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Assessment of the Annular Space in a Horizontal Directional Drilling Installation

by

Ivan J. Beljan ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of Master of Science

in

Construction Engineering & Management

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ABSTRACT

The objective of this research is to view, analyze and assess the integrity of the annular space and develop an understanding into how it's shear strength may change through time.

The annular region, or annulus, is an area that is very seldom examined because in normal circumstances cannot be scene. Through this research, there was an opportunity to view the annulus through a Horizontal Directional Drilling (HDD) installation of six pipes in two different soil types. After installation of a pipe, cross-sections were excavated at one day, one week, two weeks, and four weeks to view and test the progression of the annulus.

It was discovered that the annulus was constantly changing in shape and extent. In addition, the properties and shear strength of the annulus is largely a factor of the native soil in which the pipes are installed. Ultimately, through all the installations and excavations, the annulus seemed to provide the necessary support to the pipe and not endanger it in any matter.

Acknowledgments

I would first like to thank Vermeer Manufacturing for their exceptional generosity. Without the vision and support from companies such as Vermeer, graduate students would not get the opportunity to carry out their dreams and goals. In addition, I would also like to thank Baroid Industrial Drilling Products for their involvement both financially and intellectually. Frank Canon and Dan Gretener were both instrumental in the success of this research. Furthermore, I would like to extend my appreciation towards my examining committee, Dr. Bogdan Lepski and Dr. Hamid Soleymani, as well as fellow graduate students Jason and Don for their help in organizing the research and collecting the necessary data.

Above all, I would like to thank my supervisor Dr. Samuel Ariaratnam for his belief in me, as well as his support and guidance throughout this research. Without Dr. A's vision, this research would never have been started and I am proud to have had the opportunity to work alongside him through the course of this research.

Most importantly, I would like to thank my mom, dad, and sister for their continued support, encouragement and belief in me.

For My Mom and Dad…

The Best Parents a Kid Could Have.

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CHAPTER 1 INTRODUCTION

1.1 Introduction

The construction industry is an intrinsic component in today's world. As society grows and ages, it is left to address the demands for repairing, rehabilitating, or new construction of infrastructure. These demands placed upon the construction industry seek better safety and environmental programs, higher quality of construction without sacrificing cost, and less disruption to people and existing services. This has fostered the development of Trenchless Technologies. Trenchless Technologies can be best described as underground construction without the use of a trench or an open pit. Currently, its scope is limited to utility networks; however it has potential to be applied in other areas of underground construction. The idea of employing trenchless methods is not something altogether new, although it is only in the last thirty years that development and use has really started to flourish. With any new development, there are always questions that arise about the mechanics that serve the method. This opens the question of whether Trenchless Technologies can provide a safe and effective method of repairing, rehabilitating, or implementing a new utility network without any liabilities or side effects?

1.2 Overview

Trenchless Technologies may never replace open cut installation, but it has definitely made its mark as a viable alternative. It is important to remember that each construction project offers its own uniqueness and therefore it is important that the proper method be selected, depending on the project characteristics. Trenchless Technologies employs several methods that include microtunneling, pipe bursting, pipe lining and horizontal directional drilling to list a few.

Horizontal Directional Drilling (HDD) is perhaps the most prevalent trenchless method for new construction. HDD involves drilling a pilot bore through the ground along a proposed alignment, and then pulling through a product pipe on the backream. Through this entire process, a drilling fluid is injected through the drill bit (forward process) and the backreamer (back process). The drilling fluid is primarily a combination of water and bentonite, although other additives may be inserted to add different strength properties. Upon entering the borehole, the drilling fluid performs several functions. Some of those include: liquefying and stabilizing the soil on the borepath, removing solids from the freshly cut hole, drill pipe and transmitter sonde cooling, and drill pipe and product pipe lubrication. Once the installation of a product pipe is complete, a cake layer composed of the drilling fluid and the native soil is left behind. This is otherwise known as a slurry. This slurry surrounds the product pipe in the area called the annulus. The annulus is defined as the area between the outside of the product pipe to the wall of the borehole. The size of the borehole is determined by the back-ream, which in most cases is an industry standard of 1.5 times the size of the product pipe. Because this area can be very large (depending on the pipe size) and is filled with basically a mud composition, many questions arise as to the stability of this layer. Can this layer of mud in the annulus support the newly placed pipe? What are the actual strength properties of the annular region? Does the native soil have an effect on the strength of the annulus? What does the annular region actually look like once a pipe is installed? These are only some of the questions that have yet to be answered in regards to the annular region.

1.3 Objective

The objective of this research is to view, analyze and assess the integrity of the annular space and develop an understanding into how it's shear strength may change through time. The annular region is an area that is very seldom examined. Because of the nature of HDD pipe installations, the annulus is an area that cannot be scene and in most cases will never be scene. Through this research, there will be an opportunity to visually assess and then quantify characteristics of the annulus. Because it is impossible to view the pipe being installed underground, there are a lot of question marks as to what actually occurs during the installation of a pipe. It is the intent of this research to verify or dispute existing ideologies or possibly bring to light newfound information of the annular region. Therefore, the objectives of this thesis are as follows:

- To visually assess and analyze the annular region.
- To assess the composition and properties of the drilling fluid and subsequent slurry.
- To examine the strength properties of the annulus through insitu testing.

1.4 Method of Solution

To achieve the objectives outlined, an in-situ field experiment was deemed as the best possible method of attaining accurate results. The experiment was set-up as an actual pipe installation; thereby duplicating the reaction of the annulus as it would react in any other real world installation project. To be able to truly analyze the annulus, a number of drilling operations had to be performed. This would allow for better validation of material that would be uncovered. Therefore, three different diameter sizes of High-Density Polyethylene (HDPE) pipe (100mm, 200mm, and 300mm) along with two different soil sites (clay and sand) were used. Analyzing the properties and composition of the annulus would then be accomplished by the following:

- Upon installation of a pipe, cross-sectional excavations would occur systematically, starting from the exit pit and working our way along the pipe towards the entry pit, through a timeline progression. This timeline would be at 1 day, 1 week, 2 weeks, and 4 weeks post-installation. Once a section has been excavated, the following activities would be conducted:
  - Visual assessment of the annular region, product pipe, and adjacent area.
  - An industry standard field mud kit would be used to define the properties of the drilling fluid before insertion into the borehole and the subsequent slurry

produced through different stages of the drill/backream. These properties include viscosity, gel strength, filtrate/ filter cake, fluid density, sands content and pH.

- In-situ strength tests, with the use of a pocket penetrometer and a vane shear, would be performed on the annulus and the adjacent area.
- Samples would be collected for laboratory calculation of moisture content of the annulus and adjacent area.

The solution to understanding the annular space can best be realized through actual in-situ experiments. This insures that the results obtained carry no assumptions and no inferences. They carry only direct observed, measured, and calculated results that will assist in truly understanding the annulus.

1.5 Contribution to Industry

This research addresses a very vital and under-researched topic in the drilling industry. Many owners and city jurisdictions alike are somewhat leery of using horizontal directional drilling due to the fear of failure of the annular region. Because very little research has been done in this area, some owners are choosing the more traditional and sometimes more expensive alternative, which is open-cut construction. Many owners feel that they need proof or reassurance of the integrity of the annulus region before they attempt to use the HDD Market. It is anticipated that through this research that some of these fears can be alleviated. By creating numerous field-like drilling applications, the true nature of the annulus can be studied and the results obtained may be applied to a wide range of future drilling projects. When owners and contractors alike come to understand what has been discovered, they can better prepare for a HDD pipe installation. This could mean a different combination of drilling fluids to accommodate the native soil or preparing for a probable occurrence when drilling in that type of native soil. Whatever the case, the utility installation industry will benefit as a whole from this research by a better understanding of what may occur when horizontal directional drilling is applied to the installation of a pipe. The industry may now better judge, without fear, whether a traditional (open-cut) installation is more cost effective or an HDD application is better warranted.

1.6 Contribution to Academics

The goal of this research is to ignite research into further testing and analysis of the annulus, drilling fluids, and other aspects of the Horizontal Directional Drilling process. The purpose of this initial research was to demonstrate the properties of current methods and techniques that are in place. By examining and dissecting the results of the annulus of current methods, limitations can be identified and improved; thereby facilitating improvement of the HDD process. Therefore, this research will hopefully be an initial step into future research efforts.

1.7 Contribution to Society

With the advancement and better understanding of Trenchless Technology, society gains a method of construction that may be safer, less expensive, and more productive. The intent of this research was to gain a better understanding of one of the integral parts of the HDD process, which is the annulus. It is only by the study of each component can the whole be improved. In addition, the focus of this research could have some bearing to society when it comes to drilling underneath a highway, building, or a national monument for instance. If ground movements do occur, it could pose a cost that could not only drive the contractor out of business, but it could effect users and taxpayers of those cities. The intent of this research is to supply a tool that may assist in the decision making process of these drilling installations. If by looking at the findings of this research and applying it to a project, certain measures may then be taken to alleviate any failure of the annulus, and thereby minimizing risk for all parties concerned.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The Literature Review focuses on several related topics in underground construction. First, the review examines the beginnings of Trenchless Technologies and details all of its applications. Illustrations of the applications will be provided as well as highlighting those methods that rely on drilling fluids. Second, a detailed examination of Horizontal Directional Drilling (HDD) is presented with an analysis into the process and integral parts that comprise it. Finally, a look into some research to date that has been undertaken in the area of soil deformations due to an HDD pipe installation.

2.2 Trenchless Technologies

In simplest terms, Trenchless Technologies is construction without the involvement of a trench or pit. Underground construction traditionally has been done using an open trench. This would involve completely excavating the native soil of the area that requires the installation, repair or replacement of any underground utilities. However, because of high economic and social cost, in addition to many safety issues, a new form of technology evolved. This technology would change the industry forever by allowing work to proceed more safely, with less overall cost and with little or no damage to existing surfaces. In addition, the largest advantage it brought was that work could proceed with minor social disruption, which when related to densely populated areas, would be impossible to quantify. This Technology is Trenchless Technologies.

The North American Society of Trenchless Technology (NASTT) prefers to define Trenchless construction as " *a family of methods, materials, and equipment capable of being used for the installation of new or replacement or rehabilitation of existing underground infrastructure with minimal disruption to surface traffic, business, and* *other activities* ". Ariaratnam et al. (1998) points out that although trenchless construction is relatively new, there is evidence of trenchless techniques being employed all the way back to the 1860's. At that time, the Northern Pacific Railroad Company pioneered the use of pipe jacking techniques. By the 1930's, reinforced concrete pipe was being installed using the same technique. The following list shows a timeline of inception for trenchless techniques: (further explanation of techniques will be discussed in the upcoming section)

1. Pipe Jacking – 1860's
2. Auger Boring – 1940
3. Pipe Lining – 1960
4. Impact Moling – 1962
5. Directional Drilling – 1971
6. Microtunneling – 1973
7. Pipe Bursting – 1980

The potential of Trenchless Construction has yet to be realized. The migration towards the use of Trenchless methods began in the 1970's when pipe lining systems for deteriorating natural gas systems, water mains and sewers really began to take off. Then with the introduction of microtunneling and horizontal directional drilling in the 1980's to North America, trenchless became a preferred method of construction for many projects. To realize the growth of trenchless construction in Canada, view the growth spurt it achieved from 1992 to 1997. For new construction, municipalities in Canada increased its use in trenchless methods by 180%. For rehabilitation projects there was increase of 270%. Many municipalities and owners alike are realizing the advantages of trenchless construction.

2.3 Trenchless Construction Methods

The following section defines the different methods used in trenchless construction along with a brief description (HDD will be covered in the next section). The selection of a method for a particular project will be greatly influenced by many factors such as size of bore hole, accuracy required, depth of water table, local soil conditions, and availability of funds.

2.3.1 Microtunneling

Iseley and Najafi (1997) describe microtunneling as a highly sophisticated method of horizontal earth boring. MicroTBM's are laser guided, remotely controlled, and permit accurate monitoring and adjusting of the alignment and grade as the work proceeds. In basic terms, they are non-personnel entry tunnel boring machines. Microtunneling was developed in Japan during the 1970's and is really uniquely suited for the installation of sewer lines where a high degree of accuracy is required. Generally, most lines installed using this method are less than or equal to 900 mm but larger pipes have been installed. Figure 2-1 shows a typical set-up of a microtunneling system.

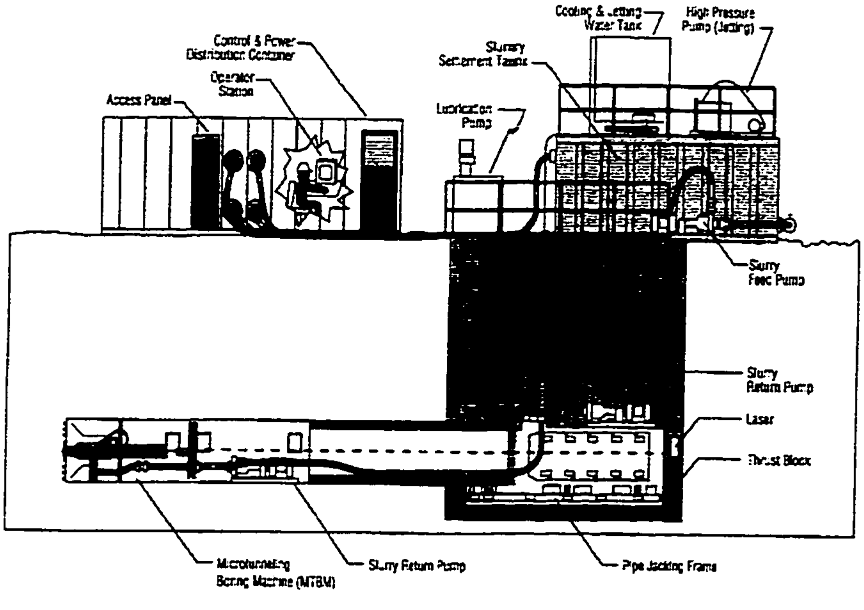

Figure 2-1 Typical Microtunneling System (Iseley and Gokhale 1997)

Microtunneling can be further broken down to two methods, which are (1) Slurry Method and (2), The Auger Method. The Slurry method cuts the soil up mechanically at the face by a cutting head and then it removes the soil by hydraulic action. The soil enters the boring head through inlet openings and is then placed in suspension in the slurry chamber. The slurry chamber is integrated in a circuit designed to handle water or a bentonite slurry. This method relies on a proper drilling fluid to be able to suspend soil particles and transport them out of the borehole. On the other hand, the Auger method involves jacking pipe with simultaneous soil cutting at the face by use of a boring head while soil removal is achieved by the use of a continuos flight auger. This method does not employ the use of a drilling fluid; instead it relies on mechanical devices to aid in the removal of cuttings. Figure 2-2 shows an actual entry pit of a microtunneling operation.

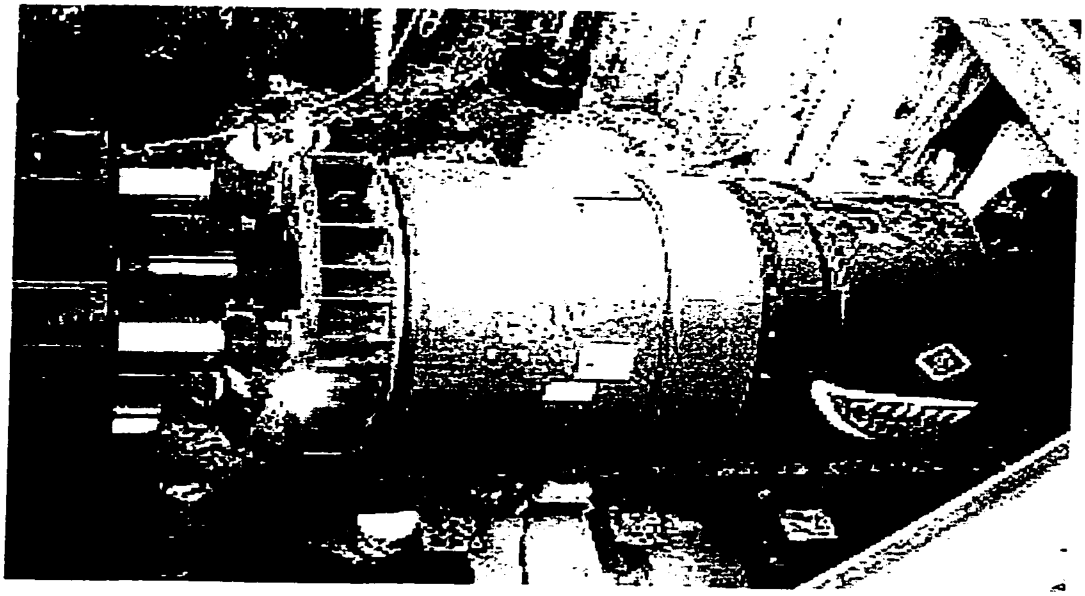

Figure 2-2 Microtunneling Entry Pit

2.3.2 Pipe Jacking

Iseley and Najafi (1997) illustrate the difference between microtunneling and pipe jacking. While microtunneling necessitates no personnel in the tunnel, pipe jacking requires workers inside the jacking pipe or tunnel. The tunnel is generally started from an entry pit and the excavation could be a very basic process of workers digging to a very sophisticated tunnel-boring machine. Because the method requires personnel working inside the tunnel, the minimum tunnel diameter recommended is 1075 mm. Once the excavation is underway through the use of an articulated shield, the spoil created is removed through the inside of the pipe to the jacking pit. It is then carted off or removed on a conveyor belt system. Once the excavation is complete, the pipe jacking process can begin. Guide rails are placed in the pit and are aligned with the proposed bore. The process involves a simple, cyclic procedure of utilizing the thrust power of hydraulic jacks to force the pipe forward. The anticipated jacking thrust will be a function of the penetration resistance, friction resistance between the pipe and the earth, and friction resistance force due to the dead weight of the pipe. Although no fluids are used in the cutting up or removal of the soil, application of bentonite or polymers to the outer skin of the jacking pipe are used. This reduces the friction between the soil and the jacking pipe and thereby reducing thrust requirements. Figure 2-3 shows an actual set-up of a pipe jacking operation.

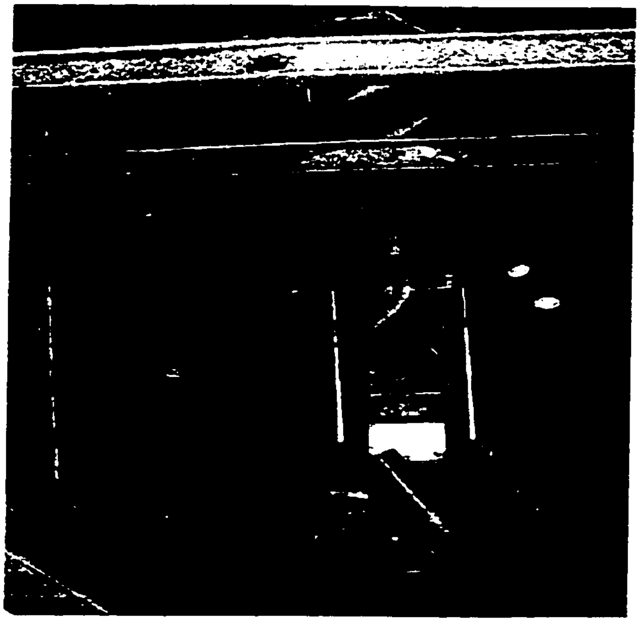

Figure 2-3 Pipe Jacking Operation

2.3.3 Auger Boring

Iseley and Najafi (1997) describe Auger Boring as a process of simultaneously jacking casing through the earth while removing the spoil inside the encasement by means of rotating flight auger. The casing supports the soil around it while the spoil is transferred back to the machine. The two main factors that effect auger boring are the torque and thrust. The torque is created by a power source and hydraulic thrust rams located at the rear of the machine create the thrust. Auger boring can be used in a wide range of soil conditions, from wet sand to solid rock. Auger Boring can be further subdivided into two different methods, which are Track Type Auger Method and Cradle Type Auger Method. In both cases, water is normally injected into the casing at the leading edge to facilitate in soil removal. As well, bentonite can be applied to the outer skin of the casing to aid in lubrication and lower friction between the soil and pipe. Figure 2-4 is a set-up of an auger bore.

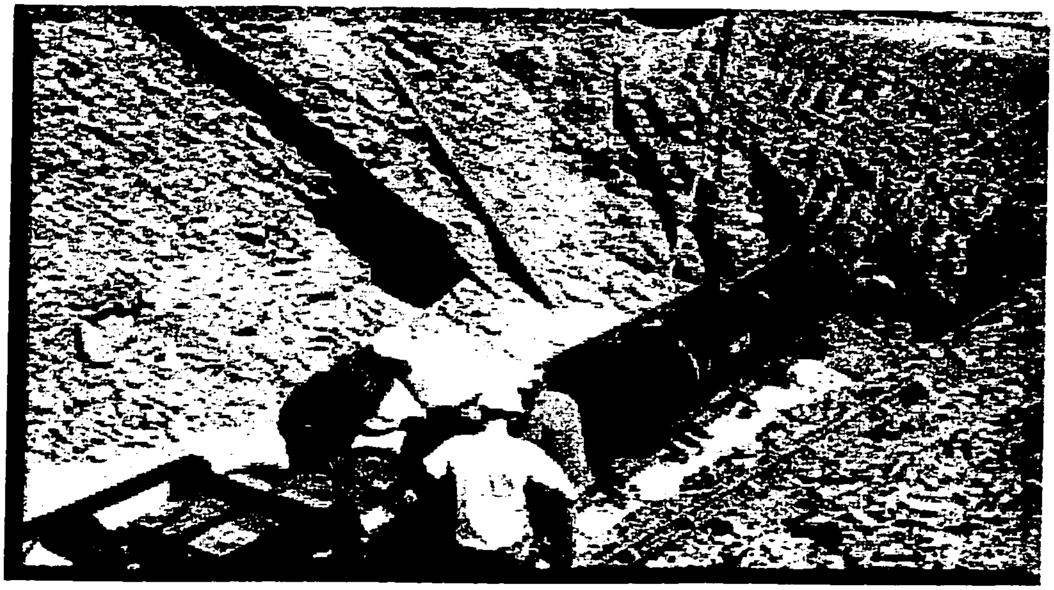

Figure 2-4 Auger Boring Set-up

2.3.4 Pipe Bursting/Splitting

Ariaratnam et al. (1998) describe pipe bursting as a method of breaking an existing pipe and simultaneously installing, by pulling or pushing, a new pipe of equal or larger diameter. The process involves the insertion of a bursting head into the old pipe. Then the bursting head receives power to break the old pipe from a pulling cable, hydraulic power to the head, or pneumatic power to the head based on the bursting system. The diameter of the bursting head is slightly larger than the inside diameter of the old pipe and slightly larger than the outside diameter of the new pipe. Once the bursting head is put into action, the diameter of the cavity expands and the old pipe breaks into pieces, while the new pipe is being pulled in from behind. The majority of pipe bursting applications in Canada is for the replacement of sewer lines. Figure 2-5 is a photo of a pipe bursting operation.

