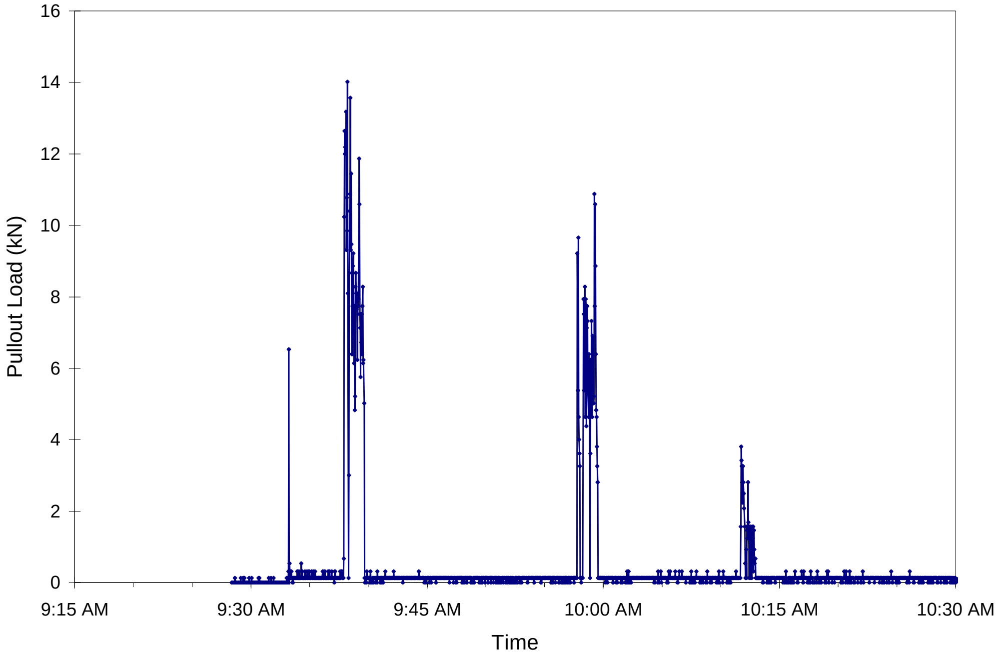


Figure 7-22: Pullout Load of 100-mm HDPE Pipe (August 12, 2005)

Similar results were encountered on the next day when the pullout of the 100-mm HDPE pipe restarted using the excavator. The peak loads were: 6.67 kN (1,500 lb), 14.0 kN (3,150 lb), 10.9 kN (2,450 lb), and 3.83 kN (860 lb).

7.3 West Well Construction Data

Following several meetings with the Contractor, Regional Municipality of Waterloo and their Consultant, it was decided that west well would be constructed using the following method:

- Drill the pilot bore using the same equipment and method used for the East Well
- Pull back 125-mm (5-inch) ID steel pipe as a carrier casing with a 100-mm (4-inch) diameter SDR-11 HDPE well pipe installed inside. The well pipe would have 3.2 mm (1/8") holes drilled at 152 mm (6") centres and 90° offsets.

Pipe deflection sensors were not installed on the steel casing because pipe wall thickness was not sufficient for these sensors. The pipe deflection was not of great concern because of the pipe material used for this attempt. It was suggested that steel would be too rigid to observe any deflection using the same displacement transducers from the East Well installation. Bore annular space fluid pressure sensors were installed in the steel casing and calibrated prior to pullback. Due to poor wire connection to the data logger, the sensors were not able to record any fluid pressure data.

Details on the West well construction are presented in Chapter 6. The following sections describe data recorded from the sensors installed on the drill rig and the 125-mm ID steel test section welded to the front of the carrier casing.

7.3.1 Pilot Bore Drill Rig Hydraulic Pressures

Drill rig rotational and pullback hydraulic pressures were monitored during the construction of the pilot bore using pressure sensors attached to the hydraulic line and a Lakewood data logger. Figure 7-23 shows the drill rig rotational hydraulic pressures recorded on February 28, 2006.

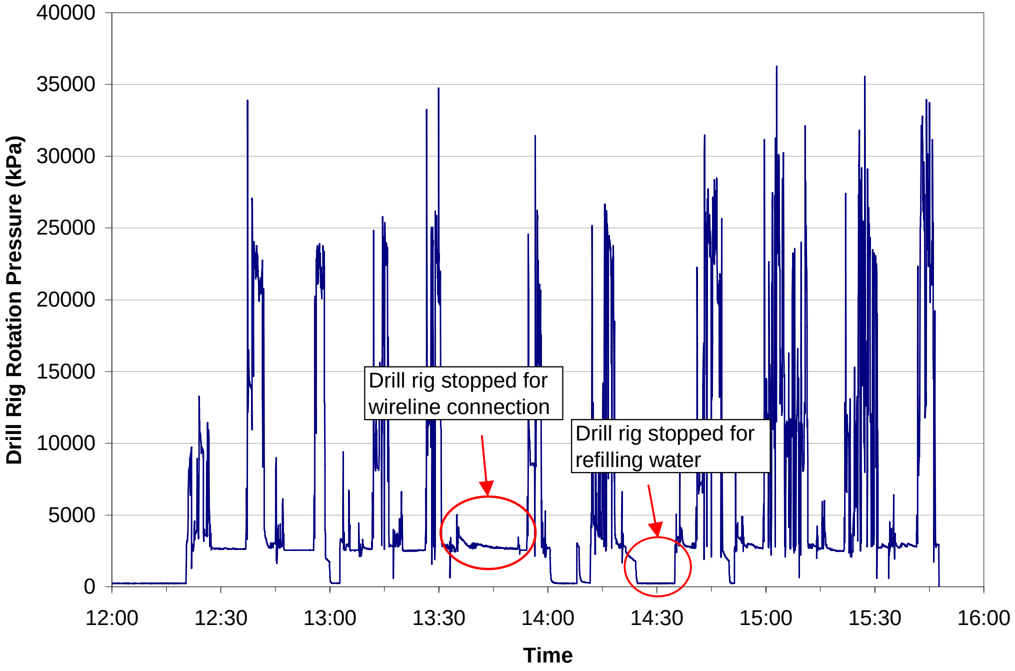


Figure 7-23: Drill Rig's Rotational Pressures During Pilot Boring (February, 28, 2006).

Figure 7-23 shows that rotational pressures were initially very low when the pilot boring began: 10,342 kPa (1,500 psi) for the first drill rod then increased to 34,130 kPa (4,950 psi) at the beginning of rod 2. The pressure then decreased to between 20,685 kPa to 24,132 kPa (3,000 to 3,500 psi). Rotational pressures remained 20,685 kPa and 24,132 kPa (3,000 and 3,500 psi) for the next several rods with the occasional spike to 34,475 kPa (5,000 psi). At approximately 2:40 p.m., the rotational pressure increased to 24,132 to 27,580 kPa (3,500 to 4,000 psi) with pressure spikes as high as 36,540 kPa (5,300 psi). This spike was near the drill rig maximum rotational pressure. Figure 7-24 shows the drill rig pullback hydraulic pressures recorded on February 28, 2006.

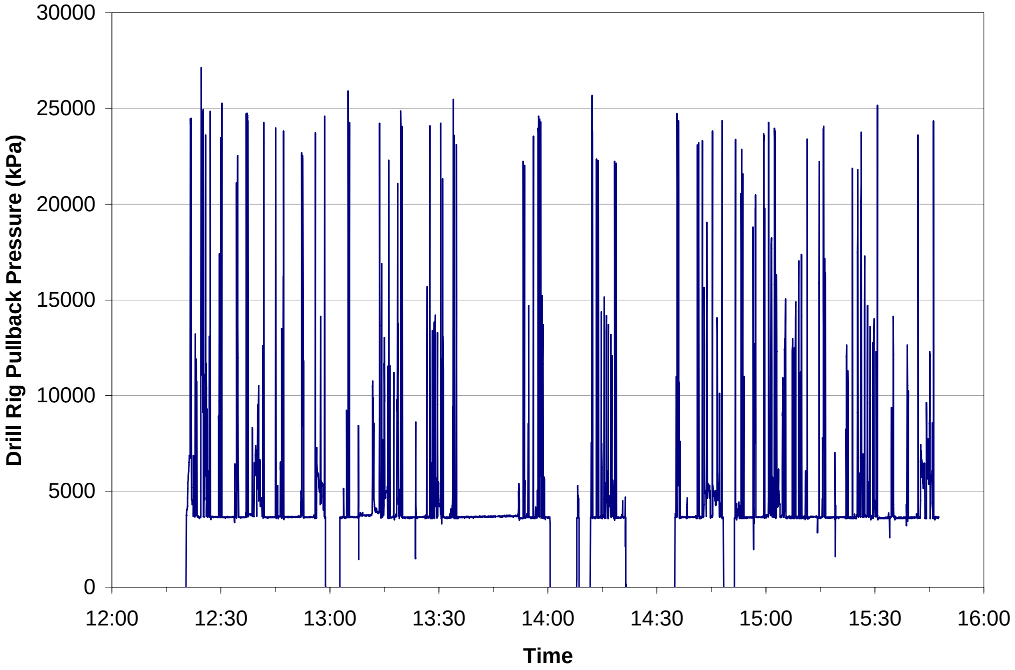


Figure 7-24: Drill Rig's Pullback Pressures During Pilot Boring (February 28, 2006).