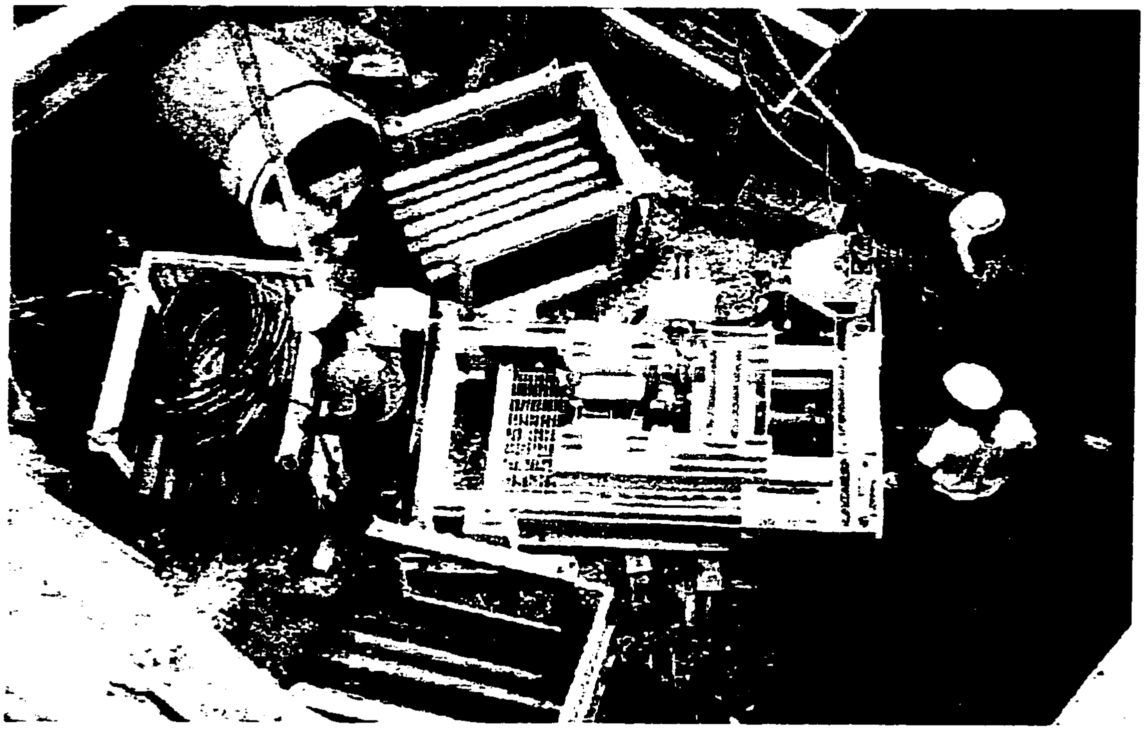

Figure 2-5 Pipe-Bursting Operation

2.3.5 Lining of Pipe

Ariaratnam et al. (1998) show that the ability to cost effectively reline existing pipe systems quickly and with minimal disruption to the public, traffic, or plant operations, have made pipe lining systems one of the most widely used trenchless technology's in the world today. There are a number of lining methods available for sewer pipes with each method having it's own specific capabilities, equipment, installation, site requirements, and design considerations. Pipe liners main function is not to act as a structural member, but rather to extend the useful life of the pipe. Traditional Sliplining is commonly used to rehabilitate sewers that have defects including extensive cracking, joint deterioration, and corrosion. The process includes the insertion of a new pipe (usually PVC) into a host pipe that has been cleaned and inspected to identify possible obstructions, and a grout is provided to fill in the annulus between the liner and existing pipeline. Other methods that have developed are Modified Sliplining, Fold and Formed Sliplining, Spiral Winding and Cured-In-Place-Pipe. As we can see by Figure 2-6, the set-up and operation occurs outside of the utility network.

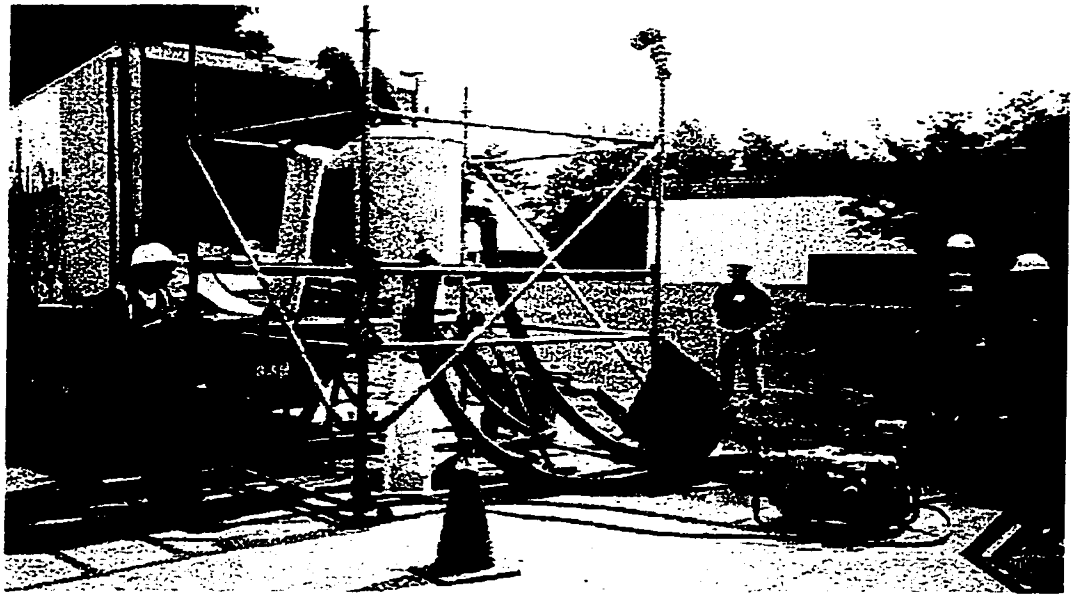

Figure 2-6 Pipe Lining Set-up

2.4 Horizontal Directional Drilling

Allouche and Como (1997) establish that Horizontal Directional Drilling (HDD) technology can trace its roots back to the utility, oil field, and water well industries. Its evolution came by combining the technologies from these respective industries. It has now evolved to the point where many municipalities and counties first preference for utility installation is HDD. There is no doubt that the fastest growing sector in the trenchless industry is HDD. The numbers speak for themselves: In 1984, there were 12 operational HDD units in North America compared to 2000 HDD units in 1995. Why has there been such growth in the HDD industry?

As with any trenchless application, the first and most obvious advantage is the fact that there is no trench to dig. Traditionally, utility installation basically involved such things as tearing the ground surface (e.g. asphalt, concrete etc.), digging around existing utilities, and placing safety contingencies when required. Not only does this usually entail large costs, it can also disrupt traffic or place a large damper on commercial activities. As we can see by Figure 2-7, an open cut operation can cause quite a disruption when employed in urban areas.

Figure 2-7 Open Cut Operation

Because there is relatively minimal excavation requirements for HDD, large populated urban areas can reap the benefits because of its decreased surface disruption. Furthermore, when obstacles such as rivers, highways, monuments, rail tracks or runways are encountered, open trenching could prove very costly and almost impossible at times. But, HDD can confront these situations and undertake them without large amounts of fear. Other advantages of HDD include:

1. The equipment utilized (Figure 2-8) requires a relatively short set-up time.
2. Labor requirements are very minimal as a crew of two could operate a small drilling rig.
3. Borehole alignment need not be straight, as it is possible to change borehole elevation and alignment to avoid existing utility lines.
4. Operation can proceed in sensitive soil conditions or environmentally sensitive areas with minimum disturbance to the surrounding environment.
5. The cost and time associated with de-watering facilities are eliminated.
6. Year round operation.
7. Safety hazards are greatly reduced because of less labour involvement, contaminant exposure is minimized, and the risk of a cave-in is eliminated.

Figure 2-8 HDD Rig

The installation of a product pipe is a relatively straightforward process. The bore is launched from the surface and the pilot bore proceeds downward at an angle until the necessary depth is reached (Figure 2-9). Once the path of the bore is brought to the horizontal, it is kept that way until it is steered by a curved path to the exit point on the surface. To control it's progression through the soil, a directional monitoring device (located near the head of the drill string), is used to track the position of the drilling head. After the pilot string breaks ground at the exit location, the bit is removed from the drill string and then replaced with a back-reamer. The pilot hole is then back-reamed (Figure 2-10), enlarging the hole to a desired diameter while pulling back the product pipe until it reaches the start point. During this whole process, a drilling fluid is injected under pressure ahead of the advancing bit. The drilling fluid will create a 'mud cake' along the wall of the borehole, thus stabilizing the borehole and reducing the friction during the pull back operation. Other services the drilling fluid provides are cooling of the electronics at the drilling head and suspending and transporting drill cuttings to the surface. At any stage along the drilling path the operator can receive information regarding the position, depth, and orientation of the drilling tool. This is done by the interpretation of signals sent by electronic sensors located near the drill head. Typical products installed using HDD include Steel, High Density Polyethylene (HDPE) or Polyvinyl Chloride (PVC) conduits, in addition to direct buried cables. During installation the pipe can encounter a combination of tensile, bending, and compressive stresses. The factors that will affect the strength of these stresses are the approach angle (angle between the drill stem and the ground surface at the entry point), bending radius, product diameter, length of the borehole and native soil properties. It is the responsibility of the project engineer to properly select the radius of curvature and the type of pipe to ensure these stresses do not exceed the product capacity during installation.

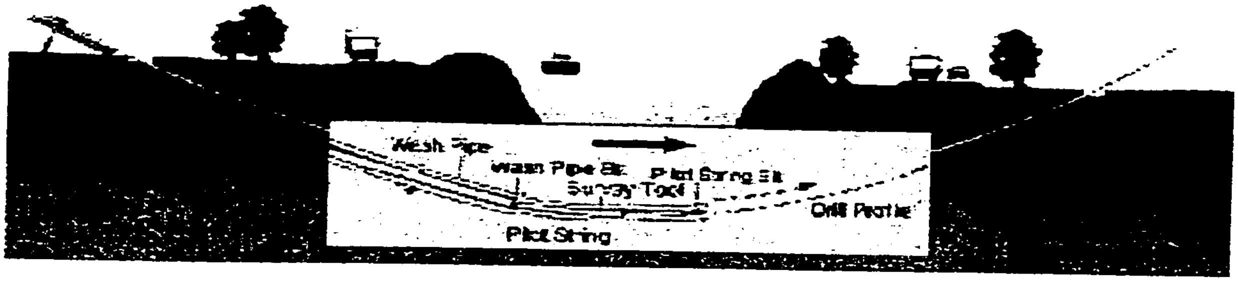

Figure 2-9 HDD Pilot Bore (DCCA, 1994)

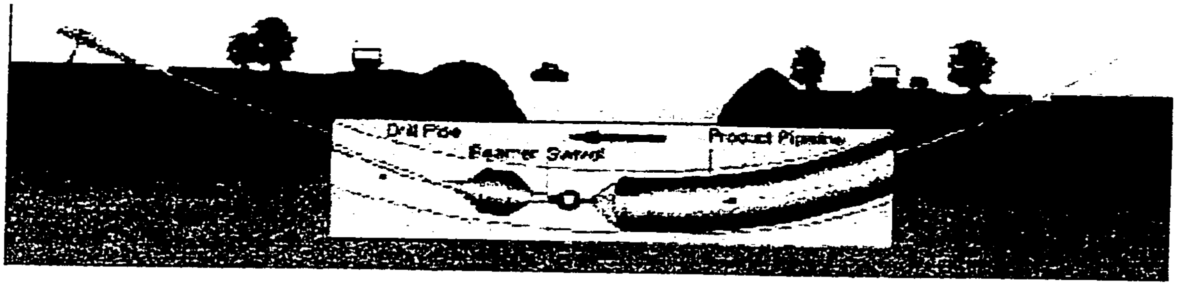

Figure 2-10 HDD Back Ream (DCCA, 1994)

The market for HDD includes many industries and the potential for many others. The installation of utilities in urban areas and across rivers and highways consumes the highest portion of the HDD market. Utility companies have used horizontal directional drilling mainly for the installation of new networks of power, natural gas and telecommunications. Other markets that have great potential for increasing HDD use are: municipal applications, pipelines, environmental applications, de-watering, pipe reaming, installation of cathodic protection systems and many other new promising applications are on the horizon.

Bennett et al. (1995) explain that drill heads (Figure 2-11) can come in many shapes and forms including compaction heads, cutting heads, and various other combinations. A compaction head is used for soft soils while a cutting head is suitable for tougher soils.

The slanted configuration for a drill head helps facilitate steering. The drill head also has openings for drilling fluid to flow through. The drilling fluid assists in cutting up the soil, borehole stabilization, drill pipe and transmitter sonde cooling, and drill pipe lubrication. Typically, a wider steering surface is used in soft soils (because of low resistance) and for hard soils a narrower steering surface is used (because of the high resistance provided by the soil). The reaming assembly consists of circular cutters, compactors, and swivels. Different types of reamers (Figure 2-11) are available including cutting, tri-action, compaction, barrel, blade reamers, or combinations. The soil condition will determine what specific type of reamer to use. As with drill heads, reamers have fluid jet openings that allow drilling fluid to flow, which will facilitate in cutting, stabilizing the hole, and lubricating the trailing pipe.

Figure 2-11 Drill Bits (top) and Reamers (bottom)

Although there are many upsides to using HDD there are also problems that can occur with the process. Allouche et al. (2000) discovered the most common problem encountered during HDD projects was loss of circulation. Simply put, this refers to the discontinuation of the flow of drilling fluids in the borehole between the location of the drilling-head/reamer and the entry pit. This loss of formation may occur because of a leak to the surface due to overpressurizing fluids in the borehole (otherwise known as a 'frac-out'). Another problem encountered in HDD operations is disturbances created by metallic objects or sources of magnetic fields on-site. These disturbances can create 'background noise' that can reduce the reliability of information obtained from the locating system. The presence of unknown buried obstacles is a risk that is present on every drilling project. Before any HDD operation can commence, locating existing utilities is a mandatory procedure. But, this procedure does not fully ensure that all possible obstacles will be discovered. Such items as existing utilities, cars, steel members, concrete, building foundations may be buried under the proposed utility installation area that could serve as a major problem once drilling has initiated. Other problems encountered during the HDD process include:

1. Breakdown of the drilling rig or the bending of the drilling rod. In most cases it can be attributed to operator error and can be alleviated by using scheduled maintenance and proper drilling practices.
2. Cave-ins of borehole can occur when drilling through unconsolidated formations (e.g. sand, gravel) or in locations where the ground water table is fast moving making it difficult to build a sound filter cake around the borehole wall.
3. Voids in the ground. There is really nothing that can be done to elude voids in the ground. Once encountered, if the void is small enough the drill string can be pushed across it, otherwise, the drill string should be withdrawn and a new alignment should be selected.
4. Inclement weather. There is nothing that can be done to alleviate this occurrence except proper gear and the availability of a sheltered operator shack.

The main concerns on any HDD utility project really boil down to these factors: location of existing utilities, local soil conditions, safety on site (e.g. traffic control), and accessibility. For environmental projects the main factors are type of contaminants, soil conditions, location of buried obstacles and location of plume. Most jobs will be a success if these factors are identified correctly and controlled properly.

The future for Horizontal Directional Drilling is very promising. A recent survey of HDD contractors found that over 80% were considering the purchase of new equipment and hiring of new personnel, and over 70% intended to increase their region of business (Allouche et al. 2000). The markets that can expect the largest growth in the industry are the utility and environmental markets, although all areas have great potential. One important consideration into HDD's growth is that because it is a relatively new type of construction there is major need to increase knowledge of this industry. With research and development, production rates can be maximized while obstacles and impediments can be better identified and rectified.

2.5 Review of Research on Soil Deformations

To date, there has been very little research undertaken on the effects Horizontal Directional Drilling has on the surrounding soil. Many industry players have gone on the notion that experience and 'a gut feeling' will be sufficient in judging the outcome of a drill. But when the stakes rise and the allowable judgement of error for a drill is miniscule, will the 'gut feeling' be enough.

Duyvestyn and Knight (2000) argue that the key to minimizing soil deformations above a HDD installed pipe is the use of good drilling fluids, drilling practice and borehole design. The design and engineering of a proper drilling fluid is dependent on complex interaction between:

1. Soil formation characteristics (include lithology, moisture content, and density).
2. Additives.
3. Make-up water.
4. Mixing equipment.
5. Bits and reamers and volume of soil removed from borepath and replaced with drilling fluid.

Duyvestyn and Knight (2000) focused only on the effects of pipe installation in cohesionless soil. The research included the condition of a pipe two years after installation. After cutting through one cross section of the pipe, it was evident from a picture taken that the outline of the borepath remained circular and no voids existed in the filter cake. The argument formed here is that because the drilling fluid was well designed, it exerted enough pressure onto the surrounding soil formation so as to minimize settlement above the pipe. Because no voids exist and the borepath remains circular, it leads one to infer that no settlement of the ground has occurred.

Further, to understand the causes of heaves and frac-outs, one needs to look at the pressure generated by the drilling fluid. Drilling fluid pressures can be separated into two components: hydrostatic fluid pressure and fluid pressure applied to create slurry flow out of the soil bore. When the fluid pressure exceeds the shear strength of the surrounding soil, the soil bore may fail through ground heave and/or inadvertent fluid returns (frac-out) to the ground surface. Therefore, one way to minimize ground surface movements is to use minimal fluid pressure throughout the entire soil bore and pipe installation and that the location of the bore, if possible, is at a sufficient depth below the ground surface to provide resistance to drilling fluid pressures. In addition, it is also possible to experience inadvertent returns and ground heave through subsurface discontinuity. At times, this may be difficult to discover prior to the drill but all avenues as to the prior use of the land should be investigated.

Duyvestyn and Knight's (2000) paper then turns to mathematical formulation and computer software to answer the question of settlement. Numerical simulations are used to characterize soil deformation trends for cohesionless soils and a computer program named FLAC, is used to simulate complex geomechanical structures that may undergo plastic flow when their yield limits are reached. Without divulging heavily into the logistics of FLAC, it works by representing materials as elements or zones within a grid. The behavior of each element is governed by prescribed linear or non-linear stress/strain constitutive relationships in response to applied forces or boundary constraints.

Duyvestyn sets up a simulation for the response of a 16 inch diameter soil void located at a depth of 6.6 feet to initial induced stresses with various applied soil bore fluid pressures. The simulated scenarios represent a worse case scenario because in reality the soil bore would be partially filled with a pipe. For this study, the soil is assumed to be homogeneous and isotropic with the vertical and horizontal stresses assumed to be equal in magnitude. Simulations are then conducted with applied pressures equivalent to 0, 2.5, 5.0, 7.5, 10, 15, 20, 25, 30, 40, 50, 100 and 125 percent of the effective vertical soil stress (for the scenario the effective vertical stress is 35kPa at a soil bore depth of 6.6 feet). The results that surface from the numerical simulations are:

1. When the applied pressures within the soil bore are less than 7.5 percent of the effective vertical stress, noticeable surface settlement deformations are observed.
2. When the applied pressure is greater than 7.5 percent and less than the effective vertical stress, insignificant surface soil movements are observed.
3. When the applied pressures are greater than or equal to the effective vertical stress the ground surface is observed to heave. The magnitude is proportional to the magnitude of the applied fluid pressure within the soil bore.

Once again, these findings generated from the use of FLAC only apply to the conditions stated above and numerous other assumptions needed to run the program.

Although they attempt to answer some questions in regards to soil deformations, there is actually very little proof or any substantial evidence to support or back-up any of his claims. For instance, he mentions frequently that the key to a good drill is the use of a good drilling fluid. What can be defined as a good drilling fluid? Because no two horizontal drills are alike, drilling fluid composition is constantly changing depending on the circumstances. It is relatively easy to say ‘use a good drilling fluid’, but extensive care and attention to detail are required in order to accommodate each drill. What makes a drilling fluid applicable and useable could be a research topic on its own. Furthermore, because the study only focuses on cohesionless soils, the findings have no applicability to cohesive soils. Because many drilling operations encounter cohesive soils, Duyvestyn’s findings are not at all applicable. More over, his work with a pipe installation into a cohesionless soil and cutting a cross section through it two years later, can be easily proved as an isolated case. This is true because he only used:

1. One cross section along the pipe to view what had happened and to make his judgements.
2. One size of pipe at a single depth.
3. One soil type.

There is a definite lack of quantitative figures and numbers that is absolutely necessary to back up his claims. Likewise, with the use of the computer program FLAC. Even though, FLAC (in a different form) has some potential for one day possibly being able to simulate the response of an HDD installation, it comes nowhere near that in it's current state. For a perfect condition where all the factors are known and there is no chance of any other possible extremities occurring, it may give the user a somewhat accurate reading. But, by the time this information is correctly gathered and compiled, the drill could be already completed. What really needs to be done is in-situ testing. Nothing can replace the results of experiments where a number of actual scenarios and conditions are played out. The results of these tests can be formulated and properly standardized, for use by future HDD users.

2.6 Review of Research on Ground Movements due to other Trenchless Methods

Concerns over ground movements in trenchless technologies are not isolated to HDD installations. Bennett and Cording (2000) studied the affects microtunneling had in relation to ground movements. Their study evaluated three microtunneling systems in a 100m long test facility through six different soil types. The ground movements were categorized as being large settlements, heaves, or systematic settlements. Their research looked at the impacts of geotechnical, operational, and geometric factors that influenced those movements. The results were as follows:

1. Large settlements occurred in two of the three-microtunneling tests. The settlements were blamed on operator error, improper machine setup, incorrect slurry mixture, and equipment malfunction.
2. Small to moderate heaves were measured at some locations on all three tests. The most common cause of heaves was overpushing or crowding of the machine into the face causing displacement upwards. (The heaves measured on these tests were below levels of serious concern.)
3. Systematic settlements were measured and calculated using the normal probability distribution curve. The results, in general, exemplified that the use of the normal probability distribution curve provided reasonable but conservative upper bound values for short-term settlement. The results obtained were that systematic settlements can be significant for large radial overcut (greater than 1 inch), large diameter pipelines (greater than 5 feet) with shallow ground cover (less than 3 times the diameter), and when tunneling through areas of fill or old utilities.

Therefore, as the results showed, ground deformations can be a very plausible occurrence on any microtunneling job. It is important to understand the potential of these ground deformations and identify and control all the factors that cause them.

Leuke and Ariaratnam (2000) discussed the effects that pipe bursting has on ground movements. The paper includes mention of many other studies that have been completed in this area. The results of their work and others in this area were developed by the use of theoretical equations, laboratory work, and surface field measurements.

At the Trenchless Technology Center at Louisiana Tech University, a study was conducted that focused on ground vibrations associated with pipe bursting. From this, they hoped they would attain a safe distance for installation of a replacement pipe from existing utilities. Their findings claimed that ground vibrations that occur in close proximity to the bursting operation quickly dissipated. In fact, it would not even cause cosmetic damage to buildings and in addition, it would also have negligible effects on buried structures and utilities. In other research, Swee and Milligan (1990) conducted laboratory tests to determine the effect pipe bursting had on soil movement and characteristics. By performing a scaled down bursting operation, the laboratory could be used to simulate an actual field pipe replacement. Through the use of transparent tank walls they could observe visually and through displacement markers, the ground movement in sand, clay, and a sandy-clay mixture. They discovered that the main factors that influence the severity of ground movements were the actual soil properties, geometry of the installation and drainage characteristics. Although both these studies introduced valuable information into the area of pipe bursting, both lacked the necessary results of an in-situ experiment. Only through an actual pipe bursting operation can the true results of soil behavior be discovered.

Leuke and Ariaratnam (2000) conducted a field study in an actual pipe-bursting project in Nanaimo, British Columbia, Canada. The project entailed the replacement of an existing 325 mm (outside diameter) asbestos cement line to a new HDPE line of 675 mm. Through the use of tilt meters and linear potentiometers, two sets of data were collected to measure actual ground movements at different depths above the replacement line. These numbers would then be compared to other numerical methods of calculating ground movements at different depths above the pipe. After completing the experiment and comparing the results, a common thread was noted. The closer the measurement was to the replaced pipe, the larger the magnitude of movement. This of course was proved previously but now the comparison of actual versus theoretical could legitimately be made. It was discovered that the numbers between them were very close and therefore these theoretical models could in fact be used to perform an initial assessment. With further data collection, these models could be better calibrated to prove even more accurate. In conclusion, the in-situ experiment helped validate current theoretical methods in place and with further data collection it could help in perfecting the models.

CHAPTER 3 DRILLING FLUIDS

3.1 Introduction

One of the vital and key components of any drilling procedure is drilling fluids. No vertical or horizontal drilling could be possible without the insertion of drilling fluids. Not only is their presence a necessity in a drill, but the correct volume and composition must also be correct to execute a good drill. This section will look into the history of the drilling fluid followed by the properties that define a drilling fluid. Then a look into the drilling fluid as it relates to HDD will be examined. Finally, problems associated with poor drilling practices (as it relates to drilling fluids) will be revealed and discussed.

3.2 History of the Drilling Fluid

Adams (1985) states that the first conception of using drilling fluids to remove cuttings from a borehole was by Fauvelle, a French engineer in 1845. His definition described drilling fluids as a broad range of fluids, both liquids and gases, used in drilling operations to achieve specific purposes. The first application of this drilling fluid was conceived for vertical drilling operations, where the fluid is pumped down the drill string, through a drill bit and returned up the annulus to the surface. It progressed, in later times, to perform many other additional functions (discussed in Section 3.2.1).

Selecting and maintaining the best drilling fluid (Bourgoyne et. al 1991), is an important step into the success of a drilling operation. When a problem does occur during a drill, the drilling fluid is related either directly or indirectly. The main factors that decide the selection of a drilling fluid are:

- The types of formation to be drilled in.
- The range of temperature, strength, permeability, and pore fluid pressure in the formation.

- The formation evaluation procedure used.
- The water quality available.
- Ecological and environmental considerations.

3.2.1 Purpose of the Drilling Fluid in Vertical Drilling

Adams (1985) discusses the purpose of a drilling fluid as it relates to vertical drilling. The major functions of the drilling fluid include the following:

- Cool and Lubricate the Bit and Drillstring – During the drilling operation, a considerable amount of heat due to friction is generated. Drilling fluids and the subsequent slurry created can help to transmit some of this heat to the surface as well as lubricate the wellbore.
- Clean the Hole Bottom – One of the most important functions of a drilling fluid is the removal of cuttings from below the bit. Cuttings removal is a factor of fluid viscosity, density of the cuttings, size of the cuttings, density of the fluid, fluid velocity and cross flow of the fluid.
- Carry Cuttings to the Surface – Transporting the cuttings, from below the drillbit, out of the borehole is essential for a mud system. It is critical for the fluid velocity in the annulus to exceed the downward falling rate, or slip velocity, of the cuttings. Important properties that affect a mud's carrying capacity include the mud weight, fluid viscosity, suspension, and gellation properties.
- Removal of Cuttings from Mud at the Surface – To prevent a high solids concentration buildup, drilled rock cuttings must be removed from the mud system at the surface. Mud pits alone do not allow sufficient time for solids to settle out. Using mechanical solids removal equipment such as shale shakers, desilters, mud cleaners, and centrifuges have proven effective in drilling operations.
- Minimize Formation Damage – The formation of a filter cake that allows the drilling operation to continue and protects a productive zone is an important consideration of a mud system. Several mechanisms can cause damage to the formation during drilling including clay swelling, solids plugging and emulsion blockage.

- Control Formation Pressure – Drilling intervals that have high formation pressures require the mud system to provide sufficient pressures to equal or exceed the formation pressure (the hydrostatic pressure of the mud system creates this). Not creating enough pressure can result in hole heaving, kicks, and blowouts.
- Maintain Hole Integrity – The drilling fluid must control such geological phenomena such as fractured zones, unconsolidated sections, hydratable clays, and pressured sections, so a drilled section can remain open and deeper drilling can proceed. Wellbores often exhibit stability problems when encountering these phenomena. In most cases, hole stability problems can be grouped as either heaving (mechanical problem) or sloughing (chemical problem) shales. Designing the mud system to maintain integrity of the hole after it has been drilled is the basis for selecting mud types and properties.
- Minimize Torque, Drag, and Pipe Sticking – Excessive torque and drag problems are common occurrences in drilling operations. The key is to select the proper mud system and additives, which can reduce the severity of torque and drag problems.

Other important functions of a drilling fluid include well logging, corrosion of drillstring/casing/tubing, contamination problems and improving the drilling rate. Due to various drilling operations and soils encountered, all functions will not be addressed on every vertical well. It is critical that those functions that may possibly play a role are properly identified and recognized. Then a mud program can be selected that focuses on satisfying the highest priority requirements first and then lower priority items, if possible, can be subsequently satisfied.

3.3 Drilling Fluid Properties

A drilling fluid can be defined by its properties. The properties tested in this research were executed by a Baroid Mud Kit. The properties, as well as the testing procedures, are defined as follows (Baroid 1999; Bourgoyne et al. 1991):

1. Funnel Viscosity – The measurement of the thickness of the fluid. It is measured with a Marsh Viscosity Funnel and is reported in seconds per quart. The test consists essentially of filling the funnel with a slurry sample and then measuring the time required for 1 quart of the sample to flow from the initially full funnel into the mud cup. Viscosity measurements are important in HDD but for different reasons than in vertical drilling. Gel strength and filtration are of more importance in horizontal drilling than is viscosity but viscosity is a by-product of achieving these properties. Because viscosity can also be defined as resistance to flow, it is important to consider that in HDD, the objective is to maintain flow. Therefore, it is important to achieve gel strength and filtration control than just adding bentonite (raising the viscosity). The objective is to design a 'skinny' fluid that will act 'fat'.
2. Gel Strength – The measurement of the suspension properties of a drilling fluid. Gel strength can be measured with a rheometer or shearometer and is reported in pounds per 100 square feet. The drilling fluid is responsible for suspending the solids and keeping them in suspension until they can be transported out of the hole. The resulting slurry (fluid and solids) acts like a conveyor belt to remove at least enough solids to make room for the product line. Gel strength is especially vital in coarse-grained soils. It is important to note that unlike vertical drilling, there is never an empty hole in HDD. The slurry aids in supporting the ceiling of the horizontal bore paths. Although, the solids will only remain in suspension to maintain the slurry with an adequate gel strength.
3. Filtration Control and Filter Cake – These two properties, although closely related, can be viewed as two separate properties. In sand, the filter cake is extremely important. The cake acts as a sealant, a grout or a stabilizing property of the fluid that maintains the integrity of the borehole. However, a good wall cake cannot be

obtained without an acceptable filtrate (water loss). The filtrate amount in sand comes second to the filter cake quality. In clay, the opposite is true. The filtrate quantity and quality is more important to prevent hydration, to keep the water phase from reaching the clay and allowing swelling to take place. In clay, the filter cake can be viewed as being incidental, however, a good, low filtrate volume cannot be obtained without a good quality filter cake. Filter cake and filtrate can be determined by a filter press, with filter cake being reported in 32nd 's of an inch and filtrate measured in cc's.

4. Fluid Density – In HDD, the density is used to measure the solids content of the fluid or slurry. The fluid density is calculated by use of a mud balance and is reported in pounds per gallon. The test consists of filling the cup with a slurry sample and determining the rider position required for balance. A formula is used to convert the density of the fluid or slurry to solids content [(Density - 8.33) X 8 = % solids (S.I. Units).]. Once this number is calculated it can be used in two ways. First, it can determine if the solids content is too high, indicating a need to turn up the pump, or if the pump is being fully utilized, the drilling or back reaming speed needs to be slowed down. Secondly, it can be used to measure the effectiveness of solids control equipment when using a recycling system.
5. Sands Content – Determines the amount of sand that is in the fluid or slurry. The sand content is simply a determination of solids larger than 200 mesh that are entrained in the fluid. Sand content can be measured with a sand content kit and is reported in percent of total volume.
6. pH – This is used as an indicator of water quality. It should be used to test water quality as is the practice in all drilling practices. Low pH may signify the presence of calcium. If the pH requires adjusting this can be accomplished by using soda ash (calcium carbonate). pH can be measured using pH indicator strips, papers or meters.
7. Lubricity – Aids in pipe installation by reducing the friction between the pipe and the soil. Maximum lubricity is always desired.

To create the optimal drilling fluid, each one of the above factors must be considered. Undoubtedly, the native soil will decide first and foremost what type of drilling fluid is required. Once the native soil is properly identified, the right type of drilling fluid can be chosen and then quantified for optimal performance.

3.4 Drilling Fluid for HDD Applications

As was stated before, Horizontal Directional Drilling evolved from vertical oil well drilling. The importance of drilling fluids for vertical drilling also applies to HDD. However, a drilling fluid property that is used in vertical drilling could be detrimental or used differently in HDD. For HDD, the drilling fluid mixture relies heavily on the soil encountered. Baroid (1999) states that for general purposes we encounter two different soil types. Either a coarse soil (sands and gravel) or a fine soil (clays and shale). When drilling through sand and gravel it is important to recognize that a drilling fluid needs to serve two important functions. First, the drilling fluid must remain in the hole and the second function is to provide suspension characteristics or 'gel strengths'. When drilling through clay, the same functions might also need to be performed, but the main purpose of the fluid will be to help the clay or shale retard swelling and reduce sticking of the soil to the product line. All in all, each soil type requires different combinations of drilling fluid. In general, for coarse soils we need a bentonite or a bentonite/polymer mix, while for fine soils we need a polymer or a bentonite/polymer mix.

When drilling horizontally it is imperative that the drilling fluids remain in the hole to provide its necessary responsibilities. Those being:

1. Assisting in cutting up the soil
2. Help liquefy and stabilize the soil on the borepath
3. Aid in the removal of solids from the freshly cut hole by it's flushing action.
4. Reduce torque associated with sticky surface conditions
5. Drill pipe and transmitter sonde cooling

6. Drill pipe and product pipe lubrication.

When drilling through sands and gravel (and possibly some fine soils), water will flow right through the native soil. This is where bentonite plays a role.

Bentonite is a clay. When added with water it becomes a mud. Robinson (1985) shows that when bentonite is mined, the clay platelets (flat plate-like particles) are closely compressed and have very little water between them. An 'aggregate' is a unit of stacked clay platelets. When water enters between some of the clay platelets, it immediately causes it to disperse, separating the clay platelets. These platelets are very small. In fact, Baroid (1999) states that if you take one cubic inch of bentonite and mix it until it's broken down to a platelet, you have enough surface area to cover 66 football fields. When the bentonite fluid is pumped into the hole under pressure, the fluid, just like water, wants to flow through the sand or gravel. However, in this case the bentonite platelets will start to plaster or shingle off the wall of the borehole and form a filter cake that cuts off the flow of the fluid into the native soil. The water that does manage to filter through the cake is termed the 'filtrate'. The filter cake quality can be improved by reducing the amount of filtrate going into the surrounding soil. This can be accomplished by one of two methods. Adding more bentonite (more platelets) or by using certain polymers in conjunction with bentonite to tighten the filter cake. It is more optimal to use the bentonite/polymer mix because it is a more pumpable fluid and more slurry will flow.

In addition to providing a cake layer, Baroid (1999) states that the drilling fluid must provide suspension characteristics or 'gel strengths' in sand and gravel. Looking at a bit or a reamer, the first function they perform is cutting up the native soil. But, they also serve a very important secondary function. That function being responsible for mixing the soils that are being cut into a flowable slurry with the fluid. The drilling fluid has to be able to support, suspend and carry these cuttings. If the fluid can not suspend the drilled material, that material will quickly pack off around the drill rods or even more dangerous, around the product line being pulled. Even if the fluid has a high viscosity (thick fluid) it may have very low carrying capacity (gel strength). This is why gel strength is more important in drilling than is viscosity. Therefore, because water on its own has low viscosity and no gel strength, and because polymers on its own have high viscosity but low gel strength, bentonite is needed to provide the carrying capacity that is required.

Another important consideration in addition to keeping the fluid in the hole (filter cake) and having good carrying capacity, is the subject of flow. When slurried spoils are flowing out of the hole either from the exit or entry side, we know that there exists an open borepath. Accordingly, if there is an open borepath, this will ensure that the drill rig or the product pipe will not get stuck. That is why the flow of the slurried spoils is so very important. When good and constant flow is maintained, the odds of getting stuck are very low and therefore good practice recommends maintaining good slurried flow on both the bore and the backream. The volume of drilling fluid to maintain flow really depends on the soil. Because sand is inert, it will not swell or get sticky. Therefore, a good flowable slurry in sand according to Baroid (1999) may be accomplished with 1 to 1.5 gallons of fluid per gallon of soil. On the other hand, clay is a reactive soil. It will swell and get sticky. Therefore, 3 to 4 gallons (or even more drilling fluid) are required per gallon of clay soil in order to maintain flow. Another important consideration is the annular space. The annular space can be defined as the distance between the outside diameter of the product pipe or drill pipe to the wall of the borehole. This space is used by the cuttings to reach the surface. There must be enough space here to allow proper flow to occur. A phenomenon called 'hydrolock' occurs when flow is lost and a hydraulic cylinder is created in front of the reamer/compactor/product line that can exert more pressure than your rig has thrust. Hydrolock can only occur if flow is lost. As long as there is flow through the annular space, there exists a pressure relief pathway. To maintain flow and prevent hydrolock from occurring, it is important to:

1. Pump enough fluid to maintain flow.
2. If needed, slow down the speed of the backreamer.
3. Only use compactors in compactable soils.

4. Pre-ream to condition the spoils into a slurry if dense clays are encountered.
5. In clay use a chopping type reamer to prevent blockage behind the reamer.

One point to keep in mind is not to force too much fluid into the borehole. If the space can not handle the volume of fluid entering the hole (in addition to the soil and product line), a 'hump' can be created on the surface that would not desirable when drilling underneath a highway for example. Because every individual soil type has different properties, drilling fluid composition and quantity must be correctly calculated to conform to the soil.

3.4.1 Annular Flow

As mentioned in the previous section, maintaining flow is an important step into the success of an HDD pipe installation. As long as there is flow in a borehole, the pipe will not get stuck. To calculate the annular flow in a borehole, the following formula is used (Baroid 1999):

$$Va = \frac{1029.4 * PO_{BPM}}{ID^2_{HOLE} - OD^2_{DP}}$$

Va = The Annular Velocity (Feet/Minute)
PO_{BPM} = Pump Output (Barrels/Minute)
ID_{HOLE} = Diameter of the Borehole (Inches)
OD_{DP} = Drillpipe Outside Diameter (Inches)

Note: The pump output on the 24*40A rig has two pumping outputs (measured at ideal conditions at sea level)(Vermeer 2000):

During drilling: 0.476 bbl/min (19gpm) (minus 25% for actual flow).
During backream: 0.905 bbl/min (38gpm) (minus 25% for actual flow).

(The annular flow results for the backream are listed in Appendix B).

3.5 Improper Application of Drilling Fluids

What can happen when the contractor:

- Does not understand the properties of the native soil?
- Does not understand drilling fluid additives and their usage?
- Does not understand how to effectively operate HDD equipment?
- Does not investigate, prior to drilling, the prior use or soil strata of the proposed site?

Nothing, possibly. Yet, on the other hand, there can be total ruin. The results of an HDD drill are never really quite known. But, proper precautions can be taken beforehand to avoid the potential of any negative results. These precautions involve understanding everything that was mentioned beforehand. Learning the properties of each individual component and how they operate as a unit will lessen the chance of any detrimental effects. In Figure 3-1, the results of not understanding how to properly install a pipe using HDD are revealed. In this case, the contractor installed the pipe at too low a speed with too much drilling fluid entering the borehole. This created too much pressure within the hole and then subsequently in-turn released, by 'popping up' or 'humping' the road above. In this case, the road was in a residential area but what if this occurred in a busy street? Or underneath a monument or an inhabited building? The costs and time associated with repairing the damage could be detrimental.

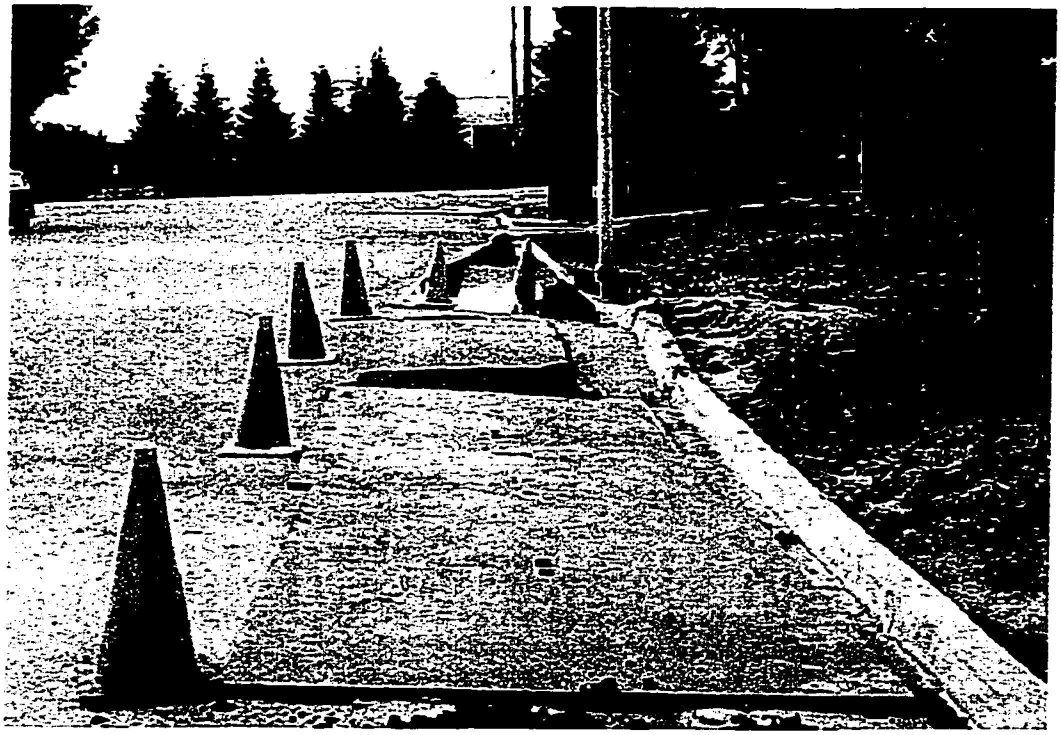

Figure 3-1 Effects of Improper Application

The important note here is that there are many ways to mangle a pipe installation using HDD. Too much drilling fluid, not enough drilling fluid, not the right components of drilling fluid, not understanding the native soil, not understanding the reaction of the native soil to the drilling fluid etc.. The list goes on and on. What's important is to be informed. Understand all the elements of the drilling operation. Understand the properties and capabilities of the:

1. Native Soil
2. Drilling Fluid
3. HDD Rig
4. Drilling Head, Reamer, Installed Pipe
5. Any Extraneous or Special Factors

If these factors can be controlled and properly understood, the success of the pipe installation can be achieved.

CHAPTER 4 FIELD EXPERIMENT

4.1 Introduction

To simulate an actual pipe installation using Horizontal Directional Drilling, an in-situ field experiment was deemed the only plausible method of simulating a real drill operation. A laboratory experiment was another option that was considered, however, it would prove too difficult because of the inability of current methods to replicate an installation. Ultimately, nothing can replace the performance of an actual drill and it was therefore decided that this would be the method for analyzing the annulus. To invoke upon a pipe installation using HDD and to retrieve all pertinent data, requires the collaboration of numerous people, instruments, and equipment. It also entails a lot of pre-installation planning so as to avoid any pitfalls and to have back-up contingencies in place, in case of unforeseen problems surfacing. The procedure we used to investigate the annulus will be covered in this section.

4.2 Procedure

A properly formulated procedure was an important step into the success of the research. To create and then execute a planned procedure would ensure that resources would be properly used and that the desired data would be retrieved. The procedure would have to include an itemized list of all activities, resources, people, equipment, and schedule of activities to occur. The major components of the procedure would include:

1. Initial Planning and Organization
2. Set-up
3. Pre-Installation
4. Installation
5. Post-Installation

4.2.1 Initial Planning and Organization

The integrity of the annular space has been in question since the induction of HDD. There are those that argue for it's capability in supporting a utility network and there are those that question it. No research to date has proven outright either side of this issue. Albeit, there are many extraneous factors that may actually affect the annular space in a pipe installation, but it is impossible to simulate every real world drilling occurrence. It is more practical to focus on those factors that play a direct role in influencing the stability of the annulus in every drill. These factors are:

1. Native soil.
2. Pipe Size and Type.
3. Drilling Fluid Composition.
4. Drilling Equipment.

To gain an understanding of the annulus, each influential component must be analyzed individually and then assessed on how it reacts together as a system. It is also important that these factors are varied and changed. How much validity can there be in passing judgement on the annular space through the installation of one drill? By drilling through a range of scenarios, there is better justification in developing an answer to the integrity of the annular space. However, because of the high costs and time intensive procedure installing pipes using HDD, a plan was devised to minimize the amount of drills performed, but maximize the amount of data collected. The plan for minimizing the number of drills was based on:

- Native Soil – 2 different soil types were selected: clay and sand. Two different sites were needed to accommodate the two different soil types.
- Pipe – The majority of all pipe installations using HDD are High Density Polyethylene (HDPE). The decision was to use this same type of pipe but vary it size (diameter) to: 100mm (4"), 200mm (8"), and 300mm (12") at a length of 61metres (200 feet) for each pipe. The depth of installation would be 0.61metres (2 feet) for the 100mm, 0.91 metres (3 feet) for the 200mm, and 1.22 metres (4 feet) for the 300mm.

- Drilling Fluid – This would vary based on the type of soil being drilled. It was important to incorporate and replicate the same drilling fluids and resulting annulus that would be created from any real world HDD pipe installation. Quality control of the mixture was maintained by an on-site Baroid representative.
- Drilling Equipment – The drill rig would stay constant throughout the drilling procedures but the drill head and backreamer would change accordingly, to accommodate the size of pipe.

All in all, this necessitated the installation of three HDPE pipes at each of the sites for a total of six pipes installed altogether. By installing this many pipes, there is enough variance in each installation that if a common thread is found, it may be enough to substantiate a proclamation on the annulus.

The next step was to tender out this work to a viable contractor. In addition to installing the six pipes, the contractor had to perform other duties including:

- Fusing the 200mm and 300mm pipes on site.
- Returning to excavate sections of the pipe. This would occur at 1 day, 1 week, 2 weeks, and 4 weeks post-installation.
- Their input and expertise in drilling on different sites.
- Numerous other miscellaneous tasks to help with the data collection.

Once the contractor was selected, two different sites were secured for drilling. In the next while, meetings were held to explain the initiatives and goals set out for this research. The meetings included the contractors, a Baroid representative, geotechnical experts, Trenchless Technology experts, and other graduate students; to bring everybody focused on what was trying to be accomplished. Information from each specific party's expertise was gathered from these meetings and combined with the initial objectives, to create a schedule and a plan of construction.

The initial role that I undertook (in this first step) was to gather information from all sources involved. First, information was gathered from the HDD industry in terms of what research could really benefit the industry. A common wish and desire was to prove that an HDD installation provided a suitable environment and adequate support to the pipe. It was decided at this point that the focus of the research would therefore be on the annular region, and more specifically, the results of the annulus through current installation methods. After the decision for the focus of the research was made, it was my role to decide how we would embark upon this assessment. Through consultation with my supervisor, Dr. Ariaratnam, we decided that assessment should occur through an actual pipe installation. It was felt that creating an actual pipe installation, whereby a contractor would install the pipe as if he would for any real world installation, would provide the results we were trying to study and ascertain. This would include the contractors normal method of installation including equipment, workers, drilling fluids and any other factors that would be incorporated. Moreover, part of the focus of the research would be to analyze the make-up of the annulus (slurry). It was suggested that a Baroid Mud Kit could be used to define the properties of the annulus. Therefore, I set up a system for sample retrievals that would allow adequate comparisons between the pipe installations and to evaluate how these samples changed within the course of a drill. Furthermore, once the installation of the pipes did occur, a method to investigate the annulus was required. We decided that periodic cross-sectional excavations to below the depth of the pipe would allow a proper assessment to occur. Once a cross-section was excavated, I would then be able to conduct my assessment. I devised an assessment plan that would occur at each installation thereby allowing comparisons to occur with subsequent excavations. In addition, other methods were sought for quantifying the annulus. Through the consultation of geotechnical experts, their recommendations for quantification were compiled and gathered. Their recommendations included the incorporation of various geotechnical instruments and testing. After gathering all the information from these various sources, an initial plan was developed.

4.2.2 Set-up

To accomplish all the objectives that were set out, some thought had to be given on how to effectively set-up the 'in-situ laboratory' outdoors. Wind, rain, sun and any other of Mother Nature's offerings could play havoc for data retrieval. Consideration for this and many other factors were thought over before deciding the set-up. The one important point I kept in mind was that our plan should remain flexible, in case we discover something while drilling that would cause us to revise our methods. Because the experiment that was planned had never been done before, we could not fully guarantee everything would work out properly. The set-up was as follows:

- The pipe installations would occur side by side at a spacing of 5 meters. The first day of drilling would see the installation of the 100mm and the 200mm pipes. The next day would be the installation of the 300mm. Enough space had to be provided to allow room for all the equipment to set-up: drill rig, water truck, drilling fluid truck, backhoe etc. (each site had ample space for set-up).
- To test the drilling fluid and mud samples, a Baroid Mud Kit would be set-up at the back of a pick-up truck. The kits are very mobile and require little set-up time. The truck provides enough space (acts as a table) and would be placed adjacent to the drill. An entry and exit pit would need to be excavated to allow for sampling.
- To complete the other objectives requires little or no set-up time except the means to dig out a section of the pipe and to have all instruments ready for use.

The actual set-up for the research was not very extensive, but proper placement of all equipment would allow for a more efficient operation. Figure 4-1 shows the set-up for the first site of installation, which was the clay site. The stakes mark out the location of each pipe.