During pilot bore drilling the rig had a maximum thrust hydraulic pressure of 24,132 kPa (3,500 psi) through the drilling process.

7.3.2 Steel Carrier Casing – 1st Installation Attempt

The installation of a 30 m (100 ft) segment of steel carrier casing commenced on March 21, 2006. The steel casing was pulled empty.

7.3.2.1 Drill Rig Hydraulic Pressures - 1st Installation Attempt

The 13,790 kPa (2,000 psi) hydraulic pressure transducers were recalibrated to measure a larger anticipated pressure range. Figure 7-25 shows drill rig rotational hydraulic pressures for the steel casing pullback and removal.

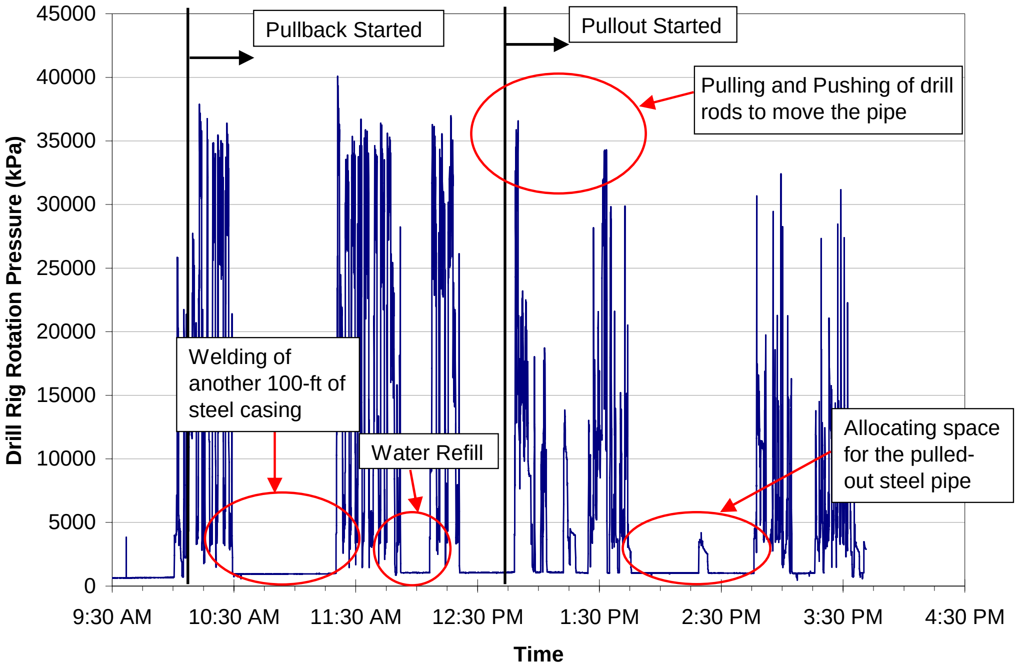


Figure 7-25: Drill Rig Rotational Pressures on 150-mm Steel Pipe (March 21, 2005)

Figure 7-25 indicates that during the pipe installation (up to 12:30 p.m.), the rotational hydraulic pressure often exceeded 35,900 kPa (5,200 psi) and in some instances spiked as high as 39,300 kPa (5,700 psi). From 12:45 to 1:30 p.m., the installation process was reversed to move the pipe back and forth to see if could be freed to complete the installation. Rotational pressures during this phase were significantly less than during the installation phase. Figure 7-26 shows the drill rig pullback hydraulic pressures.

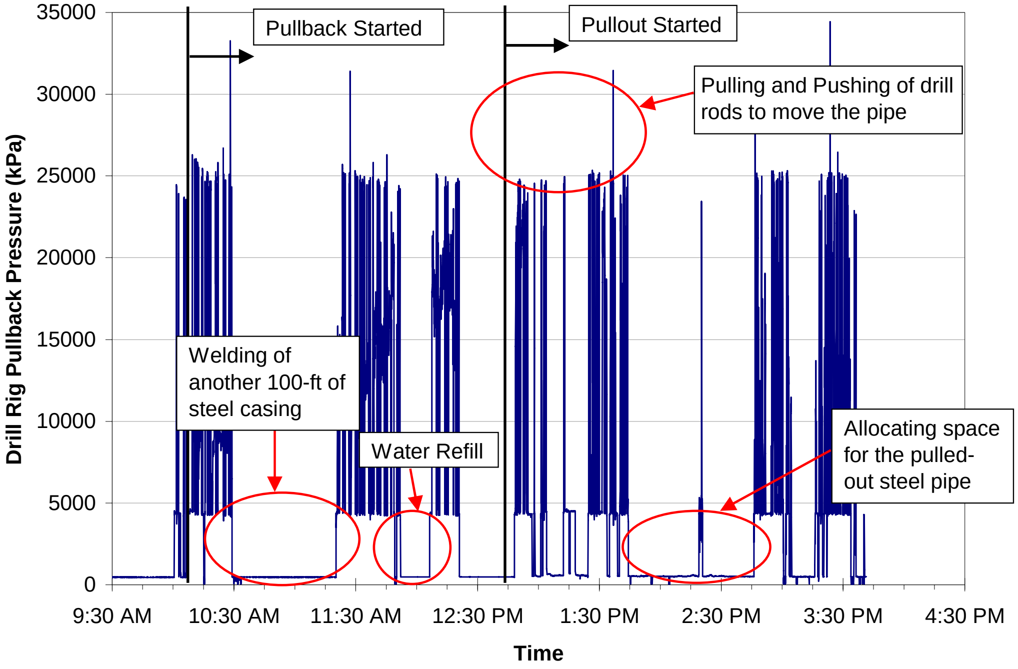


Figure 7-26: Drill Rig's Pullback Pressures on 150-mm Steel Pipe (March 21, 2005)

Figure 7-26 shows drill rig hydraulic pressures between 24,132 kPa and 27,580 kPa (3,500 psi and 4,000 psi) during the pipe installation. Pullback hydraulic pressures were typically between 24,132 kPa and 27,580 kPa (3,500 psi and 4,000 psi) with occasional spikes to 33,095 kPa (4,800 psi).

7.3.2.2 Drill Fluid Volume – 1st Installation Attempt

The estimated volume of drilling fluid volume used was 79,500 L (21,000 gal). This included the drill fluid volume used while pushing the steel casing out of bore.

7.3.2.3 Steel Pipe Load – 1st Installation Attempt

Due to budget and time constraints, a load bolt was not installed in the steel pipe test section. Pipe load can be estimated using steel modulus of elasticity and pipe strain. This will be discussed in Chapter 9 data analysis.

7.3.2.4 Steel Pipe Strain – 1st Installation Attempt

In total, eight steel strain gauges were attached to the interior of the steel casing - four in the longitudinal direction and four in the transverse direction. Figure 7-27 shows the behaviour of the transverse strain gauges during pipe installation and removal. This figure show that gauges T6 and T3 showed similar strain behaviour with the strain starting near zero percent prior to the installation. As the pipe advanced into the bore, strain gauge fluctuation between +40 με and -40 με were recorded. When the installation was stopped to refill the drill fluid tank, the strain gauges T3 and T6 recorded 0 and -20 με respectively.