Figure 4-1 Clay Site

Once the set-up had been rationalized, achieving my objectives could be accomplished through the use of specific methods defined for each activity. Each procedure invoked a resource (instrument, people etc.) used to accomplish the objective; therefore care and precision were absolutely vital. What my goals were and how I achieved them can be split into pre-installation, installation, and post-installation.

4.2.3 Pre-Installation

Before installation of the pipe commenced, there were a number of activities that were performed. Firstly, stakes were set-up to spot the location of installation for the pipes. They had to be set out far enough to not interfere with each other (5 metres was used). The next step was to mobilize all the equipment on site. This included the drill rig, backhoe, drilling fluid tank, water tank, and the pipe. Equipment accessories such as drilling heads and backreamers would also have to be transported to site. The 100mm pipe arrived on site in a spool but the 200mm and 300mm pipes came in 15.2 metre (50-foot) sections. This pipe would have to be fused with a hot plate while the preceding pipe was installed (100mm installed first, 300mm last). The next step was to dig up the entry and exit pits. This would allow for sampling of the slurry as it exits the borehole. At the same time, the Baroid mud kit would also be set-up right adjacent to the drills. This would allow for quick analysis once the samples were retrieved. The final step would see the mixture of the drilling fluid, with the addition of 3400 litres (900 gallons) of water, bentonite, and other Baroid mixing products. Once the drilling fluid was properly proportioned and mixed, drilling could now commence.

4.2.4 Installation

Installation commences with the start-up of the drill rig and the insertion of the drill head into the ground. Drill rod by drill rod, the drilling continues until the target of 61 metres is achieved. The operator performs the pipe installation just as he would for any HDD installation, thereby replicating a real drill operation. During drilling, set-up of the backream takes place. This includes setting up the reamer and product pipe at the exit pit, so it is ready for installation (fusing occurs prior to this for the 200mm and 300mm pipes). Once the drill head reaches the exit pit, the drill head is removed and the reamer is attached. The size of the reamer is 1.5 times the size of pipe installed. Once the reamer is attached, the pull back can begin. On many occasions, this may necessitate a new tank of drilling fluid to be mixed. The important consideration here was that flow had to be maintained in the borehole, therefore enough fluid had to be inserted and available for use. In addition, for the 300mm pipe installation a pre-ream was performed on the hole prior to backreaming. A pre-ream basically involves drilling an extra 61 metres above ground (in addition to the 61 metres drilled underground) and attaching a reamer at the end of the drill. The pullback begins with the pre-reamer enlarging the hole and removing a lot of the soil that the backream would otherwise have to come in contact with. The pre-ream basically eases the stresses that the reamer and the pipe face on its own. Once the pre-ream reaches the entry pit on the other end, the pre-ream reamer can be removed and the backream can now begin. The backream continues until the reamer reaches the end and the pipe is installed. During drilling and backreaming, a DigiTrack was used to make sure that the pipe stayed in the proper alignment and depth. A DigiTrack uses electronic signals sent from a sonde installed in the drill head or reamer, and can tell the user the exact location of the drill/backream. This would be accomplished by having somebody follow the sonde in the drill head/backream throughout the entire installation above ground. If the pipe is misaligned, the operator can then be notified and he can adjust his rotation or his push/ pull accordingly. In a typical drilling week, the 100mm and 200mm pipes could be installed in one day, and the 300mm pipe occurs the following day.

During the installation, my role was to gather samples from the mud tank and from the returns in the entry/exit pit and to analyze these samples. During sample retrieval, it was important that I followed a quality control procedure, whereby the correct samples would be retrieved for analysis. This would mean ensuring that the samples were from the correct locations and that they were the actual returns from that location. After the correct sample was retrieved, I would then conduct the mud kit analysis (section 4.3 on Instruments Used and Tests Performed will describe the procedure). This would approximately take between 25 to 30 minutes to complete for each sample. Proper execution along with a thorough clean up of sampling tools (for the following sample) would ensure that proper data would be retrieved. For each installation five samples were retrieved for analysis.

4.2.5 Post-Installation

Once the installation of a pipe is achieved, it remains untouched until the next day. Because the 100mm and 200mm pipes were installed in one day, they were both excavated the following day after the installation of the 300mm pipe. It was felt that the one-day excavation for the 300mm pipe was not necessary because the annulus was still relatively 'raw', and indication of the state of the annular space could be observed sufficiently enough through the 100mm and 200mm pipes (the costs associated with having the contractor return to site for a single excavation were not warranted). After the initial one-day excavation, the pipes are excavated collectively one week, two weeks, and four weeks post-installation. Excavating the cross-sections collectively in one day helped to minimize some of the costs paid to the contractor. The cross-section excavations commenced a few meters from the exit pit side of the pipe and would continue towards the entry pit on subsequent excavations. All the excavations are accomplished via a backhoe with the help of a labourer with a hand shovel. A backhoe was used to excavate to about 0.3 metres (1 foot) below the depth of installation and then the hand shovel was used to dig around the pipe. Once the area was excavated, a saw-cut was used to cut through the exposed pipe. Once the pipe had been cut, it was removed which left an open cross section to analyze the annulus.

The first step I conducted was to visually inspect the annulus. This meant getting into the trench and viewing the annular space from a very short distance while noting down any physical features it exhibited. This alone was a very important step because many have hypothesized about the short-term post installation state of the annulus yet very few have had the opportunity to actually view the annulus up close after a drill. Therefore it was very critical that every detail was studied, analyzed and photographed to get a better appreciation for the annular space. Particular reference would be made to see:

- The placement of the pipe in relation to the annular space.
- If a zone of influence existed that extends past the annular space.
- The existence of voids in the annular space.
- The depth to the crown of the pipe.
- The state of the annulus in terms of fluidity (i.e. was it still a flowable material or did it exhibit some compactive strength), texture, composition etc.

Once the visual examination of the annulus occurred, I then performed various geotechnical in-situ tests. The in-situ tests were preferred over the laboratory tests due to the fact that the change in environmental conditions (i.e. pressure, moisture content) and the disturbance of the samples when extracted, handled, and subsequently tested can greatly influence the test data. The goal was to perform most of the testing on site and minimize any laboratory testing. The in-situ tests were needed to quantify the annulus and possibly validate some theoretical hypothesis. These tests included:

- Pocket penetrometer Test
- Vane Shear Test
- Moisture Content (laboratory test)

(A better description of these tests is provided in Section 4.3 Instruments Used and Tests Performed)

These tools will aid in determining what the actual strength of the annular space and adjacent native soil are through time. Determining this will be absolutely vital.
Before backfilling the open pit, samples were periodically taken for possible future testing. These samples were placed in a cylinder and await further examination. Once the backfilling was complete this concluded all work that was completed on site.

4.3 Instruments Used and Tests Performed

The post installation visual inspection of the annulus was a critical step towards a better appreciation and understanding of the annulus. Proper documentation and illustration of what was observed would be very important when trying to establish any patterns or relationships. But, the use of instruments and associated tests would aid in validation as well. They would help by adding a quantifying factor to the annulus. By now being able to associate numerical figures to the annulus, any results or patterns can be easily produced. The important consideration was to properly use the instruments and execute the tests correctly.

4.3.1 Pocket Penetrometer

Cernica (1995) describes the penetrometer as a test used to measure the shear strength of the soil at the surface (lateral or vertical). Their use is primarily for fine-grained soils and therefore was only utilized at the clay site. Their use with coarse and gravelly sites tends to give erroneous results and therefore are not used. The procedure for using the penetrometer involves:

1. Cleaning the surface to be tested of any loose materials.
2. Pushing the penetrometer into the stratum to the calibration mark on the head of the penetrometer.
3. Recording the maximum reading on the penetrometer scale.

The reading represents the pressure in force per unit area necessary to push the penetrometer to the designated mark. In our test, the unit used was kg/cm^2. Below is Figure 4-2, which displays the actual Pocket Penetrometer used for testing.

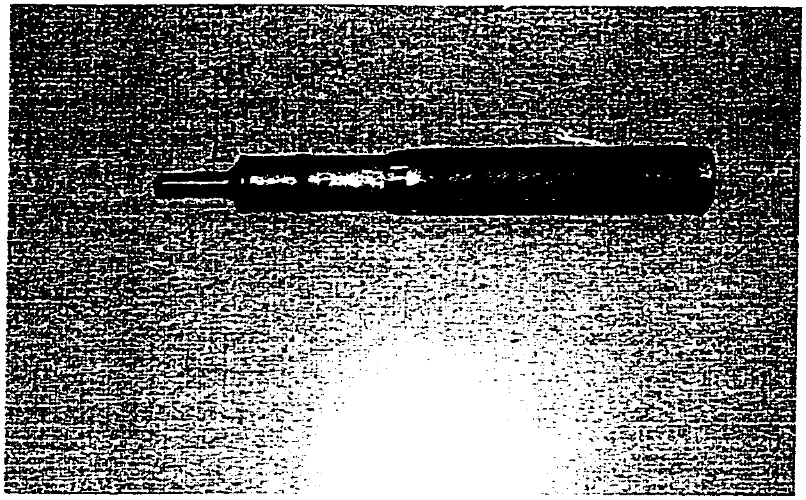

Figure 4-2 Pocket Penetrometer

4.3.2 Vane Shear Tests

The Vane Shear test is also used to calculate the shear strength of soils in situ. The instrument consists of a rod with radial vanes. The rod is carefully pushed into the stratum to be tested. The torque is then applied gradually with the peak value being noted. The shear strength (S) of the soil was calibrated into the Vane Shear and given in Kpa. In Figure 4-3, the Vane Shear used for testing at the clay and sand site is shown.

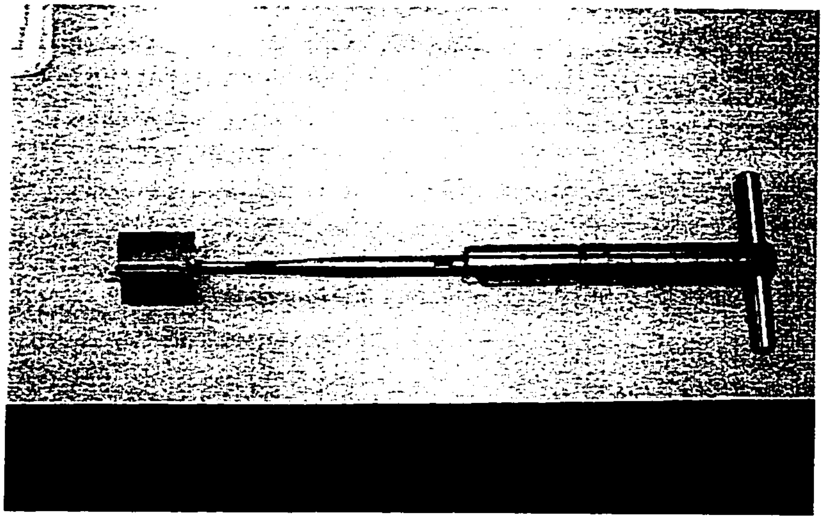

Figure 4-3 Vane Shear

When evaluating the results of the vane shear and penetrometer tests, it is important to note that the soil is not completely uniform throughout. It may naturally exhibit different shear strength characteristics in various planes and for different moisture contents. Therefore, it is important to note that the two techniques may or may not reflect the true shear strength of the soil in all directions. As well, because it is not uniform, the shear strength characteristics through time may be affected by what plane we are testing on.

4.3.3 Moisture Content

The moisture content is defined as the ratio of the weight of the water to the weight of the solid particles. The sample is first weighed and then placed in a hot oven overnight. The next day the sample is again weighed, this time with all the water evaporated. The moisture content is then calculated in percent.

The water content in sands is generally between 10 and 30%, while in clay it can range from less than 5% to over 300%. The importance of water content in a soil mass can not be understated. The water content can have a significant effect on some of the characteristics and behavior of that soil. Especially in fine grained soils where a high water content can greatly reduce the shear strength of the clay stratum.

4.3.4 Drilling Fluid and Slurry Analysis

As mentioned previously, the drilling fluid and slurry analysis would be accomplished using the Baroid Mud Kit (S.I. units). The basis for performing this evaluation is striving to obtain an optimal drilling fluid matched for that drilling application. By examining the results of the analysis, one can better understand how the drilling fluid is performing and if need be, what adjustments are required. The mud test involves the calculation of:

- Density – Measured in lb./gal. Calculated with the use of a mud balance.
- Funnel Viscosity – Measured in Seconds/Quart. Calculated by measuring the time required to fill one quart of a container by passing the drilling fluid/mud through a marsh funnel.
- pH - Measured with pH strips.
- Sand Content – Measured in Percent of Total Volume. Calculated by a simple determination of solids larger than 200 mesh that are entrained in the fluid. Sand content can be measured with a sand content kit.
- Gel Strength – Measured in lb/100ft^2. Calculated through the use of a shearometer, which basically involves dropping a 5-gram cylinder through a calibrated measuring device.
- Filtrate and Filter Cake – Filtrate is measured in cubic centimeters and the filter cake is measured in 32nd 's of an inch. Calculated through the use of a filter press. The press applies a 100 lbs. of pressure to the sample in a 7.5-minute time span. After the time has expired, the amount of water collected in the graduated cylinder is the filtrate and the thickness of the sample collected on the filter paper is the filter cake.

(A more thorough explanation of these terms was detailed in Section 3.3 Drilling Fluid Properties.).

Normally, 5 samples would be taken for analysis for each drill. Additionally, any related notes in regards to the performance of installation would also be attached to the sample. In Figure 4-4, the set-up of the field mud kit along with all the instruments is displayed.

Figure 4-4 Field Mud Kit Set-up

4.4 Equipment

The equipment was the collection of all the devices required for a Horizontal Directional Drill. Each component has a vital role in executing an installation. The operation of some of this equipment requires skill and experience, which would have to be a reflection of the contractor. This section would cover the entire compilation of equipment used.

4.4.1 Drilling Rig

The drilling rig used for all the installations was a Vermeer Navigator D24 X 40A. The features for this rig is that it carries 23,800 lbs of thrust/pullback with 4000 ft*lbs of torque ability. The rig can automatically tie all the rods together thereby limiting the need for an extra installer. Lack of mobility is not an issue with the tractor type conveyance, which allows it to work in any location. The drilling rig is obviously the key piece of equipment required in a HDD installation. Below is Figure 4-5, which displays the actual Vermeer drilling rig used.

Figure 4-5 Drilling Rig

4.4.2 Drill Bits and Reamers

The tooling used was a combination of standard drill bits and back reamers. The drill bits were a Vermeer model - Hardface Standard Bit (Figure 4-6) which are designed for longer life in abrasive soil conditions like hard packed sand (it is also able to function in other types of soil such as clay or caliche). The narrow head offers excellent steering ability in most soils. The reamers that were used for backreaming were a Vermeer model – Fluted Reamer (Figure 4-7) that are able to cut, slurrifie and displace soil to the backside of the reamer with a drilling effect. The carbide-tipped cutting teeth provide effective cutting action in tough soil conditions. It may be used in most type of soil conditions (Vermeer Product Guide 1999).

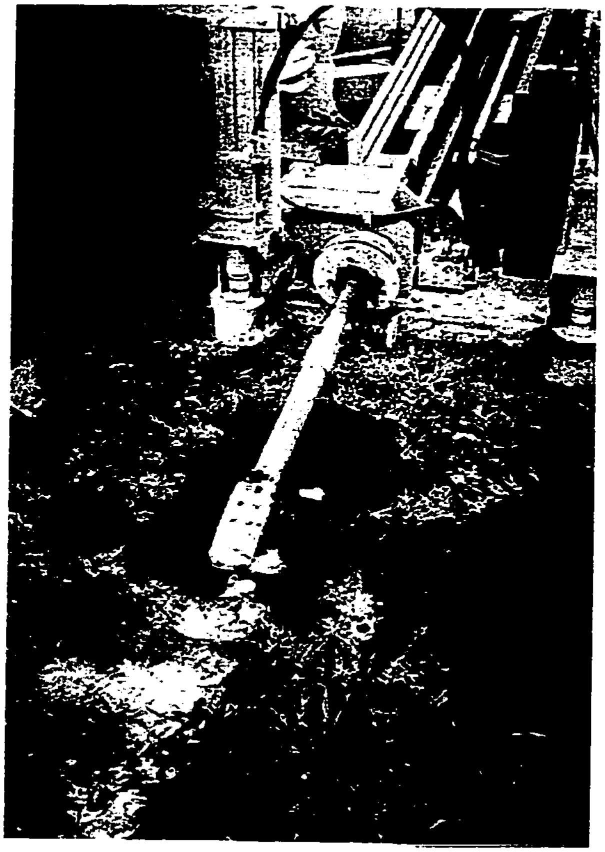

Figure 4-6 Drilling Bit

Figure 4-7 Reamer

4.4.3 Backhoe

The backhoe/front end loader was an absolute necessity on the jobsite. It performed many miscellaneous tasks that helped minimize the use of shovels or strenuous manual work. These tasks included:

- Digging up entry/exit pits.
- Placing the pipe for entry into the ground at the exit pit.
- Digging up the cross-sections and then subsequently pulling out a small cut portion of the pipe.
- Backfilling all excavated material.

4.4.4 DigiTrak

The DigiTrak Mark III locator (Figure 4-8) was used for all installations. It presented to the contractor the ability to know the continuos depth and location of the drill/backream, the rotation of the drill head, and the temperature of the sonde. The importance of this information can not be understated when drilling in an area that has other underground infrastructure. It allows the installer to execute the drill as it was designed for and to avoid any possible collisions with existing services.

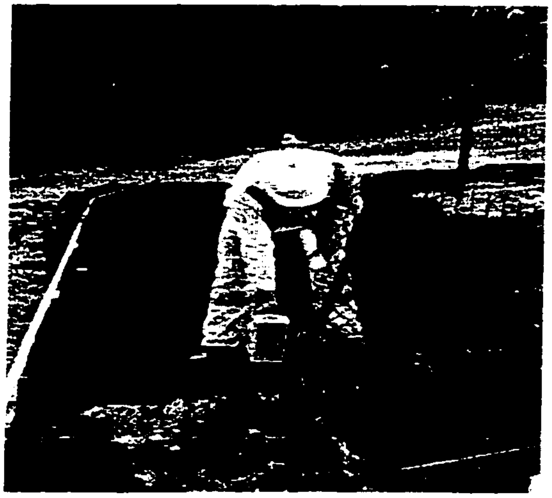

Figure 4-8 DigiTrak

4.4.5 Mud Tank

The mud tank is where the drilling fluid is concocted. Through the use of a hopper the drilling fluid components are added and then vibrated until it is properly mixed. The capacity of the tank used for our drills was 3785 litres (1000 gallons). The use of a hopper allows for easy insertion of water, bentonite, bore-gel or any other drilling products. In Figure 4-9, the mud tank that was utilized at both sites is displayed.

Figure 4-9 Mud Tank

4.4.6 Water Truck

The purpose of a water truck on a drilling site, is a source of water for the drilling fluid mixture when other sources of water are not available. A water truck is a mobile and controlled source of water with a carrying capacity of 11,350 litres (3000 gallons) (for the model used on our jobsite).

4.4.7 Fusing Plate

The fusing plate (Figure 4-10) is basically a hot plate that joins two ends of a pipe. Because it is unpractical to form and transport long sections of large pipe, it is more sensible instead to cut the pipe into smaller pieces and fuse it together on site. The operation of a fusing plate is a relatively simple process of cleaning and smoothening both ends of the pipe and then through the use of heat, molding them into one continuos pipe.

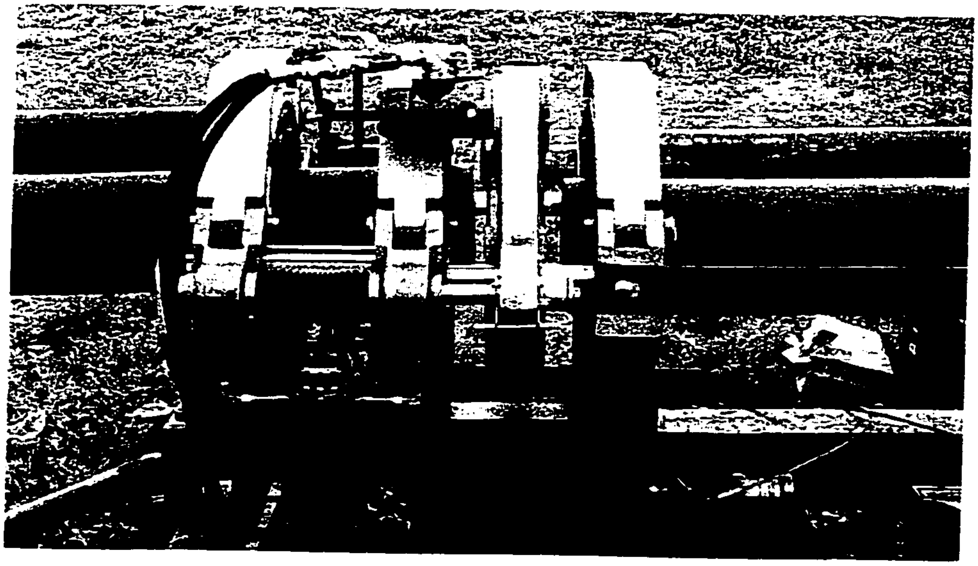

Figure 4-10 Fusing Plate

4.5 Summary

For the success of six properly executed pipe installations, a suitable procedure had to be developed. This procedure would have to coordinate the collaboration of equipment, land sites, material, and most importantly people. The procedure was broken down into the following components:

1. Initial Planning and Organization
2. Set-up
3. Pre-Installation
4. Installation
5. Post-Installation

With proper task itemization and resource allocation within each component, the success of the installations is achievable. In addition, the tests and instruments (used to execute the tests), would have to be properly understood and executed. With proper comprehension, the correct data can be properly retrieved from in-situ testing.

CHAPTER 5 ANALYSIS

5.1 Introduction

Once the installations of the pipes and the corresponding post-excavations were complete, the analysis of the annulus could begin. The compilation and comparison of all observations along with the collected data comprise this section. The analysis begins with a section on visual observations of the annulus. These observations occurred at different excavated segments of the installed pipe through a time progression of 1 day, 1 week, 2 weeks, and 4 weeks. These observations were critical in trying to understand what was transpiring to the annulus during the installation of the pipe and post-installation. It also includes actual photographs of every cross-section of pipe excavated. The following section looks into the make-up of the annular space, which is the drilling fluid and subsequent slurry. First, a list of all the components that were added to form the drilling fluid batches at all the installations will be discussed and second, examination of the properties that define the drilling fluid/slurry and how they (the properties) may change through the different stages of the installation will be presented. The next section examines the unconfined shear strength of the annular region in clay through the use of a pocket penetrometer. At each clay excavation a pocket penetrometer was utilized to measure the in situ shear strength of the annular region and adjacent areas. Comparisons of how the shear strength of the annulus may change from one pipe to another or one excavation to the next can then be made. Similarly, the next section explores the results of the Vane Shear Test (performed at both the clay and sand site), which also determines the in situ shear strength of the annular space. The Vane Shear test is a simple and practical test that may give insight into the shear strength of the annular region and how it may change through time. The last section covers the results of the moisture content of the soil in and around the annulus. An important question in HDD is: Can drilling and installing a pipe effect the area outside of the annular space? One item that may effect adjacent areas is water. The presence of water not only effects the strength of the soil but it can also alter other properties of the soil. Samples for moisture content calculation were taken at defined locations through different cross-section excavations.

5.2 Visual Observations

The importance of viewing, documenting, and then photographing the annulus as it may change through the different pipe installations, cross-sections, and progression of time cannot be understated. By simply having the ability to look at the annulus, a better appreciation for it can be gained. With each incremental excavation, comparisons from previous excavations can be made and then any patterns or developments can be identified. Therefore, in this section, each pipe installation will be first analyzed individually and then comparisons from all installations can be made.

5.2.1 Clay Site

The clay site was the first to see the installation of the HDPE pipes. The site was located in an unused portion of the University of Alberta farm fields. Figure 5-1 is a picture of the site during the first day of installation.

Figure 5-1 University of Alberta Farm Fields Clay Site

5.2.1.1 100mm (4-Inch) Pipe Installation at the Clay Site

The 100mm (diameter) pipe installation was the first pipe installed on June 14/2000. The installation went relatively well with total installation time of 2 hours and 40 minutes (drilling and reaming). There were no frac-outs or any impedance's that affected the drill. The 100mm pipe (61 meters in length) that was installed arrived to site on a spool.

In Figure 5-2, the layout of the drill and pipe placement for the 100mm pipe is displayed. The depth of the pipe was to remain at 0.6m below ground level and the length of the pipe installed was 61m. The locations of the cross sectional excavations are noted along with the number of days/weeks after installation that section was excavated.

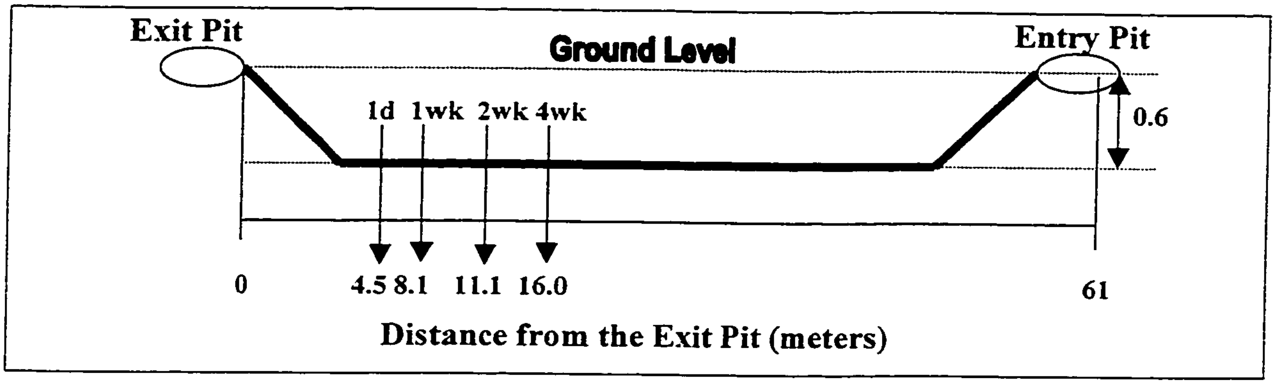

Figure 5-2 Elevation View of 100mm Pipe Installation in Clay

At each cross-sectional excavation marked in Figure 5-2, photographs were taken to capture the raw state of the annulus as it may have changed in time. In Figures 5-3 to 5-6, the actual site photographs of the cross-sectional excavations are displayed from the one-day excavation to the four-week excavation. It does appear that as the annulus ages, the amount of water present decreases and the texture of the annulus turns into a more solid state. As well, the existence of voids is not present in any of the cross-sections.

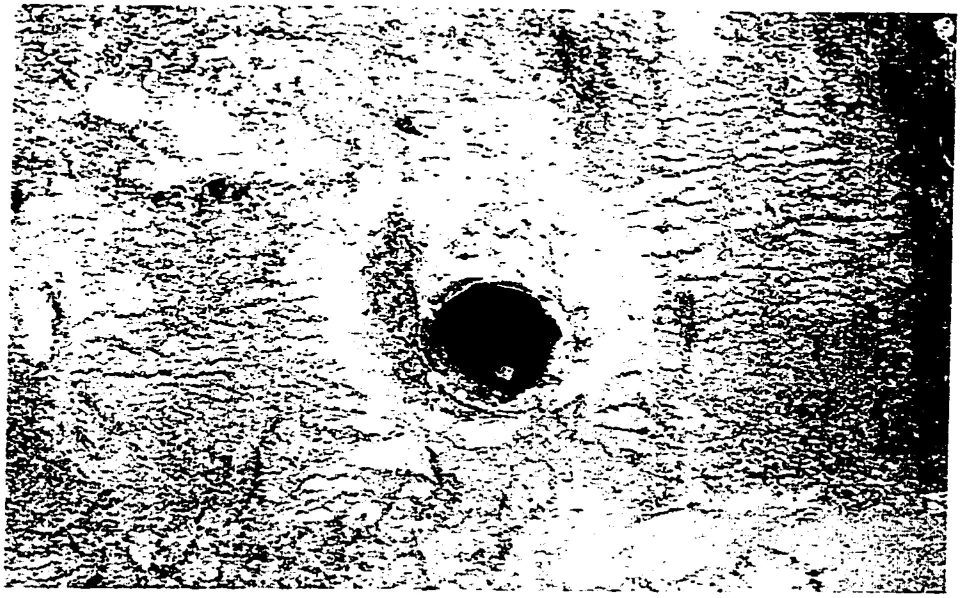

Figure 5-3 One Day Excavation of 100mm Pipe in Clay

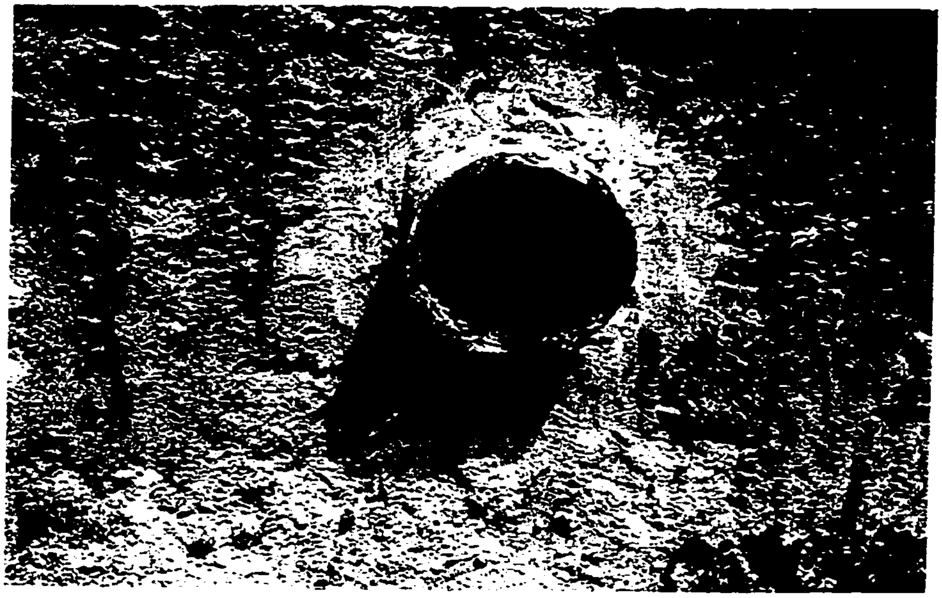

Figure 5-4 One Week Excavation of 100mm Pipe in Clay

Figure 5-5 Two Week Excavation of 100mm Pipe in Clay

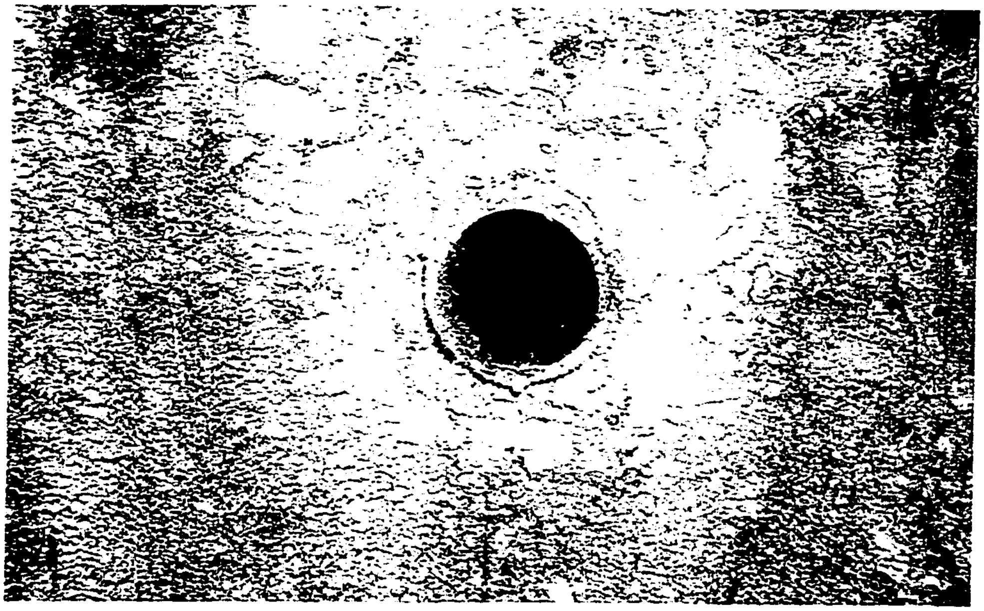

Figure 5-6 Four Week Excavation of 100mm Pipe in Clay

Placement of pipe in relation to the annulus (visual approximation):

Once the pipe was excavated and the pipe section was cut-off a visual depiction of the location of the annulus was noted. This observation was purely visual and was used as a simple observation of whether the annulus stays centered around the pipe. In Figure 5-7, the results of the 100mm pipe installation are shown. The heading shows the number of days after installation (as well as the location from the exit pit), and below is the approximate location of the pipe as well as the measurement d_c, which is the depth from ground elevation to the crown of the pipe.

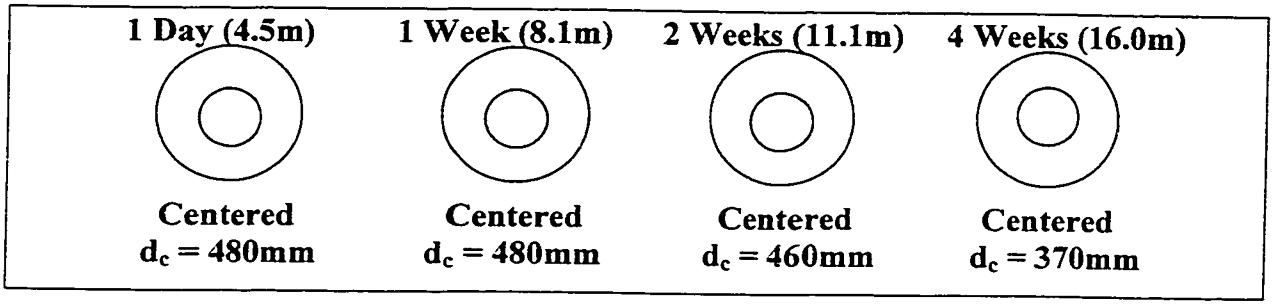

Figure 5-7 Placement of 100mm Pipe in Relation to the Annulus

As is evident in Figure 5-7, the 100mm pipe remains centered throughout the excavations. Even though the depth to crown changes through the cross-sectional excavations, the pipe remains closely centered in the annulus through each of the excavations.

Zone of Influence around the pipe (mm):

The zone of influence is basically the measured extent of the annular space. The measurement would be taken from the outer edge of the pipe until the transition point from where the slurry (combination of drilling fluid and native soil that remained in the borehole from drilling and backreaming) meets the native soil. In Figure 5-8, the zone of influence for the 100mm pipe installation is presented. A total of eight points were measured around the pipe at each excavation and shown in millimetres.

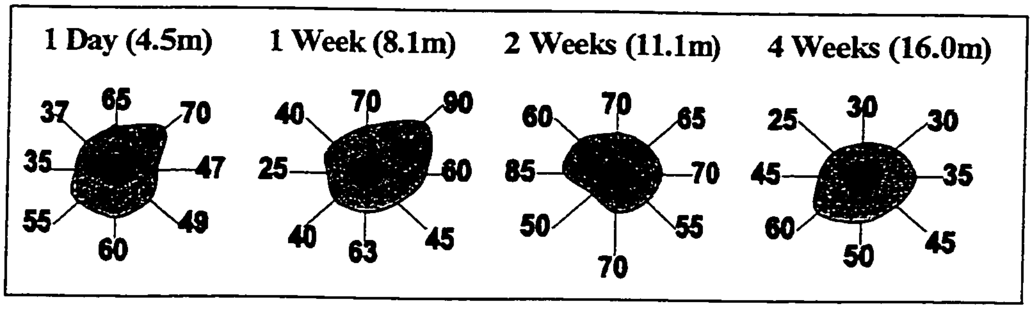
1 Day (4.5m)
1 Week (8.1m)
2 Weeks (11.1m)
4 Weeks (16.0m)

Figure 5-8 Zone of Influence around the 100mm Pipe in Clay

Although the placement of pipe remains relatively centered (as displayed in Figure 5-8), the annular space is not perfectly circular. In fact, the annular space for the 100mm installation in clay takes a very irregular shape. In addition, the extent of the annular space does not remain constant from one cross section to the next. For example, the measurement from directly right of the pipe varies from 35mm to 70mm away from the outer edge of the pipe. What could be the reason or reasons behind this? It is difficult to be absolutely positive but a possible explanation could be as follows. As we are initially drilling, the intent is to keep the drill perfectly aligned from the entry pit to the exit pit. This of course is very difficult and probably almost impossible. The machinery used in HDD does not have the capability of installing a pipe perfectly as designed, but within tolerable limits of a few centimeters. In addition, the drilling head may be influenced to follow the path of least resistance in the soil. The path of least resistance is created due to the fact that the soil is not uniform and may in fact exhibit various planes of strength. The drill head may have a tendency to follow or be deflected to a path that has the least resistance near the planned drill. Therefore, combining the slight inaccuracy of the HDD machinery with the non-uniform native soil, the creation of doglegs can occur. Doglegs are known as deviations from the straight path of the planned drill. Once the drill is complete the backreaming takes place, but like the drilling the backreaming can be prone to deviations as well. Therefore what is created is a space that is intertwined from the drill and the backream and is subsequently filled with a slurry, creating an irregularly shaped annular space. In Figure 5-8, it is very evident that the zone of influence changes from one cross section to the next and it is very likely that no two cross sections will be exactly the same.

Zone of Influence Ratio:

The zone of influence ratio is the measurement of the extent of the horizontal Z.O.I. (Zone of Influence) compared to the vertical Z.O.I.. Figure 5-9 illustrates how the horizontal and vertical Z.O.I. are calculated for the 100mm pipe installation in clay, at the 1-Day excavation. The extent of the annular space immediately to the right and left of the pipe is combined (47+35=82) and then divided by the addition of the extent of the annular space values above and below the pipe (65+60=125). The Z.O.I. ratio for the one-day excavation of the 100mm pipe is then calculated by taking the Horizontal Z.O.I. (82) and dividing it by the Vertical Z.O.I. (125), which gives the result of 0.66. The calculated ratios from each subsequent excavation can then be calculated and then compared to previous values, which may give an indication of whether the annular space is possibly changing or remaining constant. In Table 5-1, the ratios for all the cross-sectional excavations of the 100mm pipe installation are presented.

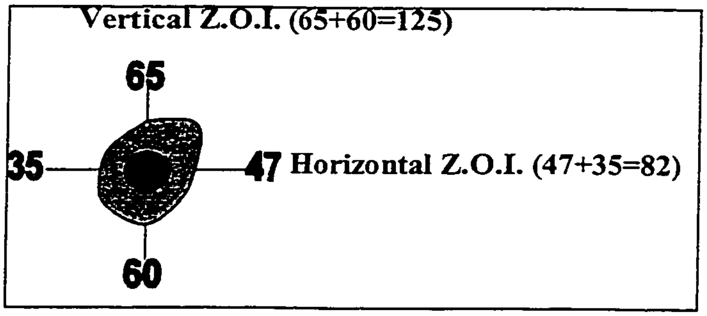

Figure 5-9 Zone of Influence Ratio Example

Table 5-1 Z.O.I. Ratios for the 100mm Pipe Installation in Clay

Excavation	1 Day	1 Week	2 Weeks	4 Weeks
Ratio (H/V)	82/125 = 0.66	85/133 = 0.64	155/140 = 1.10	80/80 = 1.0

As displayed in Table 5-1, the ratios for the 100mm pipe indicate that the annular space is constantly changing throughout the sections. In the first two cross-sections the ratio is well below one, indicating that the vertical Z.O.I. is quite larger than horizontal. For the last two cross-sections the ratios are much closer to one representing that the horizontal and vertical Z.O.I. are very close. All in all, the values are changing throughout the sections thereby reinforcing the idea that the annular space does not remain uniform.

5.2.1.2 200mm (8-Inch) Pipe Installation at the Clay Site

The 200mm (diameter) pipe installation was the second pipe installed on June 14/2000. The pipe arrived in four sections and was fused on site to the required length of 61 metres. The drilling went relatively smooth but the installation of the pipe during the last ten metres of the backream was a major problem. The pipe was evidently stuck due to the large number of frac-outs that occurred. These frac-outs were blamed on the large number of gopher holes that were present. The drilling fluid was escaping through these holes (not enough overburden stress) which then left the installer no choice but to slow down the backream so that more fluid could be pumped into the hole. The operation subsequently lasted four hours and ten minutes.

The elevation view of the 200mm pipe installation in clay (Figure 5-10) follows a similar pattern as the 100mm pipe installation but the depth changes from 0.6 metres in the 100mm pipe to 0.91 metres in the 200mm pipe, to accommodate the larger diameter pipe. As well, the cross-sectional excavation locations are altered slightly.

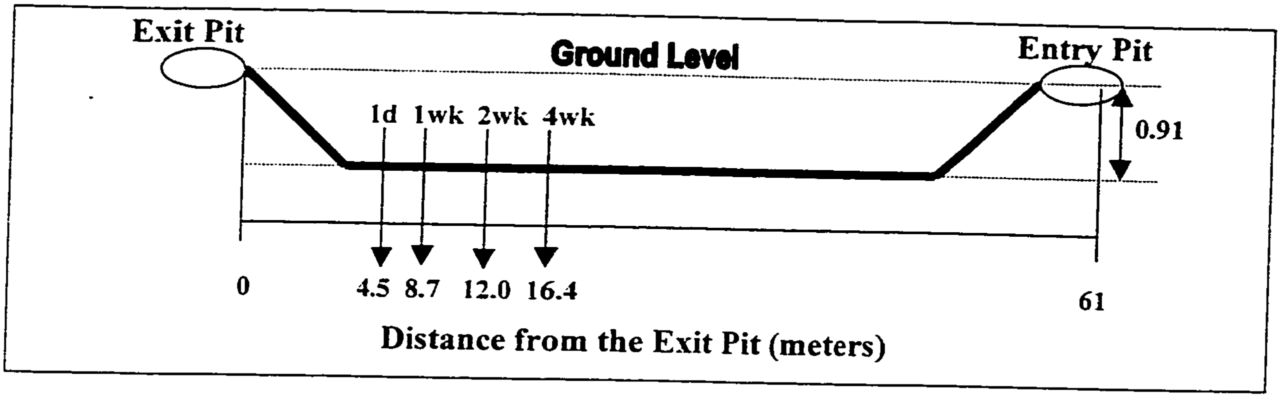

Figure 5-10 Elevation View of 200mm Pipe Installation in Clay

Photographs of each cross-section were also taken for the 200mm pipe installation. Figures 5-11 to 5-14 display the annulus from different stages of post-installation. It is clearly evident that the annulus in the 200mm pipe installations exhibits far less water presence as compared to the 100mm pipe and has the appearance of a more advanced solid state.

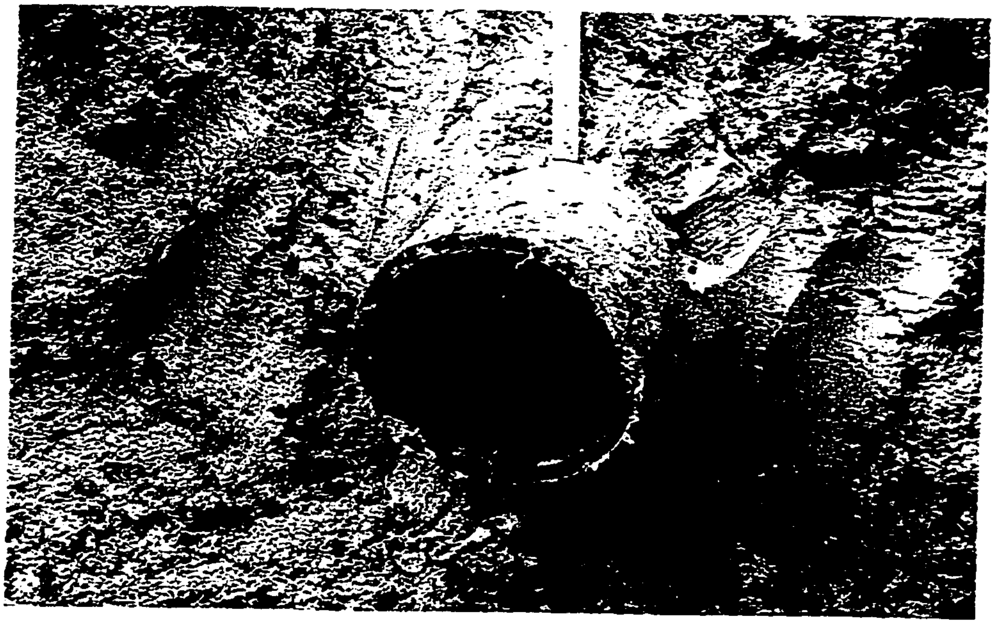

Figure 5-11 One Day Excavation of 200mm Pipe in Clay

Figure 5-12 One Week Excavation of 200mm Pipe in Clay

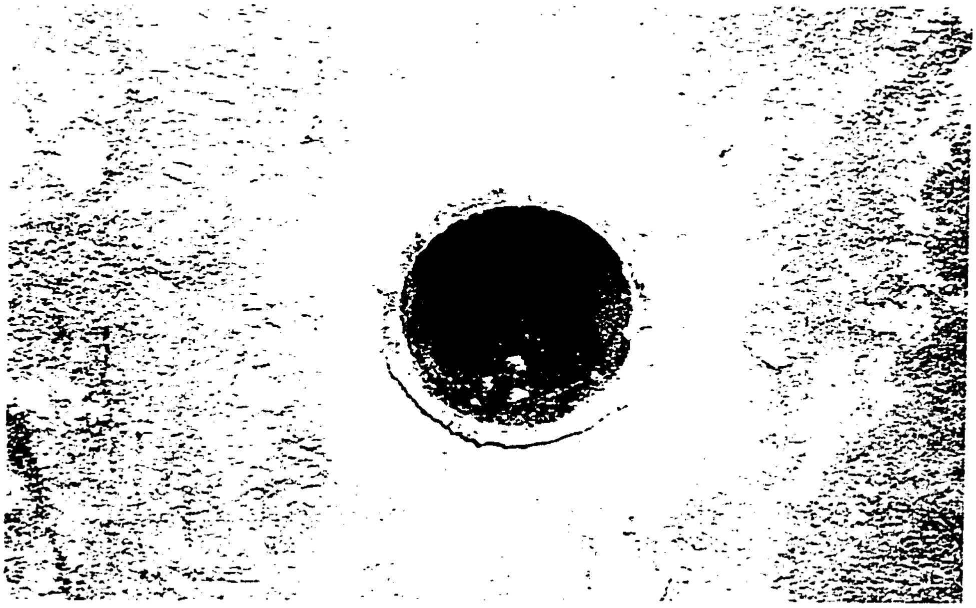

Figure 5-13 Two Week Excavation of 200mm Pipe in Clay

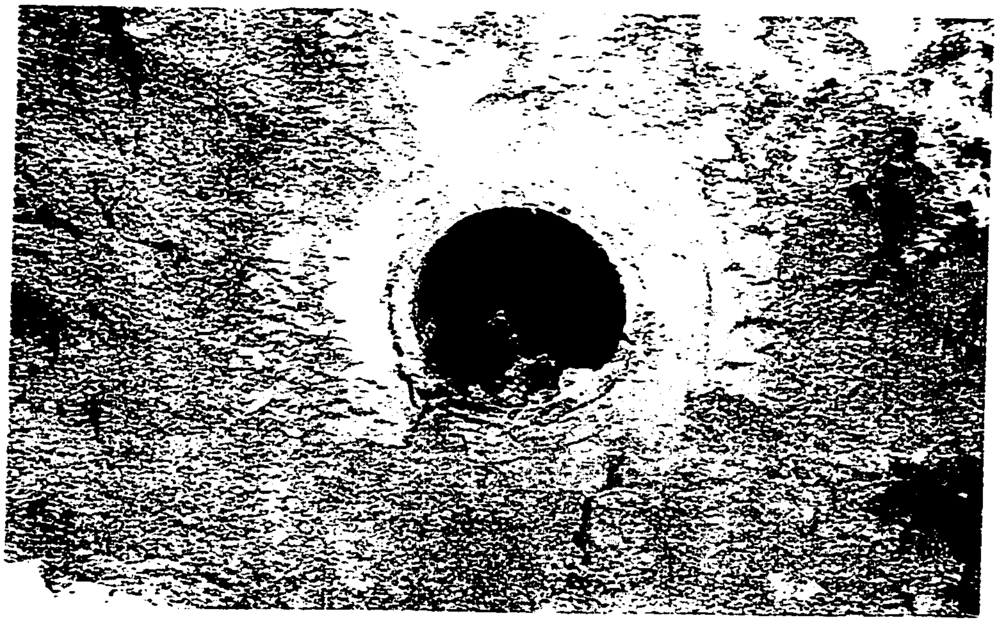

Figure 5-14 Four Week Excavation of 200mm Pipe in Clay

Placement of pipe in relation to the annulus (visual approximation):

In the 200mm pipe installation, the placement of pipe in relation to the annulus is slightly different than that of the 100mm pipe. As displayed in Figure 5-15, the one-day excavation had the pipe placed in the lower right corner for the first cross-section while the rest of the cross-sections displayed the pipe being centered in the annulus. A possible explanation for this is the fact that the pipe was stuck for the last 10 meters of installation. At that point the pulling force on the rig was maximized to help increase the speed of the installation but this did little in the way of helping. The flow in the annular region was lost due to the large number of frac-outs that occurred, and therefore the last 10 meters of installation was an abnormally long process. Therefore combining the fact that the pipe was forcefully being pulled and flow was lost in the borehole, this may have caused the last section of pipe to cut through the bottom of the annular space while all other sections under normal circumstances were centered.