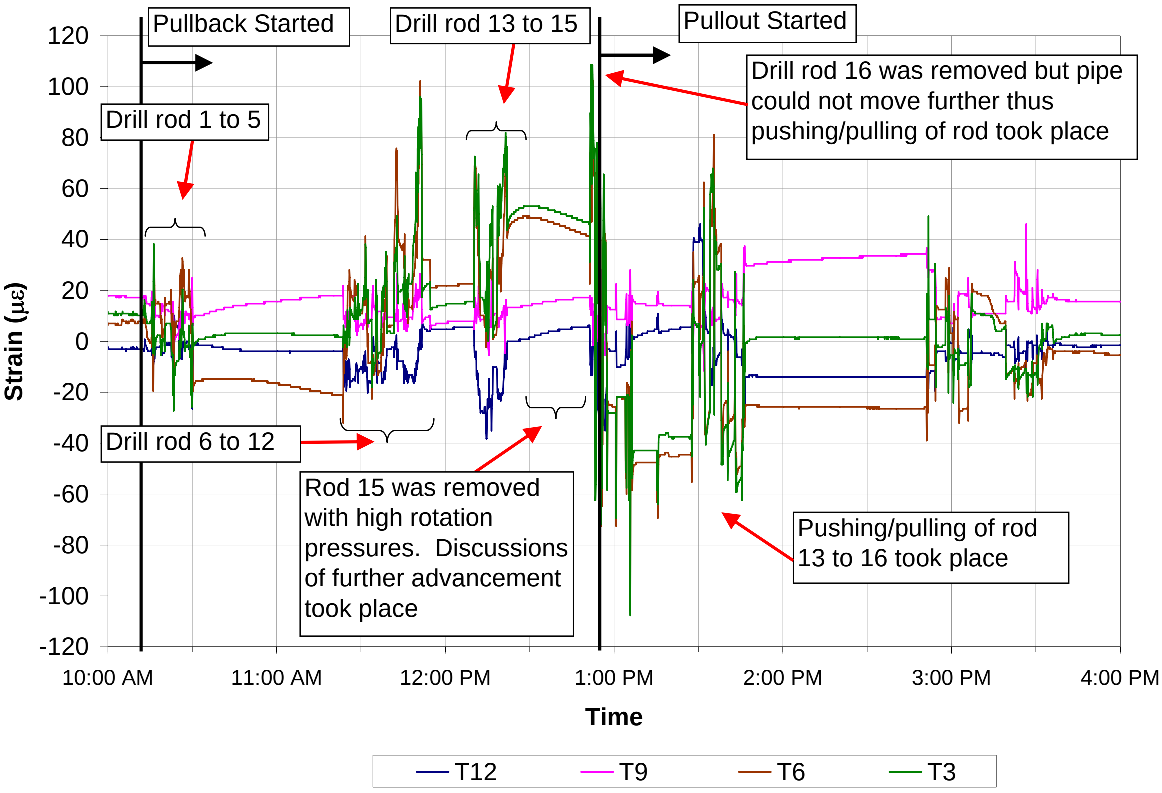


Figure 7-27: Strains of 150-mm Steel Pipe in Transverse Direction (March 21, 2006)

When the pipe installation resumed, T3 and T6 strain gauge readings increased linearly to +90 and +100 με, respectively. When the installation was paused to refill the drill fluid tank for the second time, both strain gauges declined to +20 με. When the installation was resumed, both gauges recorded strains as high as +80 με. When drill rod 15 was removed from the bore, the installation was paused and the strain gauges recorded +50 με. During pipe removal (drill rod 16), the steel pipe became stuck and pulling and pushing of the drill rods occurred. During this period strain gauges, T3 and T6 recorded strains in the order of positive and negative 100 με. Attempts to move the steel pipe by pulling and pushing the drill rods continued until 1:45 p.m.

Gauges T12 and T9 showed consistent but opposite responses. During pipe installation, strain gauge T9 fluctuated between 0 με and +20 με while gauge T12 recorded strains between 0 με and -40 με. During pipe removal, gauge T12 recorded negative strain between 0 and -40 με at 12:50 p.m. and a positive strain reading of +40 με at 1:30 p.m. Gauge T9 recorded positive strain between 0 and 40 με. Figure 7-28 shows longitudinal strain gauge behaviour during the steel pipe installation and removal.

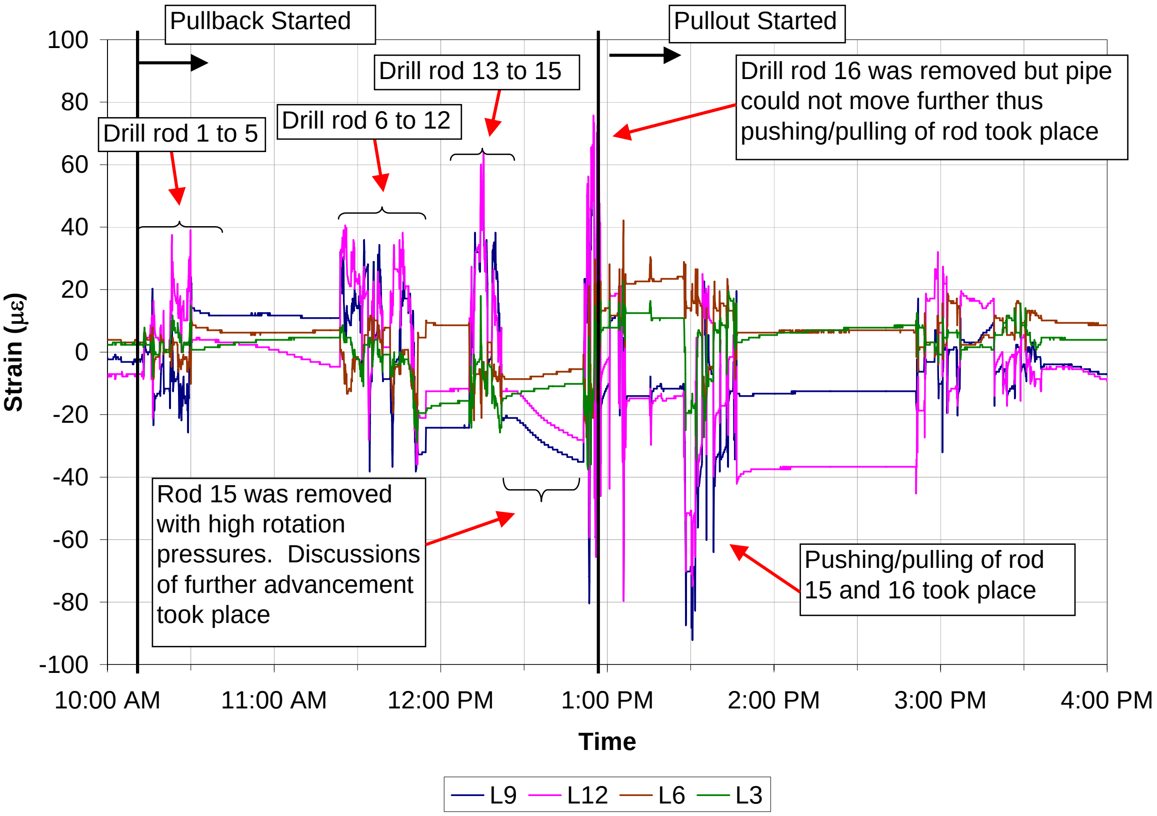


Figure 7-28: Strains of 150-mm Steel Pipe in Longitudinal Direction (March 21, 2006)

Pipe installation into the bore started at 10:15 a.m. During drill rods 1 to 5 removal, all strain gauges had similar readings. Strains gauges L3 and L6 remained constant between +20 με and -20 με while gauges L9 and L12 fluctuated between +40 με and -40 με between 11:25 a.m. and 11:50 a.m. Moreover, L12 reached +60 με and L9 reached +40 με during the pulling of drill rod 13 to 15. During pipe removal (drill rods 16), strain gauges L12 and L9 recorded fluctuated strains between +80 and -80 με while gauges L3 and L6 showed peak strain of -40 με and -20 με. Where strain remained very low, between 10:30 a.m. and 11:25 a.m. and between 1:45 p.m. and 2:50 p.m., the refilling of water tank took place.

7.3.2.5 Casing Interior & Annular Space Temperature – 1st Installation Attempt

The thermocouples located on the pipe surface and inside the pipe measured temperature changes during the installation. Figure 7-29 shows the temperature trends on the pipe surface and inside the pipe.

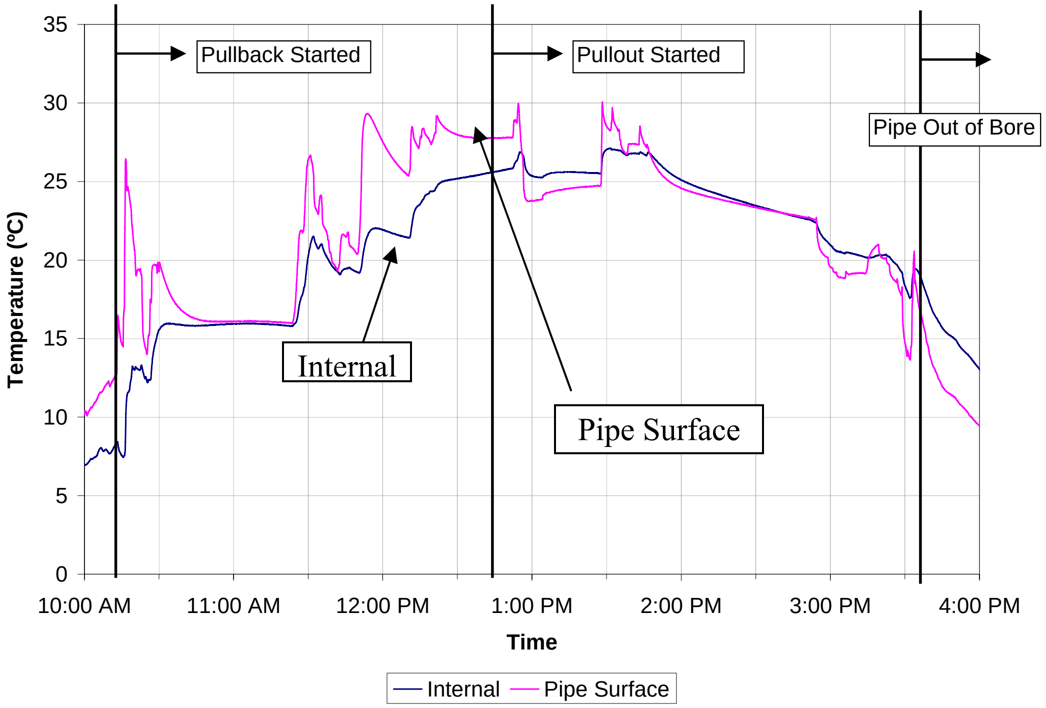


Figure 7-29: Internal & External Temperature of 150-mm Steel Pipe (March 21, 2006)

The internal temperature began at 7ºC prior to the pipe entering the bore at approximately 10:15 a.m. Once the pipe was inside the bore, the internal temperature increased to 13ºC. The temperature continued to increase to 16ºC and remained constant as the pipe advanced through the bore path. Just before 11:30 a.m., the internal temperature was at 21ºC with a linear increase to 26ºC. During pipe removal, the internal temperature remained at 27ºC with a gradual decrease to 20ºC.

7.3.2.6 Annular Space Fluid Temperature - 1st Installation Attempt

The external thermocouple, which represents the annular fluid temperature, showed a rapid increase from 12ºC to 27ºC with a subsequent rapid decrease to 15ºC. From 11:50 a.m. to 1:00 p.m., the external temperature fluctuated between 22ºC and 30ºC while following the same increasing trend as the internal thermocouple. The temperature decreased to 25 ºC during drill fluid tank fill up. A peak temperature of 30ºC was recorded at 1:30 p.m. The temperature then decreased gradually until the end of the installation.

7.3.3 100-mm HDPE Well Installation

The pullback of the 100-mm (4-inch) pipe started on July 19, 2006. After pulling the pipe 91.5 m (300 ft) it had stopped advancing. The drill rig rotational pressure and pullback hydraulic pressures are shown in Figure 7-30 and Figure 7-31, respectively. The maximum rotational pressure recorded was 34,500 kPa (5,000 psi).

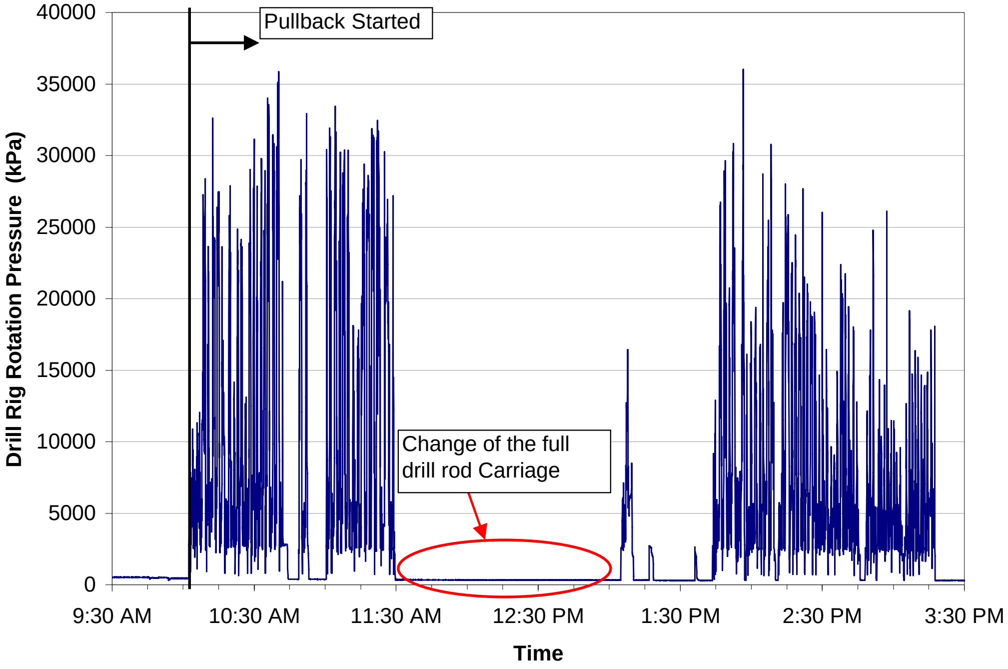


Figure 7-30: Drill Rig's Rotational pressure on 100-mm HDPE Pipe (July 19, 2005)

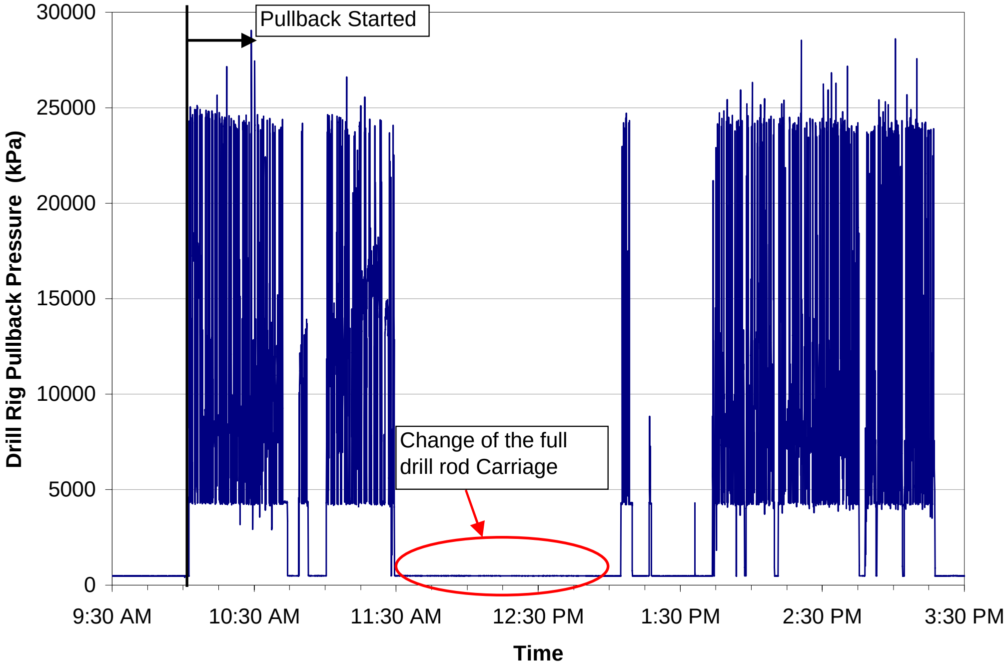


Figure 7-31: Drill Rig's Pullback Pressure on 100-mm HDPE Pipe (July 19, 2005)

The pullback pressure was maintained at 24,132 kPa (3,500 psi) with some spikes as high as 27,579 kPa (4,000 psi). The overall trend of the pullback pressure was constant. The volume of drill fluid used was estimated at 10,600 L (2,800 gal).

Chapter 8 - Discussions of Field Results

8.1 Introduction

This Chapter compares data collected from the well installations and discusses the results.

8.2 East Well Field Results

Discussions presented in this section focus on data collected from the first well construction and HDD equipment. Problems encountered during pilot boring, pullback, and pullout were provided with potential causes. Data presented in Chapter 7 were interpreted and related to these causes.

8.2.1 Leachate Volume

Leachate elevations at the site were anticipated to be at least 15 m above the East Well bore exit location. During pilot bore exit and pipe pullback, very little leachate was observed to flow out of the bore. This would indicate that the leachate vertical distribution was not continuous as it would have flowed out of the bore at a high rate unless the bore collapsed. Cox et al (2000) found that MSW horizontal permeability is greater than the vertical permeability. The lack of sufficient leachate flow would also suggest that the leachate was perch on top of daily cover layer within the landfill. COX et al (2000) reported similar findings. The increase in flow rates out of the bore during precipitation events also suggested that the cover material was permeable. The lack of drill return during all drill phases would also suggest that the daily cover was very permeable. Although the installation of the 100-mm (4-inch) HDPE well did result in some leachate flow, the flow was not considered to be significant or to be continuous. No well testing was completed to determine leachate flow rates.

8.2.2 Bore Annular Space Fluid Pressure

Figure 8-1 shows the pressure transducers response on August 3, 2005 plotted with the internal load bolt response. Both pressures transducers showed a similar response during pipe installation. At approximately 11:07 a.m., PT-02 showed a significant pressure reduction at the same time when the internal load bolt failed. The offset between the two transducers after this point was inferred to be due to the failure of the load bolt.