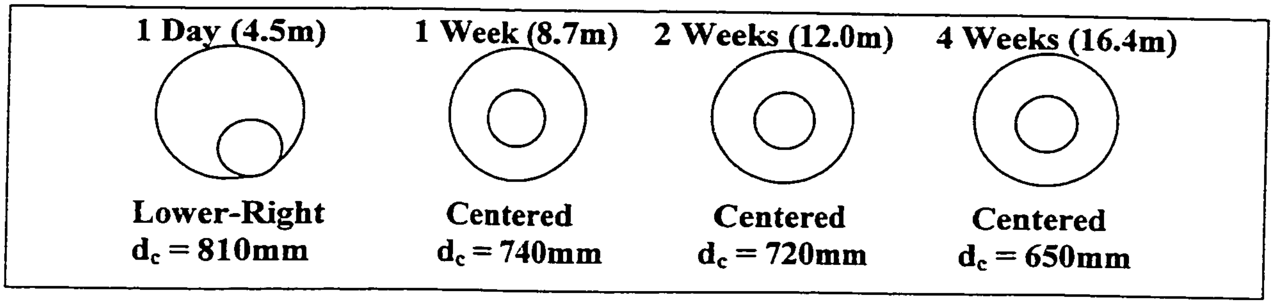

Figure 5-15 Placement of 200mm Pipe in Clay in Relation to the Annulus

Zone of Influence around the pipe (mm)

For the Z.O.I. for the 200mm pipe installation (Figure 5-16) again we see the irregular shape of the annular space. In most cases it does follow a partial circular pattern but the extent of the annular space is constantly changing. For the 200mm pipe installation, the extent of the annular space by all means should be 300mm in all directions. This is true because for the 200mm pipe installation a 300mm reamer was used (1.5 times the size of the pipe). If we remove the size of the pipe from the fold, the annulus should extend approximately 100mm in a straight path from all sides of the pipe. As is evident in Figure 5-16, our values range from 125mm to 235mm in length, which is quite a bit larger than 100mm. This again can be possibly contributed from the fact that the drilling and backreaming do not follow the exact path. Although it is very close, each one can create doglegs along their path or other minor deviations, which ultimately creates a larger borehole and annular space.

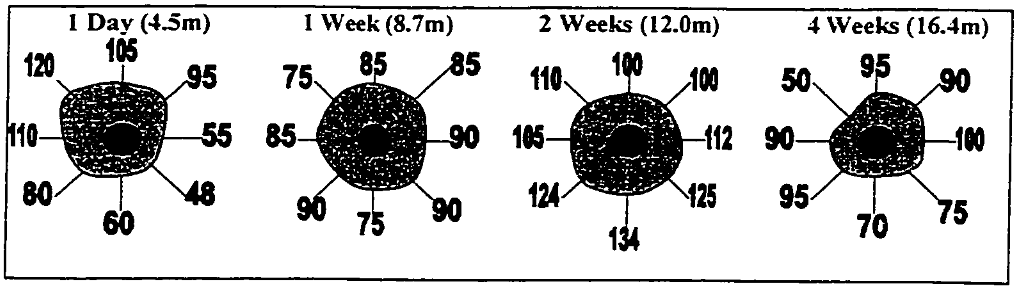

Figure 5-16 Zone of Influence around the 200mm Pipe in Clay

Zone of Influence Ratio:

The ratios in Table 5-2 for the 200mm pipe installation indicate that although the values are changing through the sections, the ratio does remain close to one. This means that the horizontal and vertical Zone of Influence are similar and may in fact resemble a circular shape.

Table 5-2 Z.O.I. Ratios for the 200mm Pipe Installation in Clay

Excavation	1 Day	1 Week	2 Weeks	4 Weeks
Ratio (H/V)	165/165 = 1.0	160/175 = 0.91	217/235 = 0.92	190/165 = 1.15

5.2.1.3 300mm (12-Inch) Pipe Installation at the Clay Site

The 300mm pipe was installed the following day on June 14, 2000. Because of some of the problems that were encountered in the 200mm pipe installation, it was decided that a pre-ream would be done. This would be the best way to avert any potential of the pipe getting stuck. As with the 200mm pipe, the pipe arrived in four sections and was fused together on site. The installation was a success, with no problems and with a total installation time of approximately four hours.

The elevation view of the 300mm pipe installation in clay (Figure 5-17) resembles the same pattern as the other installations except that the depth of installation increases to 1.22 metres below ground. In addition, the one-day excavation for the 300mm pipe was not done because it was not cost feasible to have the contractor return the next day just to excavate for the 300mm pipe alone. Because the 100mm pipe and the 200mm pipe were excavated immediately after the 300mm pipe installation, it was felt that there should be enough representation from those two installations for the one-day excavation to not warrant the cost of having the contractor return the next day.

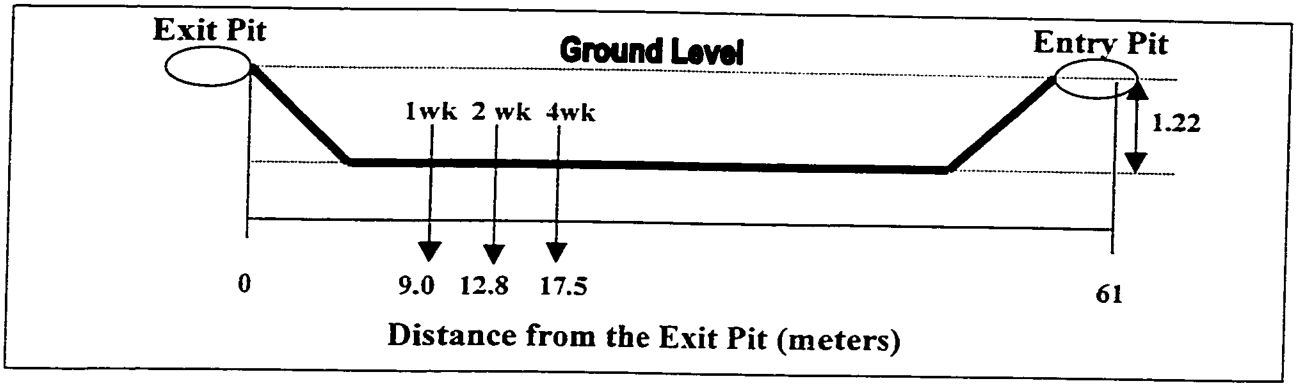

Figure 5-17 Elevation View of the 300mm Pipe Installation in Clay

The photographs displayed in Figures 5-18 to 5-20 display the annulus from different stages of post-installation for the 300mm pipe. As with the other two installations, there is no presence of voids and the annulus does exhibit a more solid state as time progresses.

Figure 5-18 One Week Excavation of 300mm Pipe in Clay

Figure 5-19 Two Week Excavation of 300mm Pipe in Clay

Figure 5-20 Four Week Excavation of 300mm Pipe in Clay

Placement of pipe in relation to the annulus (visual approximation):

The placement of pipe for the 300mm pipe in comparison to the previous two pipes is very different. As shown in Figure 5-21, the placement of the pipe starts from lower-right of the annulus than proceeds to upper-right than ends up centered in the last section. It is important to remember that it is not in fact the pipe that is moving in the annular space but the annular space itself. This is true because a 300mm diameter pipe could not displace or disfigure itself by that amount in a span of approximately 4 meters (distance from cross-section 1week to 2weeks). The annulus, as explained previously, is changing in size, shape, and location due to the methods and equipment used. Therefore placement of pipe in relation to the annulus could be factor of how much deviation was encountered through drilling or backreaming. Another possible explanation could be that the pipe was not always in line with the reamer. The reamer could be slightly deviated from the pipe causing the pipe to locate itself in different regions of the annulus.

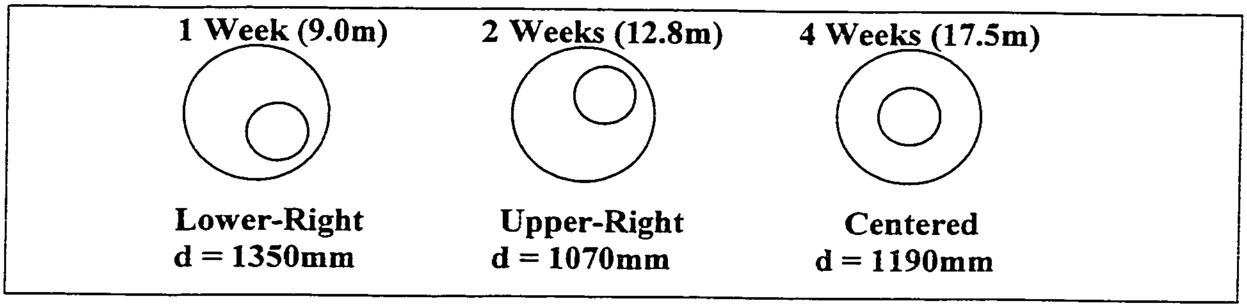

Figure 5-21 Placement of the 300mm Pipe in Clay in Relation to the Annulus

Zone of Influence around the pipe (mm):

The Zone of Influence for the 300mm pipe (Figure 5-22) follows in accordance with the other installations, in the fact that there is no real pattern for the annulus and the size of the annular space is larger than can be attributed to from the reamer alone. The reason for the irregular and inconsistent shape and size of the annulus is the same justification that was presented for the other size of pipe. This being that the drilling and backreaming cannot be perfectly installed as designed, but within tolerable limits of a few centimeters. Another consideration that may cause irregular shapes of the annulus is the fact that the clay is not perfectly uniform throughout. It contains pockets of soil that may have different strengths and properties. Therefore, when drilling or backreaming through the clay, small pockets of clay that are adjacent to the borehole may fall into the borehole because of the disturbance that is created when drilling or backreaming. It may not have enough strength to hold itself in place and therefore becomes part of the borehole, thereby possibly creating an irregular shape to the borehole.

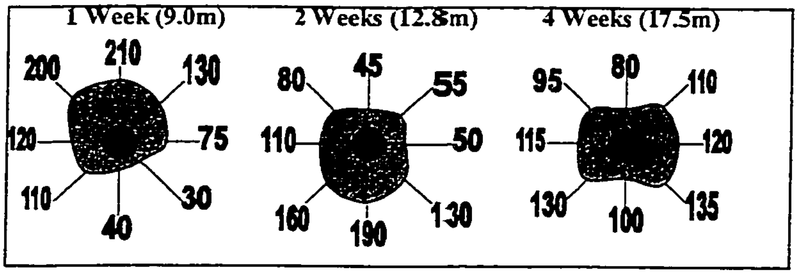

Figure 5-22 Zone of Influence around the 300mm Pipe in Clay

Zone of Influence Ratio:

The ratios for the 300mm pipe begin with a large Vertical Z.O.I. than end up with a large Horizontal Z.O.I.. There is little that can be interpreted from this except for the fact that the annulus is constantly changing in shape and therefore the ratios are as well.

Table 5-3 Z.O.I. Ratios for the 300mm Pipe Installation in Clay

Excavation	1 Week	2 Weeks	4 Weeks
Ratio (H/V)	195/250 = 0.76	160/235 = 0.68	235/180 = 1.31

5.2.1.4 Existence of Voids in the Clay Installations

Through each cross-sectional dig-up, inspection for the existence of voids would be made. The inspection would occur just within the annular space and would be made at every cross-sectional dig-up through all the pipes. Through each of the pipes in clay and their cross-sectional dig-ups there were no evident signs of voids. The eleven photographs of the cross-sectional excavations in this section reaffirm the non-existence of voids in the clay installations.

5.2.2 Sand Site

The sand site was the other soil site chosen for the installation of the HDPE pipes. The site was located just North of Edmonton in the town of Bruderheim. The installations and cross-sectional excavations would follow the same pattern as the clay site. Figure 5-23 is a picture of the site in Bruderheim.

Figure 5-23 Bruderheim Sand Site

5.2.2.1 100mm (4-Inch) Pipe Installation at the Sand Site

The 100mm pipe installation was the first pipe installed in the sand site on July 11, 2000. The installation of the pipe was a success with no major difficulties and a total duration time of 2.5 hours. This installation duration time was very close to that of the 100mm pipe installation in clay (2 hours and 40 minutes).

The elevation view of the 100mm pipe installation in sand (Figure 5-24) exhibits the exact same characteristics of the 100mm pipe installation in clay, except that the cross-sectional excavations are altered slightly. It was necessary to keep all the features the same, thereby allowing valid comparisons between all the installations.

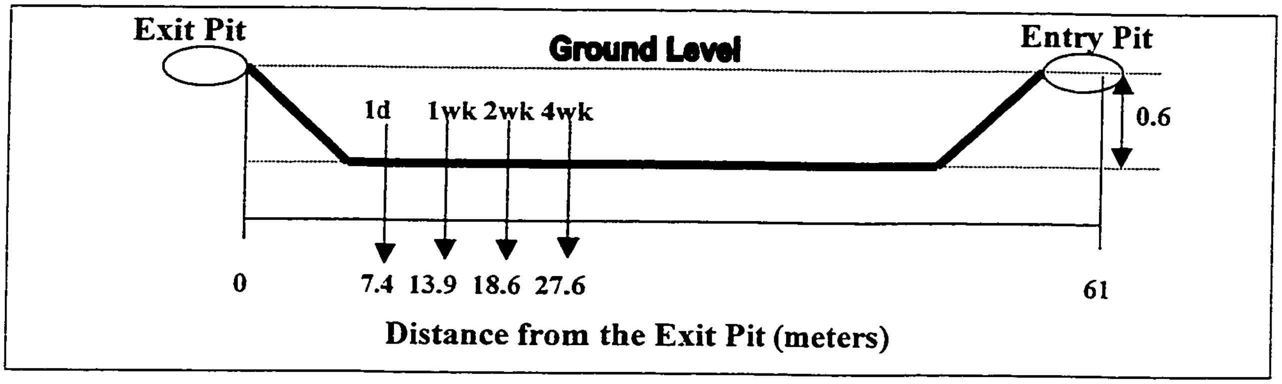

Figure 5-24 Elevation View of the 100mm Pipe Installation in Sand

As with the clay installations, photographs of all the excavations were taken. In Figures 5-25 to 5-28 the cross-sections of the 100mm pipe in sand are displayed. Through all the cross-sections, there are clear signs of voids present adjacent to the pipe.

Figure 5-25 One Day Excavation of the 100mm Pipe in Sand

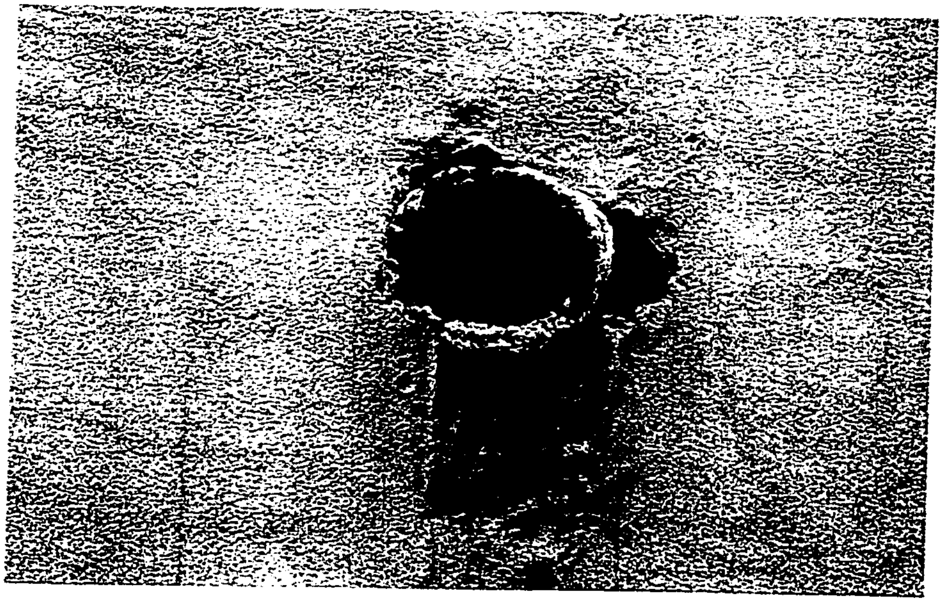

Figure 5-26 One Week Excavation of 100mm Pipe in Sand

Figure 5-27 Two Week Excavation of 100mm Pipe in Sand

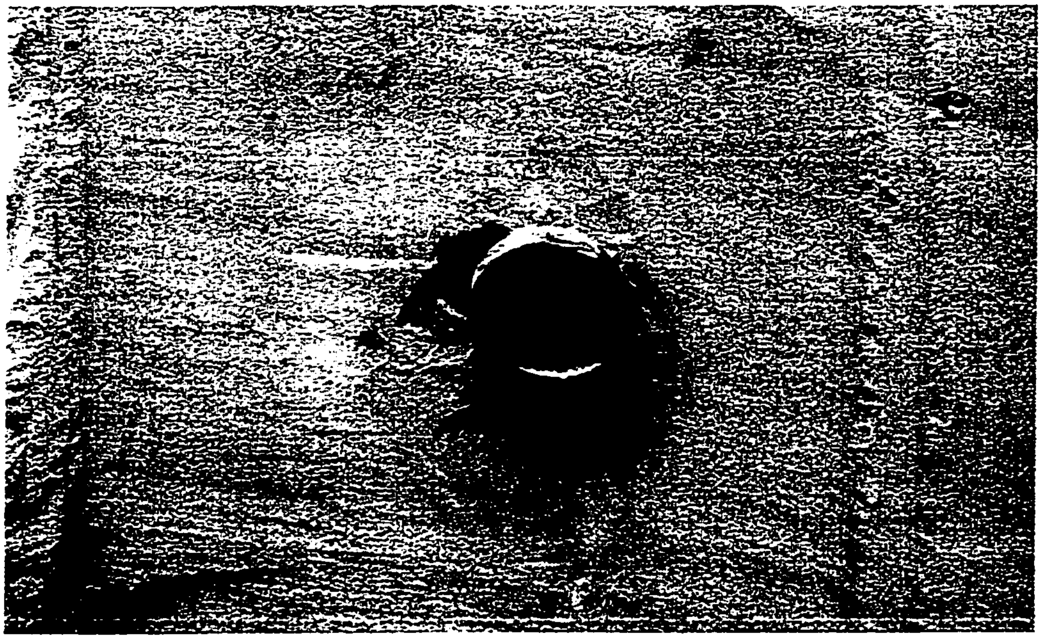

Figure 5-28 Four Week Excavation of the 100mm Pipe in Sand

Placement of pipe in relation to the annulus (visual approximation):

The placement of pipe in relation to the annulus for the 100mm pipe in sand, as shown in Figure 5-29, is quite different from what was observed at the clay site. In the sand site, the 100mm pipe is consistently in the upper quadrant of the annular space, either centered or off to the side. What would cause the pipe to be continually in the upper region of the annulus? One possible solution is the fact that the strength of the raw annular space within the sand during installation does not have the strength to withhold the pipe in a lower region. Because of the curved shape of the pipe (created from the path upwards of the pipe from entry to exit pit), it may have the tendency to remain upwards because of the lack of strength of the annular space to keep it lower (buoyancy of the pipe). Therefore the pipe will remain continually in the upper region of the annulus because of the relative weakness of the annular space during installation.

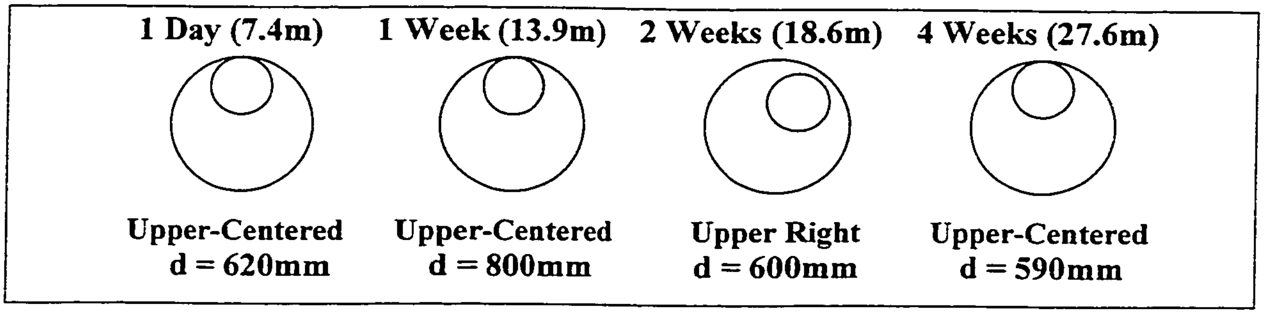

Figure 5-29 Placement of the 100mm Pipe in Relation to the Annulus

Zone of Influence around the pipe (mm):

The zone of influence created from the 100mm pipe installation in sand (Figure 5-30) again is irregular in shape and never remains consistent. The one common thread is the fact that the zone of influence is much larger below the pipe than above. The reason for that, as mentioned above, is possibly due to the fact that the annulus does not have the immediate strength capabilities to withhold the pipe lower. Therefore the pipe sits in the upper region of the annulus. It appears that a large Z.O.I. is created below the pipe but this is only due to the fact that the pipe is in the upper region. Besides that, the characteristics of the annulus and the Z.O.I. are similar to the clay findings, in the fact that the shape and extent are irregular. By comparing the reamer size (152mm) to the exact size of the annular space created, one can see that the annular space is almost two times larger in certain sections and non-uniform throughout all the sections. The justification for that again is the minor deviations, or doglegs, that are created in the same way that they are in clay.

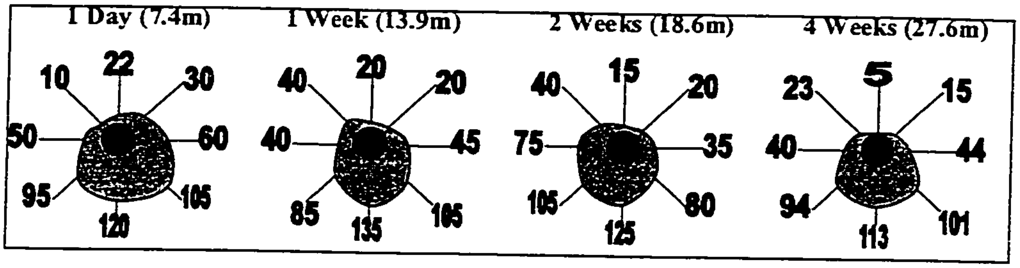

Figure 5-30 Zone of Influence around the 100mm Pipe in Sand

Zone of Influence Ratio:

The ratios for the 100mm pipe are once again sporadic as displayed in Table 5-4. Although, unlike the clay installation, the sand ratio consistently shows that the vertical Z.O.I. is always larger than the horizontal. Why would this occur? Once again, it is very difficult to know exactly why this would happen but a possible reason may be the following. As explained previously, the 100mm pipe is found consistently in the upper quadrant of the annular region due possibly, to the weak state of the annulus. The pipe may in fact be not only cutting through the weak state of the raw annular space but in fact be creating a larger annular space by pushing slightly upwards onto the native soil. Because of the slight U-shape of the installed pipe, the pipe may create enough force onto the native soil that it may expand the annular region slightly more vertically. It does not have the strength to create any large displacements but it could possibly add a few centimetres to the vertical range of the annulus. Combine this with the any deviations created from drilling and backreaming and this may explain why the ratios are consistently below one.

Table 5-4 Ratio Table for the 100mm Pipe Installation in Sand

Excavation	1 Day	1 Week	2 Weeks	4 Weeks
Ratio (H/V)	110/144 = 0.76	85/155 = 0.55	110/140 = 0.79	84/118 = 0.71

5.2.2.2 200mm Pipe (8-Inch) Pipe Installation at the Sand Site

The 200mm pipe installation was the second pipe installed immediately following the 100mm pipe installation. Because of the problems that arose from the 200mm pipe installation in clay, we discussed the possibility of pre-reaming the borehole. But, according to the contractor, under normal circumstances they would not pre-ream a 200mm installation and they felt that the previous 200mm pipe installation in clay was an exception. Therefore, no pre-ream was done and the installation went through with no problems. The total duration of installation was 3 hours. Figure 5-31 displays the characteristics of the 200mm pipe installation in sand. The layout remains the same except for the cross-sectional excavations, which are altered slightly.

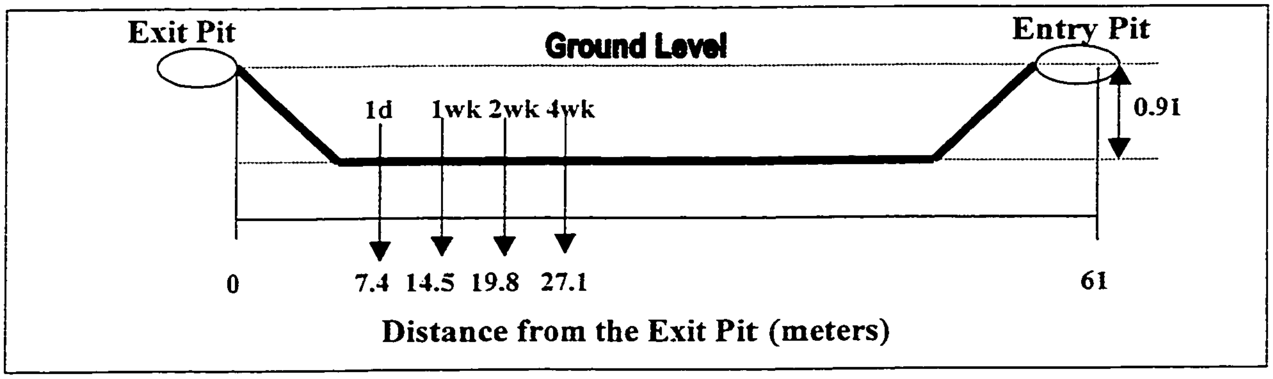

Figure 5-31 Elevation View of the 200mm Pipe Installation in Sand

The cross-sectional excavation photographs in Figures 5-32 to 5-35 display the results for the 200mm pipe installation. Once again the presence of voids is visibly noticeable through the 200mm installation in sand.

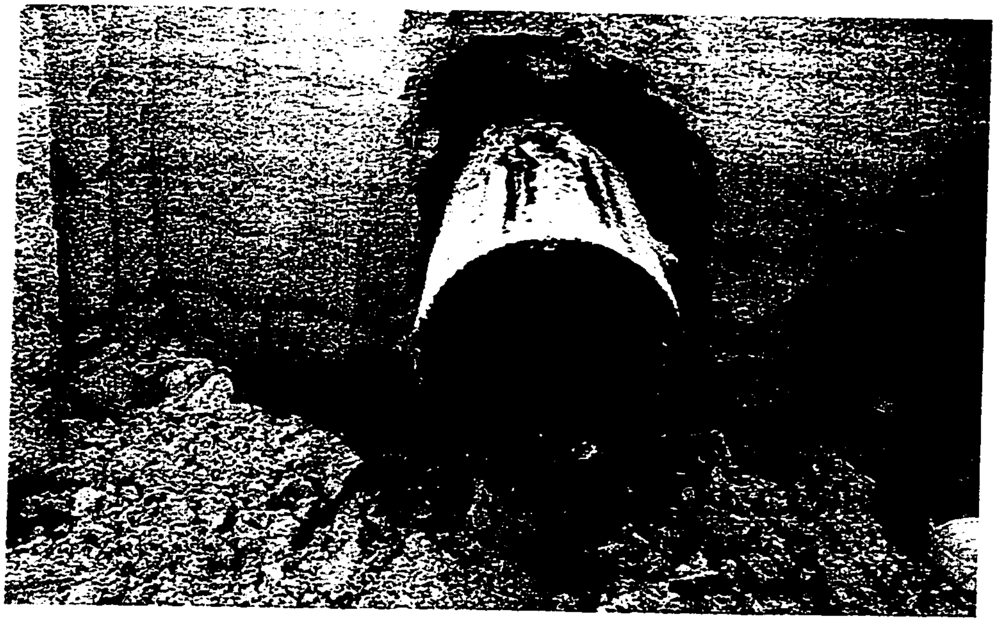

Figure 5-32 One Day Excavation of 200mm Pipe in Sand

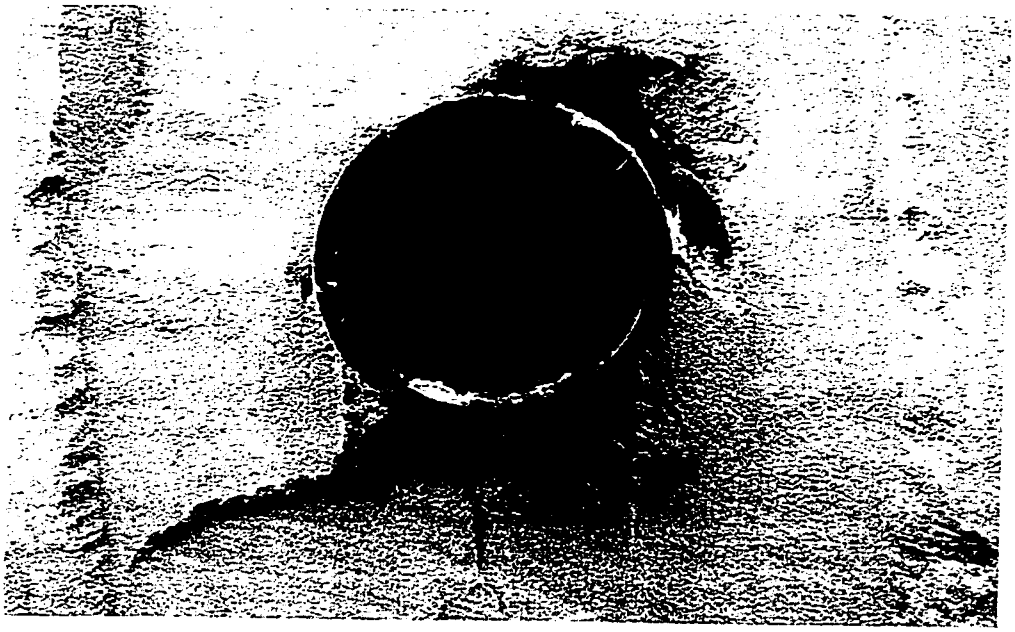

Figure 5-33 One Week Excavation of 200mm Pipe in Sand

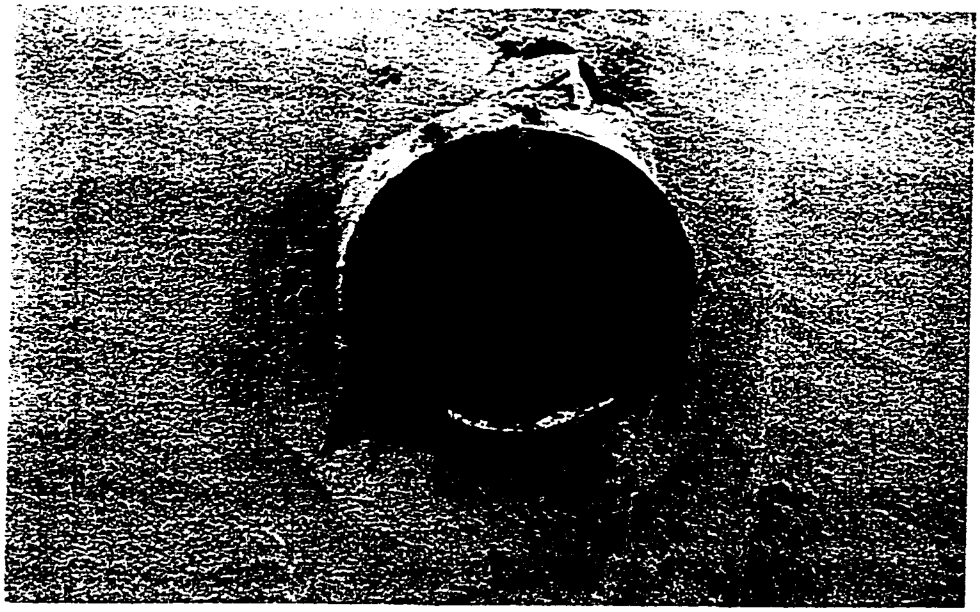

Figure 5-33 Two Week Excavation of 200mm Pipe in Sand

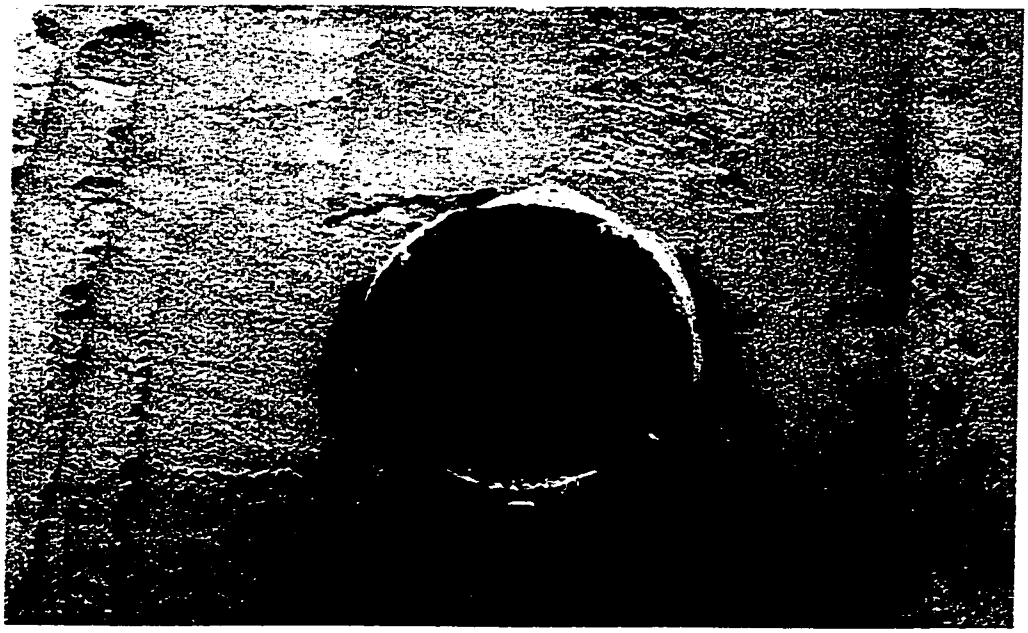

Figure 5-35 Four Week Excavation of 200mm Pipe in Sand

Placement of pipe in relation to the annulus (visual approximation):

The placement of pipe for all of the cross-sectional excavations in the 200mm pipe installation result in the pipe being placed in the upper quadrant of the annulus as shown in Figure 5-36. These results resemble those of the 100mm pipe installation in sand whereby the pipe remains in the upper quadrant, either centered or off to one of the sides. Therefore, because this occurrence is transpiring through eight cross-sections there is a definite trend in the sand installations. As explained for the 100mm pipe installation in sand, a possible explanation stems from the fact that the weak state of the annulus allows the pipe to remain in the upper quadrant (buoyancy of the pipe). The pipe is partial to the upper quadrant due to the fact that it has a U-shape when installed into the ground. The slight elastic bending that is occurring to the pipe may somehow produce a tendency for the pipe to straighten out causing an upward force. Although, there is not enough stress to cause any large displacement but there could be enough to cause a minor shift of the pipe. Thereby creating a constant pipe placement in the upper region.

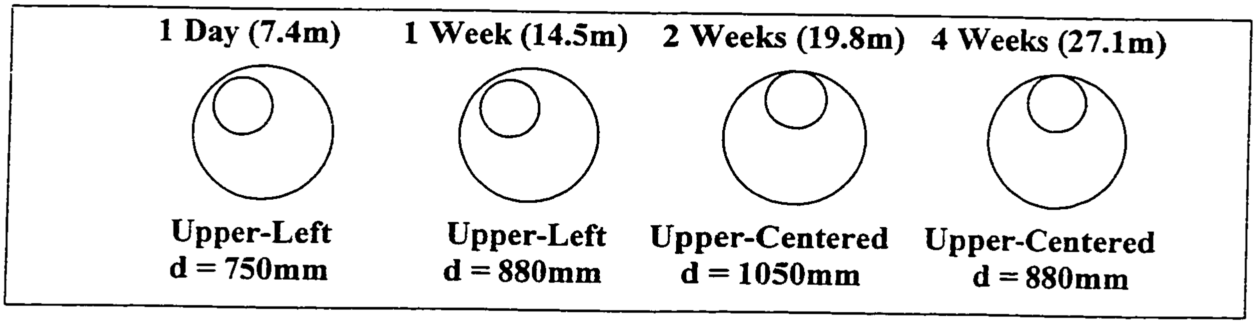

Figure 5-36 Placement of the 200mm Pipe in Sand in Relation to the Annulus

Zone of Influence around the pipe (mm):

The Zone of Influence around the 200mm pipe (Figure 5-37) resembles that of the 100mm pipe installation in sand. Whereby, the Z.O.I. is much larger beneath the pipe than it is above. As explained in the previous section, the pipe remains in the upper quadrant for the 100mm pipe and the 200mm pipe in sand, thereby producing a Z.O.I. that will be continually larger below than above. As well, the non-uniform shape of annulus is common throughout the sections in Figure 5-38 (as they were in all previous cross-sectional excavations).

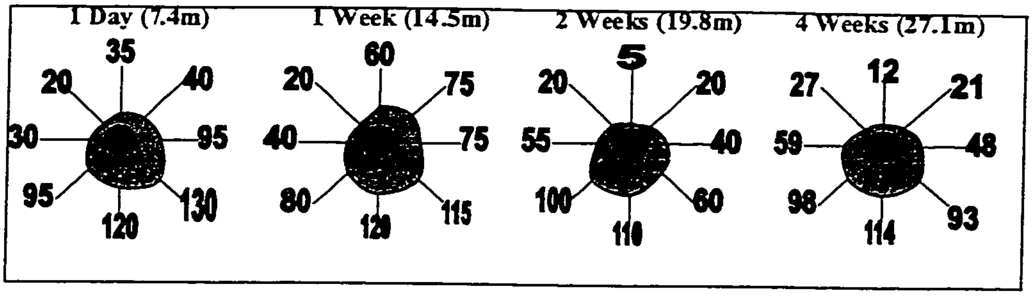

Figure 5-37 Zone of Influence around the 200mm Pipe in Sand

Zone of Influence Ratio:

As shown in Table 5-5, the ratios for the 200mm pipe installation are all below one. This indicates that the Vertical Z.O.I. is consistently larger than the Horizontal Z.O.I. in all the cross-sections. This of course occurred in the 100mm pipe installation in sand as well and therefore, the same explanation can be used to justify how it is occurring in the 200mm pipe. In addition, the values are constantly changing from section to section, reinforcing the idea that the annulus does not remain constant in any section.

Table 5-5 Z.O.I. Ratios for the 200mm Pipe Installation in Sand

Excavation	1 Day	1 Week	2 Weeks	4 Weeks
Ratio (H/V)	125/155 = 0.81	115/180 = 0.64	95/115 = 0.83	107/126 = 0.85

5.2.2.3 300mm (12-Inch) Pipe Installation at the Sand Site

The 300mm pipe was the final pipe to be installed. The installation took place on July 12, 2000, one day after the installation of the 100mm and 200mm pipe installations. As with the 300mm pipe installation in the clay site, a pre-ream was done on the borehole to allow for a smoother installation. The total installation time, including pre-ream, was 6 hours with no major problems or stoppages.

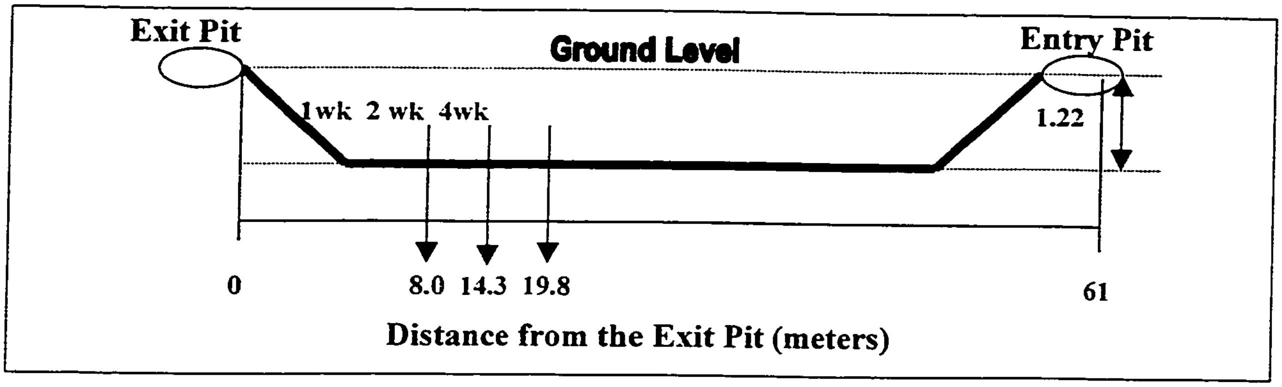

Figure 5-38 Elevation View of the 300mm Pipe Installation in Sand

The three cross-sections photographed, as shown in Figures 5-39 to 5-41, display the evident sign of voids in the 300mm installations. In addition, the state of the annulus is still very raw and in a fluid-like state throughout the 300mm pipe excavations.

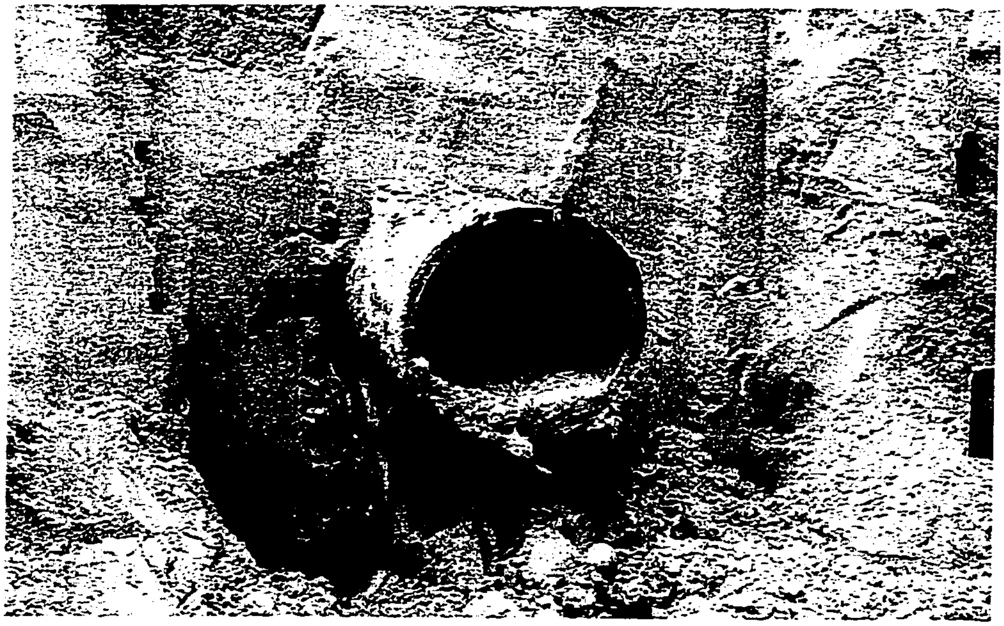

Figure 5-39 One Week Excavation of 300mm Pipe in Sand

Figure 5-40 Two Week Excavation of 300mm Pipe in Sand

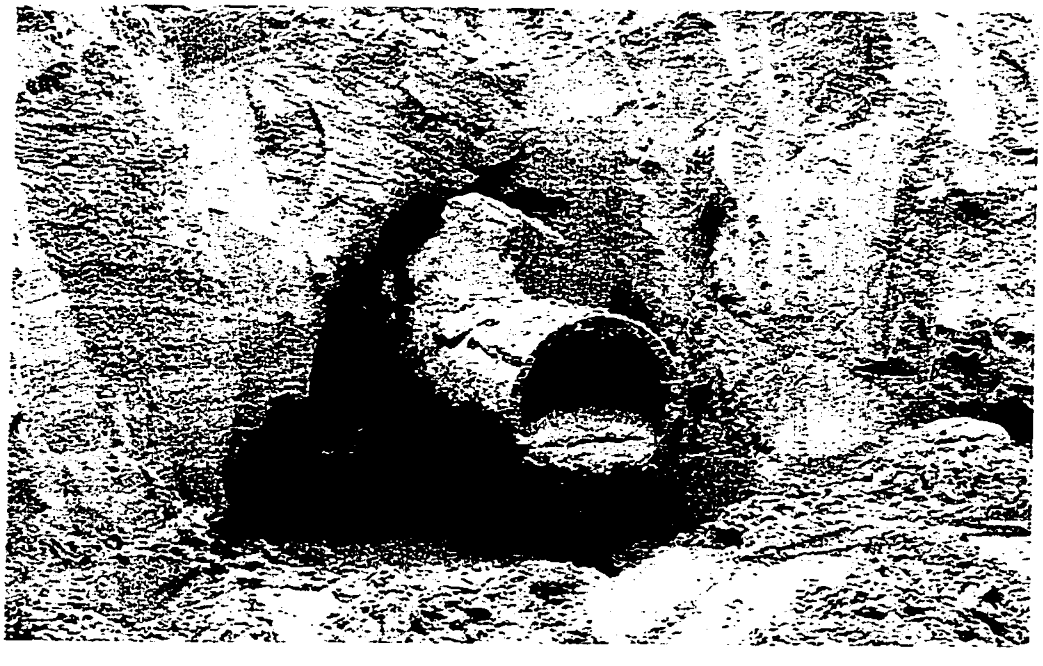

Figure 5-41 Four Week Excavation of 300mm Pipe in Sand

Placement of pipe in relation to the annulus (visual approximation):

Once again, as shown in Figure 5-42, the pipe remains in the upper quadrant. This is a common occurrence for all the sand installations; the only difference being this time is that it is consistently on the right side of the upper quadrant. Why it is consistently on the right side may be a factor of how much deviation there was from drilling, pre-reaming, to backreaming. The backream may have been pulled more to the right than the drilling or pre-reaming. Or possibly, the reamer may have been slightly pulled to the left side while the pipe remained straight. It is difficult to know the exact cause of this right deviation. The explanation for why the pipe is placed in the upper quadrant consistently, is the same as the other sand installations. Pointing to the fact that the raw state of the annular space exhibits low strength, combined with the layout shape of the pipe installed, which causes the pipe to be in the upper quadrant.

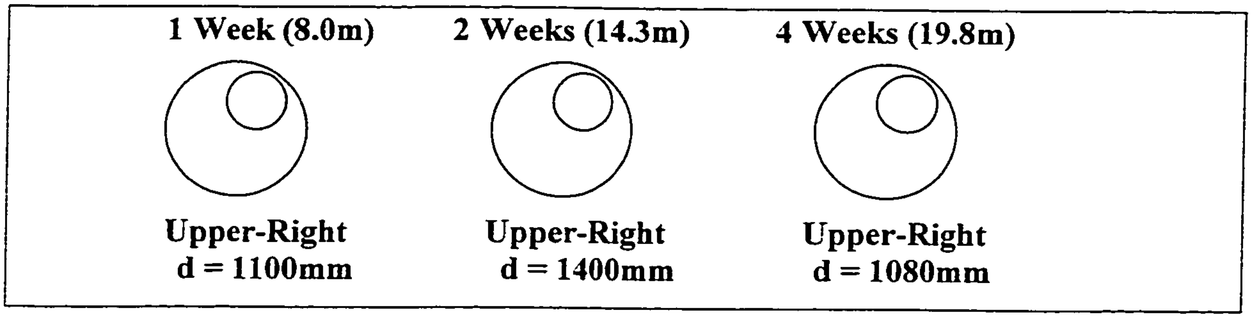

Figure 5-42 Placement of the 300mm Pipe in Sand in Relation to the Annulus

Zone of Influence around the pipe (mm):

The Z.O.I. around the 300mm pipe, Figure 5-43, resembles the other two sand installations whereby the Z.O.I. underneath the pipe is much larger than below the pipe. Because the same things are occurring over and over within the sand installations, there is a definite trend that can be associated with all the Z.O.I.'s of the sand installations. This trend is that the pipe is constantly in the upper quadrant, thereby creating a large Zone of Influence below the pipe.