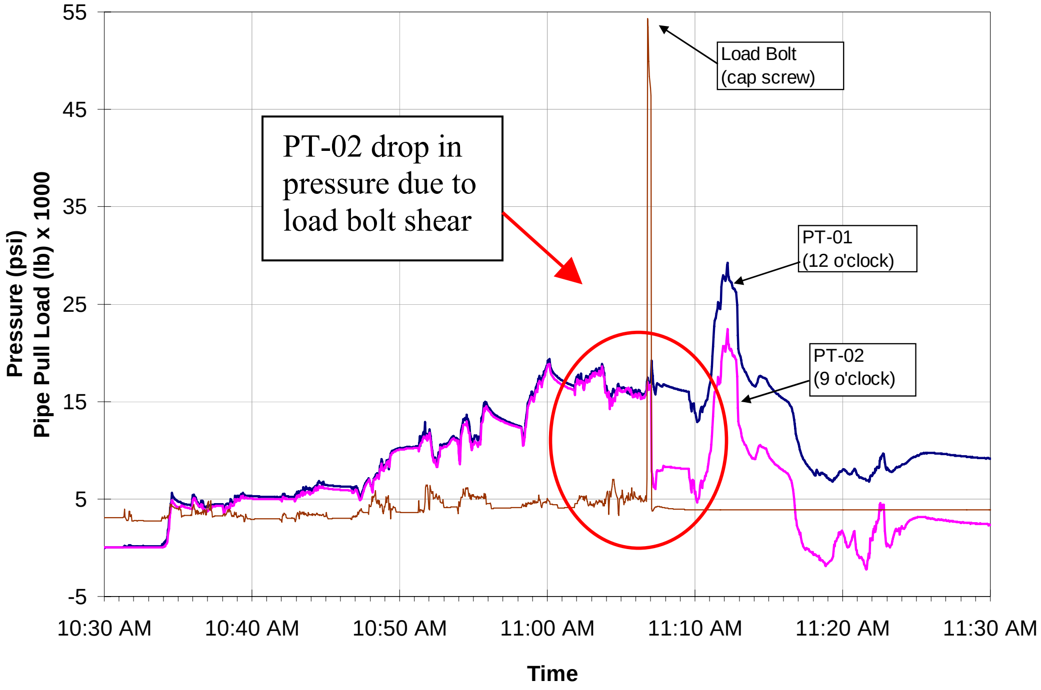


Figure 8-1: Pipe Pull Load & Fluid Pressure of 200-mm HDPE Pipe on August 3, 2005

Both pressure transducers showed a linear increase in pressure during pipe installation after approximately 10:48 a.m. Peak pressures were also observed to decay during stoppages required to remove drill rods. This decay was in the order of 35 kPa (5 psi) and would indicate that the MSW had sufficient permeability to quickly dissipate the drilling fluid pressures. The lower bound recorded pressure was inferred to be the leachate pressure adjacent to the pipe wall. Before failure of the load bolt, the peak leachate pressure was approximately 131 kPa (19 psi) at 11:00 a.m. Using a fluid unit weight of 9.81 kN/m^3, this pressure was equivalent to 13.4 m of drill fluid head. The maximum leachate pressure record was approximately 110 kPa (16 psi) which is equivalent to 11.2 m of leachate head.

During pipe removal, a peak fluid pressure of approximately 207 kPa (30 psi) was recorded. This pressure recording was not considered to be representative of the leachate or drill fluid pressures for the following reasons: the load bolt had failed; drill fluids were being pumped into the bore to aid in the pipe removal; and the drill rig was pushing while the excavator pulled on the pipe,

8.2.3 Drill Rig Hydraulic Pressures

Figure 8-2 shows the rotational and pullback hydraulic pressures during the installation of the HDPE carrier casing on July 28, 2005.

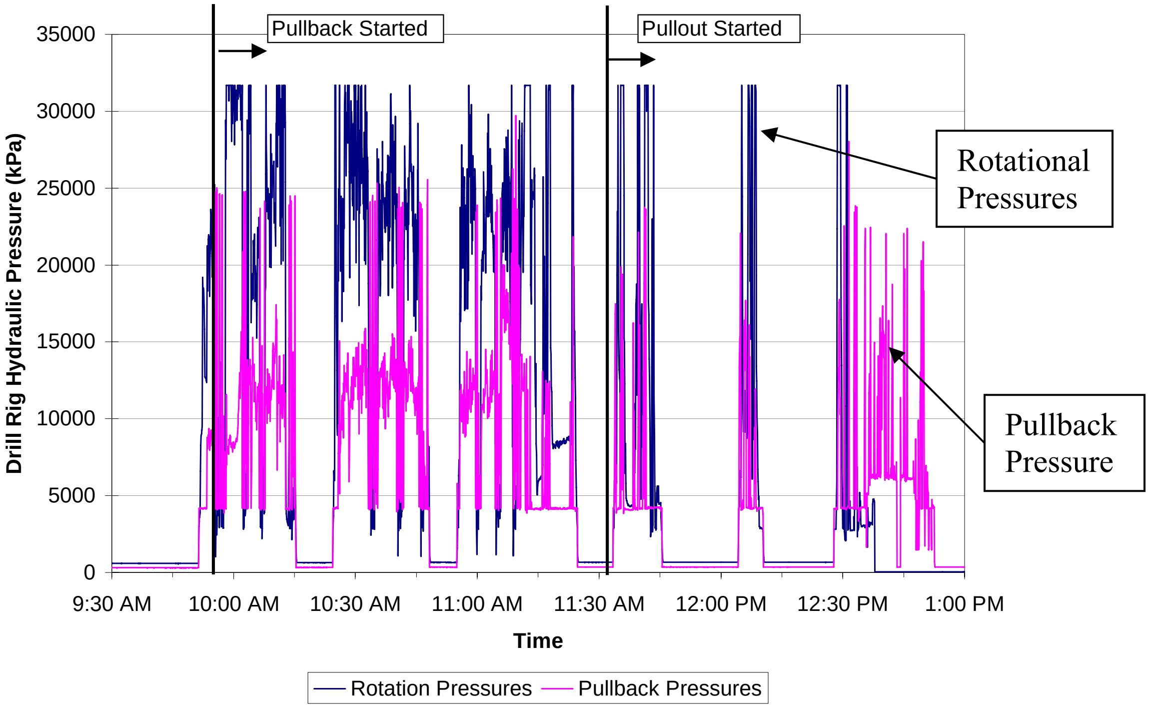


Figure 8-2: Drill Rig Hydraulic Pressures of 200-mm HDPE Pipe on July 28, 2005

In Figure 8-2, it was apparent that the rotational pressures exceeded the sensor maximum set range of 31,716 kPa (4,600 psi) and that the maximum recorded pullback pressures of approximately 24,132 kPa (3,500 psi) were below the maximum set value. Figure 8-3 shows the rotational and pullback pressures for 10:20 to 11:05 a.m. when drill rods 5 to 8 were removed.

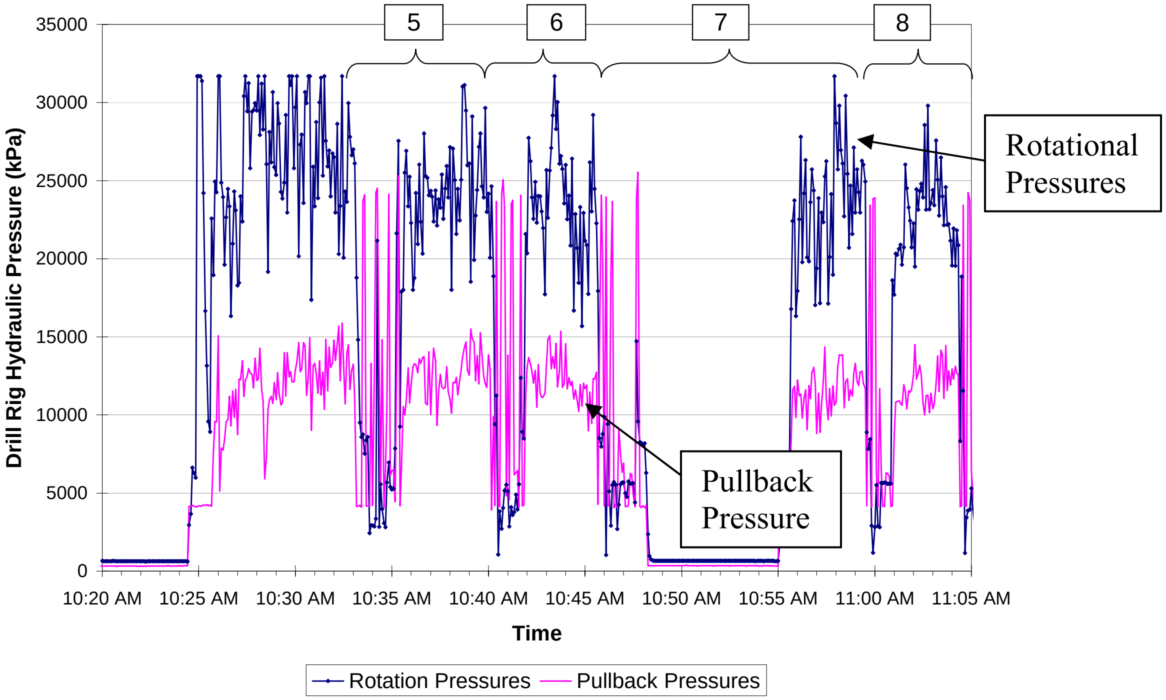


Figure 8-3: Close Scrutiny of Drill Rig Hydraulic Pressures of 200-mm HDPE Pipe

Figure 8-3 indicates that a correlation exists between drill rig rotational and pullback hydraulic pressures as the two pressure plots tend to have coinciding peaks and are parallel for drill rods 5 to 8. More research is required to determine the correlation factor. When the pipe entered into the bore, it first had to pass thorough the clay toe berm. To reach the waste area, approximately four drill rods had to be removed.

Based on review of the field monitoring results, observation of the drill rig hydraulic gauges, and discussions with the driller, it was concluded that due to the wrapping of material and fibrous waste around the reamer, swivel and carrier casing that the drill rig capacity of 8.8 kN-m (6,000 ft-lbs) of torque was not sufficient for this type well construction. It was also felt that a large drill rig (greater than 445 kN (100,000 lbs) of pullback) would have a good chance at installing the carrier casing.

8.2.4 HDPE Carrier Casing Strain

This section contains the analysis of pipe strain with respect to the pipe load. Correlation between pipe loads and pipe strains is presented to determine whether or not the conversion from strain to pipe load is feasible. The correlation between pipe strain and pipe pull load is illustrated in Figure 8-4.

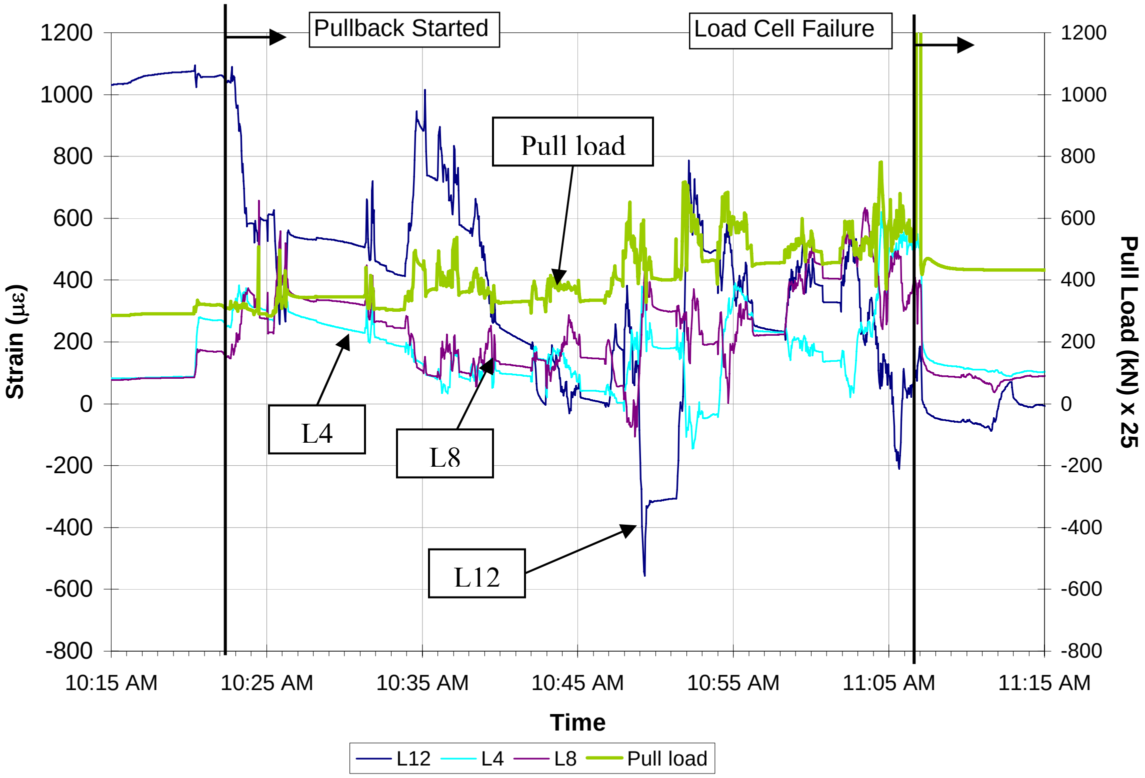


Figure 8-4: Strain Loads on 1st Pullback of 200-mm HDPE Pipe on July 28, 2005

The recorded pipe load somewhat showed a correlation with the longitudinal pipe strains: when the pipe load spike, pipe strains show an increase as well. However, the magnitude of increase does not correspond to the increase in the pipe strain data. For example, gauge L12 increased more drastically than the other two gauges at the peaks of pipe load data. Thus, it was suggested that the pipe load correspond more to gauge L4 and L8. However, a closer examination between pipe load and gauges L4 and L8 nullified that conclusion. At 10:51 a.m., when pipe load spiked, L4 and L8 increased in opposite direction: one was experiencing compression while the other experienced tension. At 10:58 a.m., similar trend was observed and continued until 11:05 a.m. Thus, it was concluded that there was no direct correlation between the pipe load and the pipe strain.

To verify that conclusion, recorded pipe load and pipe strain data were used to back calculate the elastic modulus using Equation 5.4. Figure 8-5 shows the calculated modulus values with respect to each pipe load and pipe strain data point.

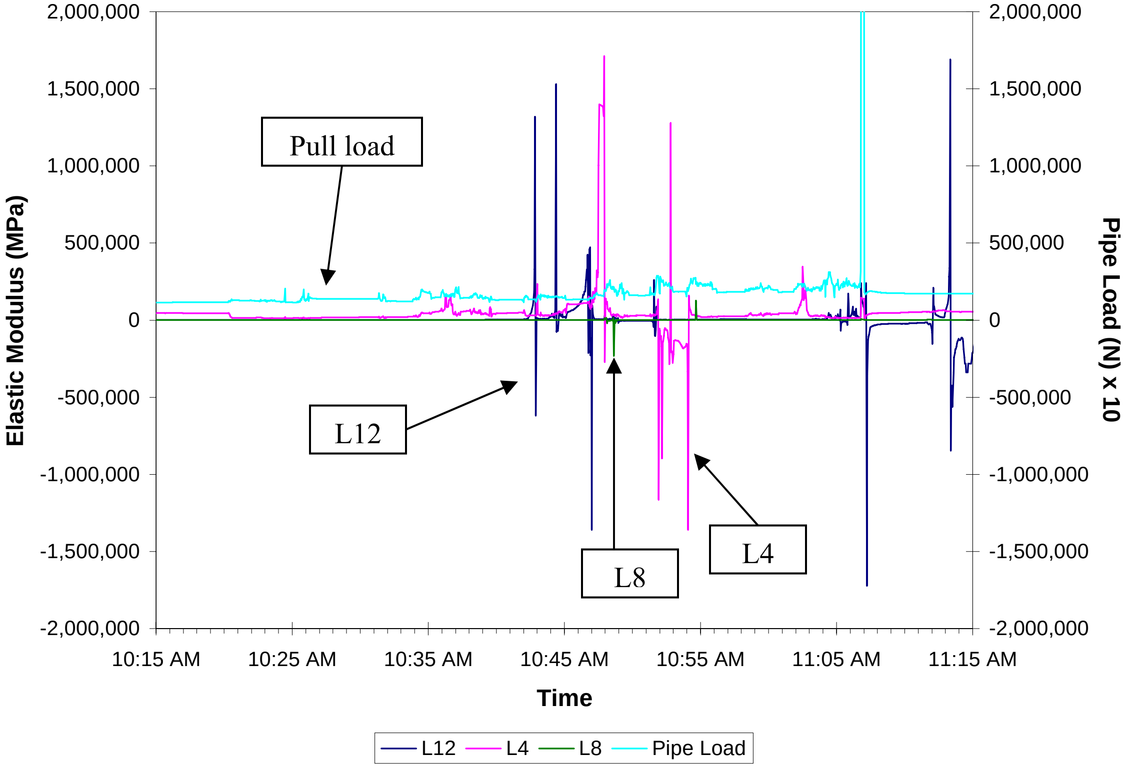


Figure 8-5: Calculated Elastic Modulus for 2nd Pullback Installation on August 3, 2005

In Figure 8-5, the pipe load does not correspond to any of the modulus calculated with respect to the strain gauges. It was therefore inferred that there might be other factors that resulted in the increase of pipe strain during pipe installation.

8.2.5 HDPE Carrier Casing Pull Load on August 3, 2005

Figure 8-1 in Section 8.2.2 also shows the load recorded by the internal load bolt during the 2nd installation attempt. This figure shows that the load increased from 22.4 kN (5,000 lbs) to 240 kN (54,000 lbs) over a five second period. This sudden and dramatic load bolt spike resulted in the failure of the 149 kN (33,500 lbs) load bolt.

Using the recorded peak load and a bolts cross sectional area of 2.84 cm^2 (0.44 in^2), the stress at failure was determined to be 847,434 kPa (122,910 psi). Inspection of the bolt failure surface showed evidence of a circular conical failure that would suggest that the cause of the bolt failure was mainly shear and not tension. The failure type, the rapid spike in load, and the fact that the reamer and swivel was wrapped with wire, rope and other fibrous material upon removal would strongly suggest that the swivel stopped freely rotating. This then resulted in the load bolt being subjected to torsion (rotation) forces for which it was not designed for carry.

Figure 8-1 shows that a pull force of 133 kN (30,000 lbs) was required to start to mobilize the carrier casing out of the bore. The safe pull load calculated for the 200-mm HDPE at temperature of 38˚C was approximately 99 kN (22,320 lbs). It was clear that the internal load bolt failed before the HDPE pipe failed. Due to failure of the internal load bolt during the 2nd installation attempt, only external load cell pullout loads were recorded during the pullback of the carrier casing following the 3rd installation attempt on August 4, 2005. To mobilize the pipe out of the bore, a pull force of 218 kN (49,000 lbs) was required. The high recorded pull out force required to mobilize the pipe out of the bore indicated that the head was severely stuck or that the bore collapsed around the carrier casing. Insufficient data exists to confirm what locked the pipe in place.

8.2.6 HDPE Well Pipe Pull Load on August 11, 2005

Figures 8-6 and 8-7 shows the drill rig rotational and pullback hydraulic pressures for the 100-mm HDPE well pipe installation.

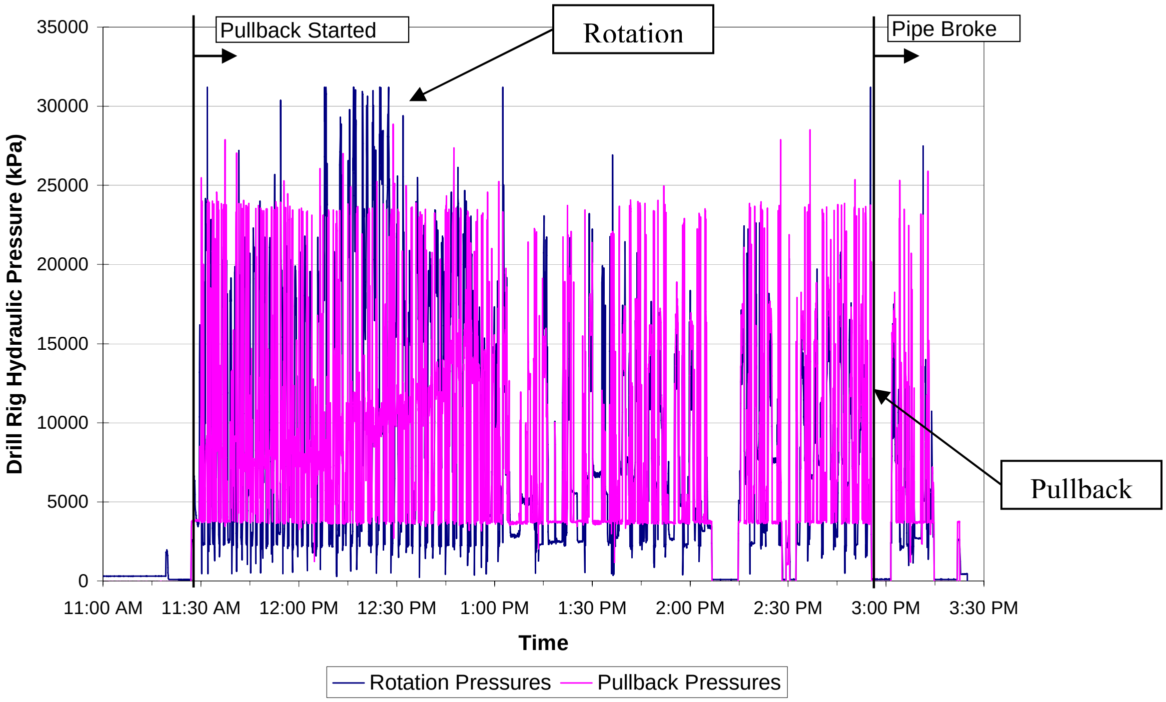


Figure 8-6: Drill Rig Hydraulic Pressures of 100-mm HDPE Pipe on August 11, 2005

Figure 8-6 shows the pressure sensor reading during the complete monitoring period. Figure 8-6 indicates that the rotational pressure was maintained below 24,132 kPa (3,500 psi) with some spikes increasing as high as 31,026 kPa (4,500 psi). These values were lower than those recorded during the installation of the HDPE carrier casing. The peak load required to pull the 100-mm (4-inch) pipe well out of the bore was approximately 54 kN (12,000 lbs). The safe pull load calculated for the 200-mm HDPE at temperature of 38˚C was approximately 27 kN (6,000 lbs) and the pull load measured at temperature of 38˚C was approximately 28.5 kN (6,400 lbs). As a result, the 100-mm (4-inch) pipe was stretched. Figure 8-7 shows the rotational and pullback pressures for 11:25 to 11:40 a.m. when drill rods 1 to 6 were removed.

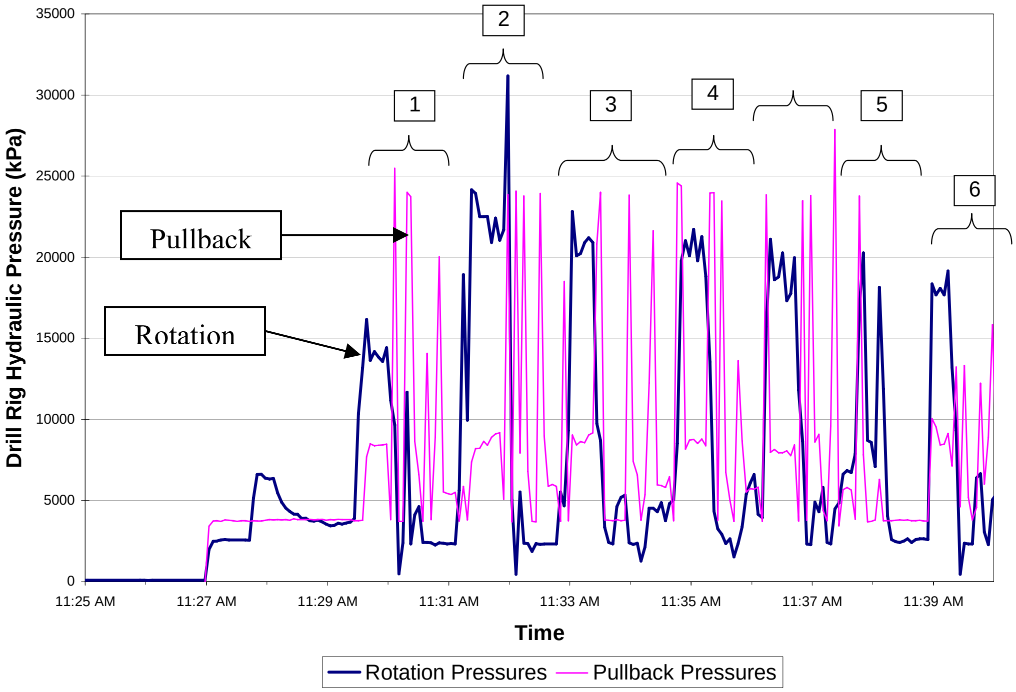


Figure 8-7: Close Scrutiny of Drill Rig Hydraulic Pressures of 100-mm HDPE Pipe

8.2.7 HDPE Carrier Casing Pullout Load on July 29, 2005

The pullout load for the HDPE carrier casing were recorded on July 29, 2005 and it is shown in Figure 8-8. This figure presents both internal load bolt and external load cell data. It should be noted that the internal load bolt data logger was recording and saving readings every ten minutes while the external data logger was recording and saving readings every three second. The internal load bolt was programmed to initially record data at a two second interval for a period of 24 hours then to automatically change to record data at a ten minute interval. Since the pipe was stuck in the bore for a period greater than 24 hours sensor readings were taken at only ten minute intervals.

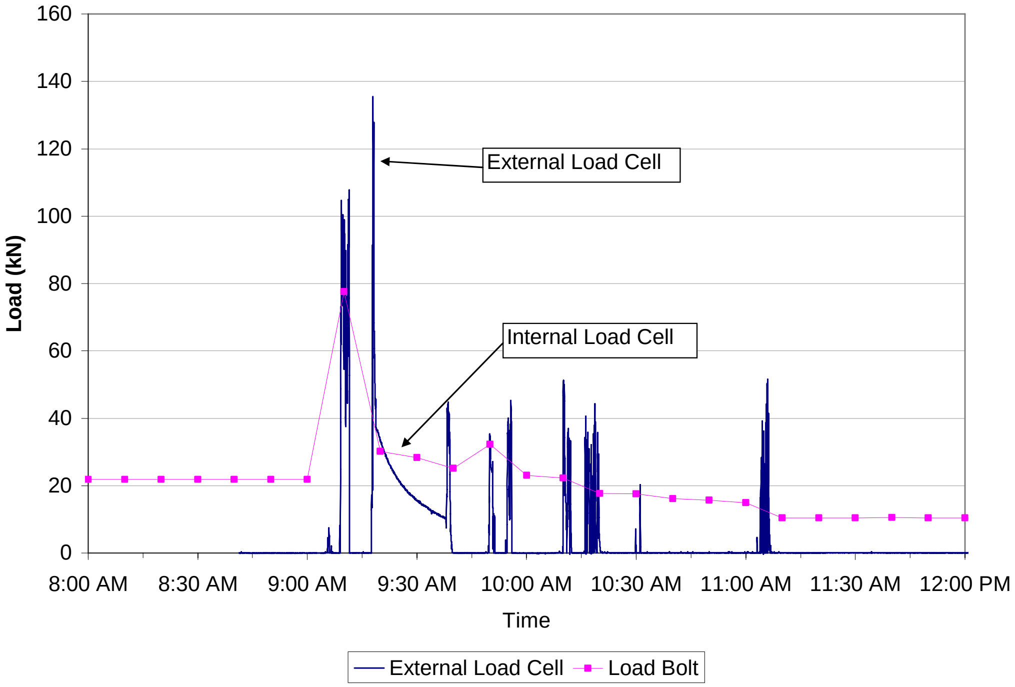


Figure 8-8: Pull Loads (Internal & External) of 200-mm HDPE Pipe on August 3, 2005

Figure 8-8 shows that the internal load bolt peaks do coincided with external load cell peaks. Unfortunately due to the long time between internal load bolt recording and the short duration of the applied load, the internal load bolt did not record peak loads applied to the carrier casing.

8.3 West Well Field Results

Discussions presented in this section focus on data collected from the second well construction and HDD equipment. Problems encountered during pilot boring, pullback, and pullout were provided with potential causes. Data were also presented in Chapter 7 and interpreted and related to these causes.

8.3.1 Leachate Volume

Leachate elevations for the West Well were anticipated to be higher than for the East Well bore exit. However, during pilot bore exit and pipe pullback, no leachate was observed to flow out of the bore. The lack of drill return during all drill phases would also suggest that the daily cover is very permeable. Although the installation of the 100-mm (4-inch) HDPE well did result in some leachate flow, the flow was not considered to be significant or to be continuous. No well testing was completed to determine leachate flow rates.

8.3.2 Drill Rig Hydraulic Pressures

Figure 8-9 shows the rotational and pullback pressures applied. Drill rig hydraulic pressures in the West Well installation were higher than those recorded for the East Well installation. It was concluded that the West Well drilling occurred in denser, non-decomposable wastes which required higher rotational pressures.

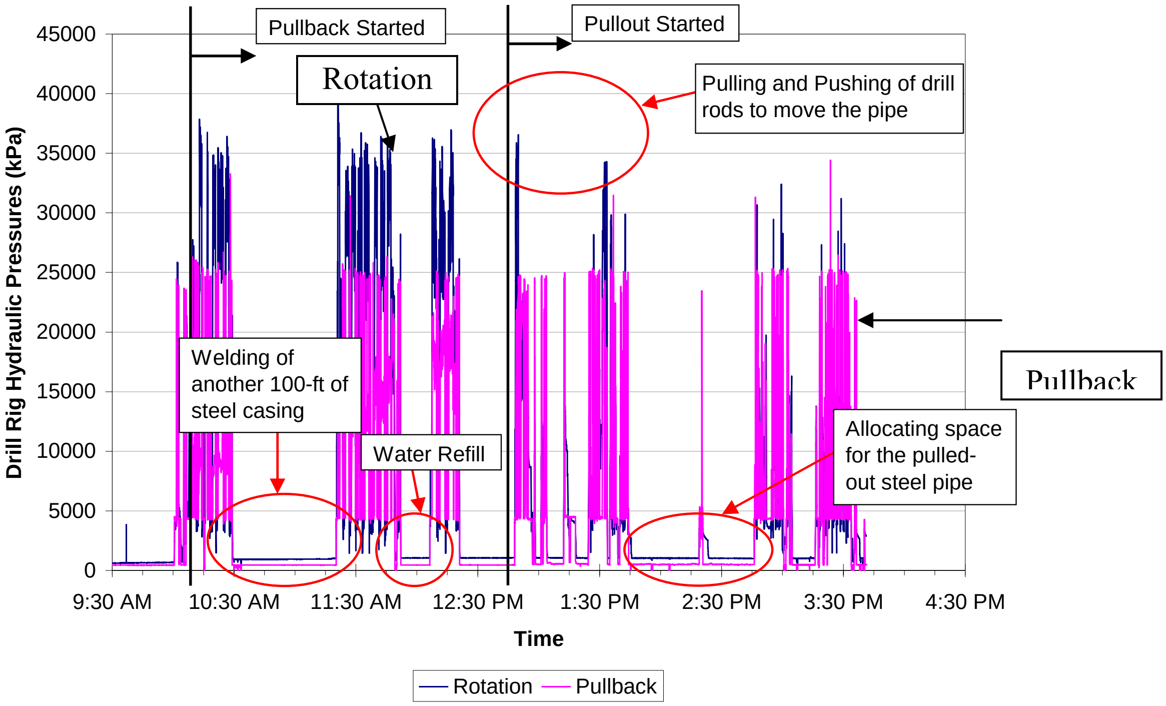


Figure 8-9: Drill Rig Hydraulic Pressures of 125-mm Steel Casing on March 21, 2006

The rotational pressures in Figure 8-9 show pipe pullback profile and that higher rotational pressures than during pipe pullout was required. In the pullout stage, rotational pressures were applied to reduce friction. In pulling out the steel casing, drill rig was used as a secondary source and thus rotational and pullback pressures were maintained between 24,131 kPa (3,500 psi) and 27,579 kPa (4,000 psi) range.

Chapter 9 - Conclusions & Recommendations

9.1 Conclusions

This thesis documents:

- Leachate mounding in municipal solid waste facilities.
- The use of directional drills for the construction of leachate collection wells in municipal solid waste.
- The development of a monitoring system that can monitor drill rig performance during well construction and well installation.
- The construction and behaviour of two gravity directional drilled wells constructed at the Region of Waterloo Solid Waste facility.

Key research findings included:

Pilot Bore Drilling

- Pilot bores can be drilled on line and grade through mixed municipal solid waste with a wireline tracking system and a bogs hog drill bit.
- No drill returns were observed. Thus, the waste was found to be very permeable.
- When the drill head exited the bore very little leachate flowed out of the bore path. This was inferred to be due to the functioning perimeter leachate collection system.

Well Installations

- The directional had insufficient rotational torque and pull back to install the 200mm HDPE and 150 steel carrier casing into the bore path while reaming. The causes of the failure were found to be a combination of: closure of the waste around the carrier casing; wrapping of fibrous waste material around the reamer; and bore path obstructions.
- Installation of a 100mm HDPE well in the bore paths failed part way into the bore by necking and rupture. High internal waste temperature was inferred to soften the pipe material.

Monitoring System

- Drill rig hydraulic monitoring showed high and sudden increases in rotation torque during pipe installation.
- Bore pressure monitoring showed that drill fluid pressures decreased rapidly during drill stoppages and that the leachate head can be measured during the pipe installation.
- The field monitoring system worked well.
- A correlation was found between pipe loads and drill rig hydraulic pressures.
- Failure of the load cell bolt found that the load on the pipe can increase rapidly (within five seconds). Failure of the load cell bolt was inferred to be due to material wrapping around the swivel causing it not to rotate freely.
- Monitoring system provided valuable data on the performance of the drill rig and pipe during installation.

Well Construction

- Installation of a carrier casing without pre-reaming the bore did not work well.
- Placement of shield over the swivel would prevent material wrapping around the swivel.
- The drill rig used did not have sufficient torque to complete the installation of the carrier casing.
- Steel is a preferred carrier casing material due to it high tensile strength, the ability to ram and to take higher pull loads.
- Waste and leachate temperature softened the HDPE pipe.
- Gravity well construction is deemed to be possible using a steel carrier casing and a maxi drill rig.
- Non aggressive reamers with the ability to compact and cut are required.
- Improvements are needed in making wireline connections and measurements especially in cold weather.
- The main purpose of the drill fluid was to cool the tracking sonde. Thus, water only was sufficient for this project.

9.2 Recommendations for Future Work

Based on this project the following recommendations for future work are made.

1. There is a need for the development of a real time data logging system so that the drill operator can make adjustments to the drilling process during drilling and/or the pipe installation.
2. There is little understanding of leachate distribution within solid waste. The pulling of a pressure transducer through the waste can provide valuable information on leachate distribution. This information is critical for the design of retrofit leachate collection systems.
3. Use of a direction drill for the construction of gravity well is possible. However, research is required to improve and optimize the installation process. Thus, the installation of more monitored gravity wells is required.
4. Prior to attempting to install a carrier casing the bore should be pre-reaming to its final diameter and swabbed. This would condition the bore and increase the probability of a successful carrier casing installation.

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