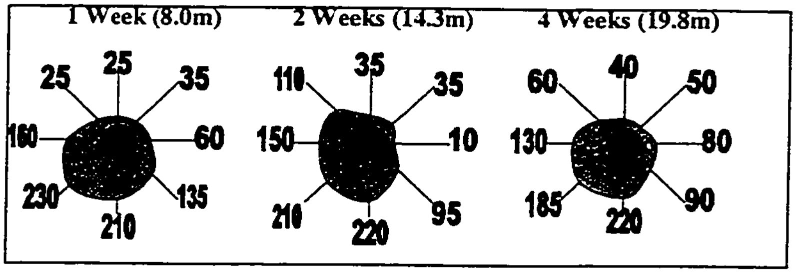

Figure 5-43 Zone of Influence around the 300mm Pipe in Sand

Zone of Influence Ratio:

The Zone of Influence for the 300mm pipe in sand (Table 5-6) yields results of ratios all being below one. This was expected in the 300mm pipe as well since the same results were produced in the other two sand installations. The vertical Z.O.I. is consistently larger in all cross-sections in sand, which may reinforce the idea that there is something causing the annular space to enlarge vertically that cannot be attributed to deviations alone. This was explained (in the other sand Z.O.I. ratio sections) as being caused by the slight uplift of the pipe into the native soil area, causing enough disturbance to enlarge the annular space vertically.

Table 5-6 Z.O.I. Ratios for the 300mm Pipe Installation in Sand

Excavation	**1 Week**	**2 Weeks**	**4 Weeks**
Ratio (H/V)	220/235 = 0.94	160/255 = 0.63	210/260 = 0.81

5.2.2.4 Existence of Voids in the Sand Installations

For the pipe installations in sand it was difficult to determine whether voids existed in the annular space. Because of the disturbance created when digging and cutting up the pipe, the slurry in the fragile and very liquefied annular space would sometimes flow out of the cross-section that was just created. Once the slurry stopped flowing and the annular space was intact, a clear and evident sign of a void was present. These voids always occurred beside the pipe and never below or above. The difficult question that was faced was whether these voids existed before the cross-section was dug up or was this result of the disturbance that was created when the cross-section was made. The answer to this question was answered once closer inspection of the annulus with the void was made. When looking into the void, it is very evident that the void was not local to that cross-section but in fact spreads right continuously through as far as it can be visually scene. Therefore, voids do exist in the annular space for some of the sand installations.

5.2.3 Summary of Visual Observations

The visual observations of the annulus, as it progressed from the first day of post-installation to four weeks after installation, were an important step into comprehending some of it's more important characteristics. The most important and yet simplistic method in studying the annulus was to have the ability to be able to view the annulus in-situ. Viewing the annulus, through the different stages of post-installation, was critical in trying to gather a sense of appreciation for the annular region.

There were many important items that were discovered from visual observations. The most important discoveries were:

1. The placement of pipe for the clay and sand installations were not consistently in the centre of the annulus. The clay installations were for the most part centred but certain cross-sections did locate the pipe in different quadrants. The sand site did not contain any cross-sections that had the pipe centred, but in fact, all cross-sections had the pipe in the upper quadrant.
2. The Zone of Influence for the pipe was never consistent from one cross-section to the next. The extent of the annulus was constantly changing in size and shape for both the clay and site.
3. The Zone of Influence Ratio was consistently random for the clay installations either above or below one. In the sand, the numbers were again random, but they were all consistently below one.
4. There were no voids discovered in the clay installations. Conversely, the sand site did exhibit voids through many of its cross-sectional excavations.

5.3 Drilling Fluid Analysis

Understanding the properties of the drilling fluid along with how they perform once combined with the native soil (subsequently called a slurry) is an important step into maximizing the performance of the drill. The focus of this section is to analyze the key properties of the drilling fluid/slurry, as well as how the properties may change during installation of the pipe. The properties that will be covered include; density, funnel viscosity, pH, sand content, gel strength and filtrate/filter cake.

5.3.1 Drilling Fluid Composition

The composition of the drilling fluid that was batched in the Mixing tank was decided by best practices for the given soil conditions. In Table 5-7, a list of all the drilling fluid mixtures for each installation is presented. For each batch, a cup of soda ash (approximately 1lb) was also added into the mixture and the reason for that was to bring the pH to an optimal level of 9 or 10. When the pH is at that level, the Bore-gel reacts better and is able to perform its necessary functions.

The constituents of the drilling fluid are all products that are produced by Baroid Industrial Drilling Products (1999 Product Guide). These products (and many others) are used by HDD Installers to maximize drilling performance for a wide range of HDD projects. Bore-gel, is the most abundant component in the drilling fluid. When combined with water, it transforms in to an easy-to-pump slurry with optimal fluid properties for HDD Installations. Its function is to create borehole stability (especially in poorly consolidated soils), reduce filtration rate thus improving stability of water in sensitive clays, provide an optimum viscosity with maximum clay platelets for borehole cleaning, and provide gel strength for cuttings suspension and transport. Furthermore, EZ-Mud

Table 5-7 Summary of Drilling Fluid Batches

Pipe Size	Soil Type	# of Batches	Water	Bore Gel	E-Z Mud	ConDet	Other
100mm (4")	Clay	1	900gal	150lbs	2L	2L	
200mm (8")	Clay	2	900gal	150lbs	2L	2L	
300mm (12")	Clay	2	900gal	150lbs	4L	2L	2 lbs of No-Sag
100mm (4")	Sand	1	900gal	250lbs	-	-	
100mm (8")	Sand	1	900gal	250lbs	-	-	2.5 lbs of No-Sag
300mm (12")	Sand	2	900gal	250lbs	-	-	5 lbs of No-Sag

was another component that was added to our batch (only in the clay installation). When it comes in contact with water, its molecular weight and optimum charge density provide excellent borehole stability through a coating mechanism. It is used in a wide variety of drilling operations especially in formations that are water sensitive. ConDet, is a wetting agent that works to keep the drill bit clean, counteract the sticking tendencies of clays, create a slow breakup of cuttings in the annulus while it is being pumped to the surface and promote settling of cuttings at the surface. Likewise (with the E-Z Mud) it was only utilized at the clay sites. Finally, No-Sag was used primarily at the sand site to increase gel strength of the drilling fluid for better suspension of drilled cuttings and coarse sand. It works to enhance the carrying capacity for solids suspension at lower viscosity to ensure flowabality on long drills and backreams.

5.3.2 Sample Locations

Samples of the drilling fluid/slurry would occur at the same locations for each drill. Samples would be taken as follows:

1. The first sample would be taken right out of the mixing tank. This would happen approximately 10 minutes after all mixtures had been added. This is known as the **I**nitial sample and is a composition of only the drilling fluid (I).
2. The next sample would be taken from the entry pit approximately 3-rod lengths into the drill. This sample is a combination of drilling fluid and the native soil (slurry). This sample is known as **R**eturns-**E**ntry Pit-**D**rilling (RED).
3. The subsequent sample is taken from the exit pit. This is a sample of the slurry once the drill head comes through the exit pit. This sample is known as **R**eturns-e**X**it Pit-**D**rilling (RXD).
4. The following sample would be taken from the exit pit once the backreaming had begun. Once 5 rods were pulled in a sample would be taken. This sample is known as **R**eturns-e**X**it Pit-**B**ackreaming (RXB).
5. The final sample is taken just prior to the completion of the installation. When the backream is near to the finish, the last sample is taken and is known as **R**eturns-**E**ntry Pit-**B**ackreaming (REB).

Each sample would undergo the Baroid Mud Kit Test which would define the properties of the fluid for density, funnel viscosity, pH, sand content, gel strength, and filtration/filter cake. The table of results as well as the summary graphs of each installation can be viewed in Appendix B. The summary graphs show how each individual property reacted through the course of the installation.

Note: (The results will be displayed in S.I. units due to the testing equipment being calibrated in S.I. units)

5.3.3 Density

The density is used to measure the solids content of the drilling fluid or slurry. Once the density is calculated with use of a mud balance it can then be used to determine whether the solids content is too high. Just as a note, the density of water is 8.33 lbs/gallon. Figure 5-44 represents the results of the density measurements in clay.

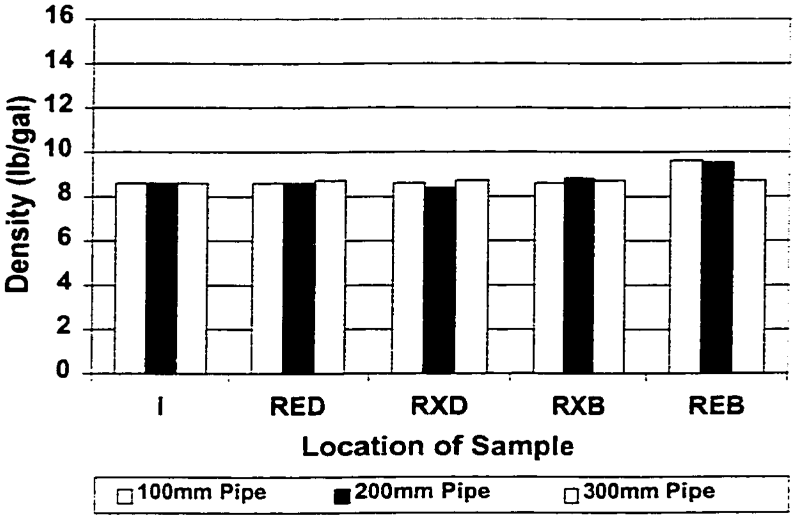

Figure 5-44 Density in Clay

Throughout the installations in clay, the density remained relatively constant at a value just above that of water. Regardless of size of pipe or location of the sample, the density did not vary. This can be seen by comparing the initial drilling fluid (direct from the mixing truck) to the subsequent slurries, where the density value does not vary much from the initial. This represents the fact that there are very little in the way of returns in the clay installations.

On the other hand, the density of the drilling fluid in sand (Figure 5-45) is quite different than that in clay. In the sand sample, it is very clear that the density does rise in the slurry samples. This equates to large solids content in the returns. This means that large returns (of sand) were flowing out of the entry and exit pit, which is the intent for all installations (good flow signifies a good installation). The density between the different sizes of pipe is relatively the same except for the initial samples of the 300mm pipe. Its density was lower initially but during the backream it adjusted itself to close range with the other installations.

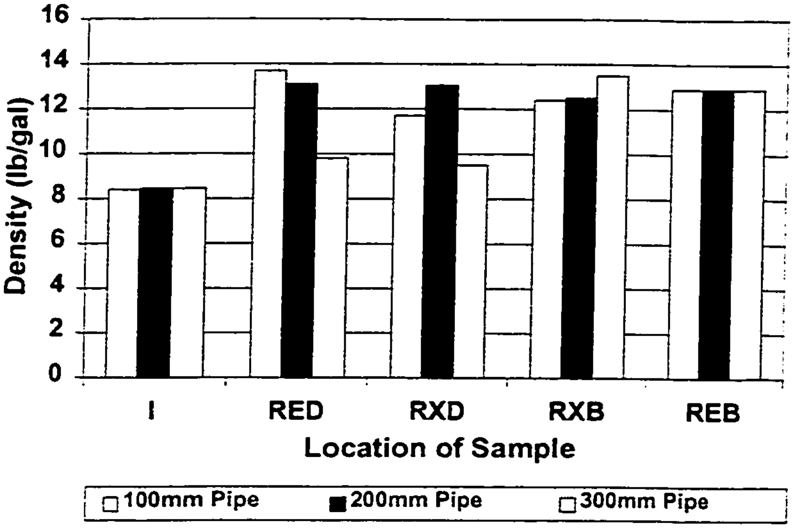

Figure 5-45 Density in Sand

If comparing the average density for all sizes of pipe in the different soil types at the different locations, it is clearly evident that the sand has a higher density, which in turn means a higher solids content. As illustrated in Figure 5-46, initially the samples had approximately the same density but the return samples had significantly different densities. Why? Possibly because the large returns in the sand installations caused the density to largely increase, while the clay installations had very little returns or sand content in the samples. With minimal returns, the pipe may be at risk to getting stuck (which occurred in the 200mm installation in clay).

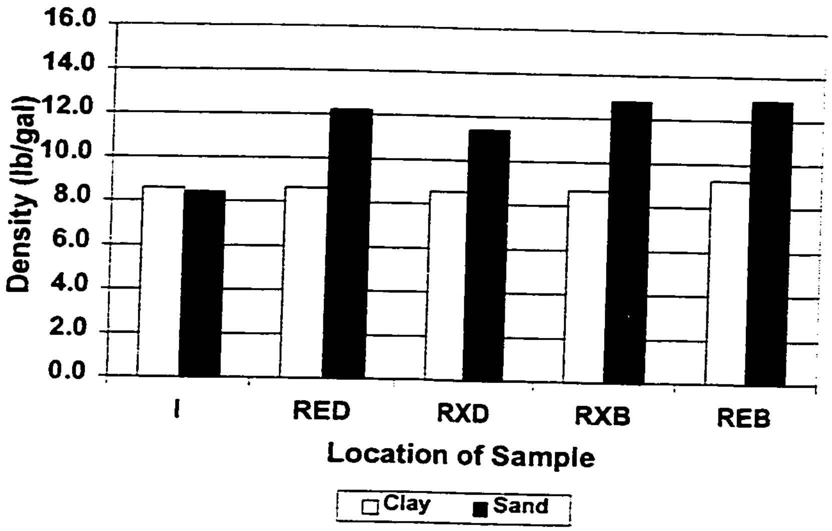

Figure 5-46 Average Density in All Soil Types

5.3.4 Funnel Viscosity

The funnel viscosity is a measurement of the thickness of the fluid. It is measured with a Marsh Viscosity Funnel and is reported in seconds per quart. An optimal viscosity time is between 45 to 65 seconds per quart. Anything above or below this time is not a favourable condition for drilling.

The funnel viscosity in the clay samples (Figure 5-47) all begin relatively the same but variations exist between the subsequent samples. In the 100mm pipe installation in clay, the funnel viscosity remains around 40 seconds while the other two installations displayed higher viscosities than the original. It is difficult to understand exactly why this would occur considering that the 100mm batch and the 200mm batch had the exact same proportioned components.

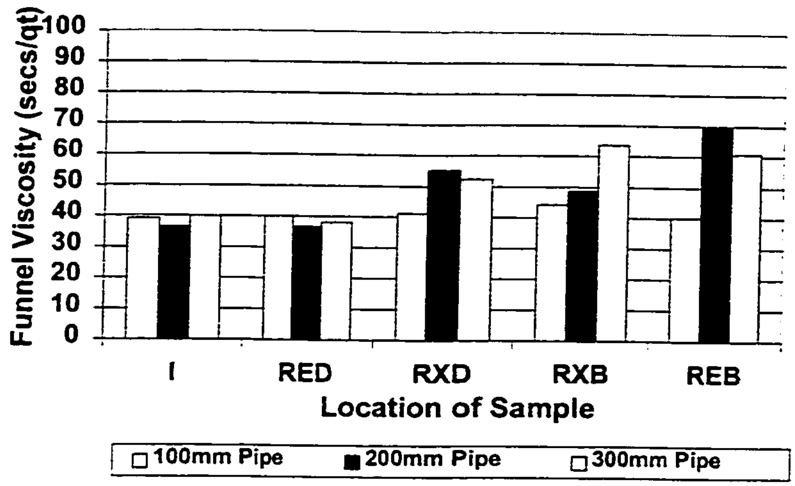

Figure 5-47 Funnel Viscosity in Clay

The funnel viscosity in sand displayed in Figure 5-48, had some unusual results. The first item that really stands out is the 100mm pipe sand sample in location RED. The funnel viscosity was measured at 128 seconds/quart, which was extremely uncharacteristic of all other results. A possible explanation for this may be traced to the mixing of the drilling fluids. It is very difficult to create a perfectly uniform drilling fluid. In most cases, the drilling fluid will be closely uniform but there may a small percentage that has not been properly proportioned. If these non-conglomerated parts just happen to be coming through when sampling occurs, what is created is an uncharacteristic result. Therefore, it is important to understand the importance of mixing well to keep the drilling fluid uniform thereby creating accurate results. In most cases this will occur, but occasionally there is a chance that these uncharacteristic samples do occur. Besides the high spike in the 100mm pipe and some low results for the 300mm pipe in the earlier samples, all sand installations follow a rising trend with optimal viscosity (45-65 seconds) attained for most of the samples.

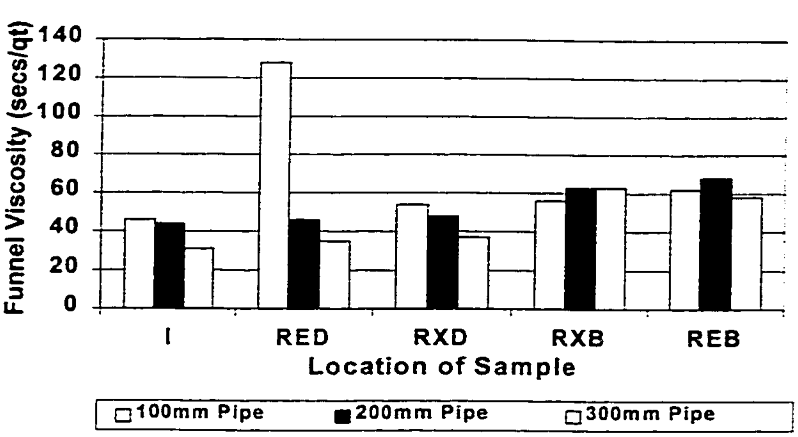

Figure 5-48 Funnel Viscosity in Sand

Comparing the Average Funnel Viscosities for all size of pipe in the sand and the clay installations (Figure 5-49), the samples do remain relatively the same. The only noticeable difference was in location RED where the sand funnel viscosity is close to thirty seconds larger than the clay. This can be attributed to the irregular result in the 100mm installation in sand. Besides that, on average, the funnel viscosity remained in the optimal zone of 45 to 65 seconds for most of the samples.

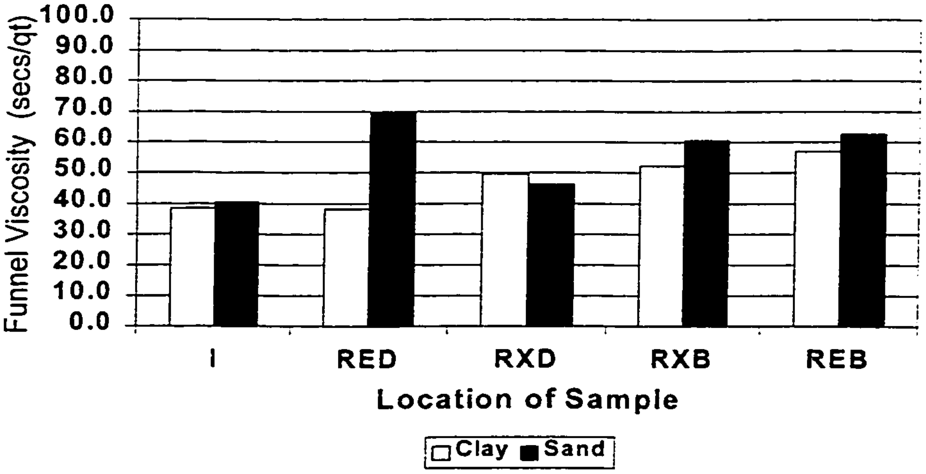

Figure 5-49 Average Funnel Viscosity in All Soil Types

5.3.5 pH

The pH was calculated with the use of pH indicator strips. As is evident in the summary graphs in Appendix B, the pH stayed relatively the same for all samples. An ideal pH for water to mix with the bentonite is at a pH between 8 to 10 and this was achieved with the addition of soda ash for all the batches.

5.3.6 Sand Content

The sand content (Appendix B) is simply a determination of solids larger than 200 mesh that are entrained in the fluid. The sand content can be calculated by the use of a sand content kit and it is reported in percent of total volume. For the clay installations, the sand content ranged from 0% to 2.5%, which for the most part is negligible. On the other hand, the sand content in the sand installations could not be accurately read due to the fact that the actual amount was above the maximum reading. The sand content kit allowed for readings up to 20% on the instruments, and therefore, every sample was given 20% sand content based on the fact that each sample attained atleast that amount. It was expected that the amount would be that large due to the fact that the drilling is occurring in sand and the returns would be comprised of a slurry made up of sand. The sand content value is more significant when recycling systems (for the slurry) are in use. This is when sand could pose a detriment to the equipment.

5.3.7 Gel Strength

The gel strength (Appendix B) is a measurement of the suspension properties of the drilling fluid. It was calculated with the use of a shearometer and its value is given in pounds per 100 square feet. The gel strength is an important property of the drilling fluid because it is responsible for suspending the solids and keeping them in suspension until they can be transported out of the borehole. That is why gel strength is more of a concern in coarse-grained soil because in coarse-grained (non-cohesive) soils the solids will not combine to form a fluid but instead the drilling fluid must have the ability to carry the large particles out. With cohesive soils, there is a greater ability to combine with the drilling fluid and flow out of the borehole instead of being carried out. That is why there is little to no gel strength evident in the clay samples. Besides a few minor readings in the 100mm and 300mm pipes, the clay slurry exhibited very little gel strength. On the other hand, the sand samples had more frequent and larger gel strength exhibited than the clay did. But, the gel strength for the sand did exhibit a peculiar feature in that as the size of pipe increased, the gel strength decreased. This was to the point that the 300mm pipe installation in sand exhibited zero gel strength. This may be due to the fact that a lot of drilling fluid is pumped through the 300mm installation (which means a lot of water) and there may not have been enough No-Sag added to compensate for this. It is difficult to be absolutely positive but this is one possibility.

5.3.8 Filtrate/Filter Cake

By the use of a filter press, the filtrate and the filter cake are calculated (Appendix B). The filtrate is measured in cubic centimetres while the filter cake is measured in 32nd 's of an inch. In clay, the filtrate quantity is important because it is very critical to keep the water from reaching the clay and allow swelling to take place. On the other hand, the filter cake value is important in sand because it acts like a sealant or a grout in that it stabilizes and maintains the integrity of the borehole. Therefore, observing the values of the filtrate in clay (Appendix B) the values do remain relatively low with each installation achieving a similar average value. There were certain samples that spiked but on the whole the values remained constant. This is also true for the filter cake in the sand installations. The filter cake quantities remained between 2 to 8 32nd's of an inch besides one spike of 14 occurring in the 4" installation. On the whole these values remained constant and in good range for a properly developed filter cake in the borehole.

5.4 Pocket Penetrometer

The pocket penetrometer was an important tool in analyzing the shear strength of the annulus and surrounding area. The instrument, as shown in Figure 5-50, is a favorable tool because it is small and very accessible. As well, using the penetrometer to obtain shear strength readings is a simple matter of pushing it into a stratum to the calibration mark and recording the subsequent reading. The penetrometer used in this research was calibrated to read the unconfined shear strength in kg/cm^2. The pocket penetrometer was only utilized at the clay site because its use is targeted for fine-grained soil.

Figure 5-50 Pocket Penetrometer Field Test

For each cross-sectional excavation that occurred in clay, the pocket penetrometer was used to determine the unconfined shear strength. Comparisons could then be made between the different pipe installations and how the shear strength may have changed with time. The pocket penetrometer test would then be performed in four quadrants around the pipe. As illustrated in Figure 5-51, the test would be performed directly right and left of the pipe as well as below and above the pipe. The test would occur in increments from zero to fifty centimetres from the outside edge of the pipe right and left, and would extend zero to thirty centimetres below and above the pipe. The increments would be between 2.5 and 5 centimetres. In addition, a second reading would be done, by hand excavating 15 centimetres further and duplicating the test at the exact same locations. Therefore two values would be produced with the average value used to represent the shear strength for that point (Appendix C lists all the results of the test).

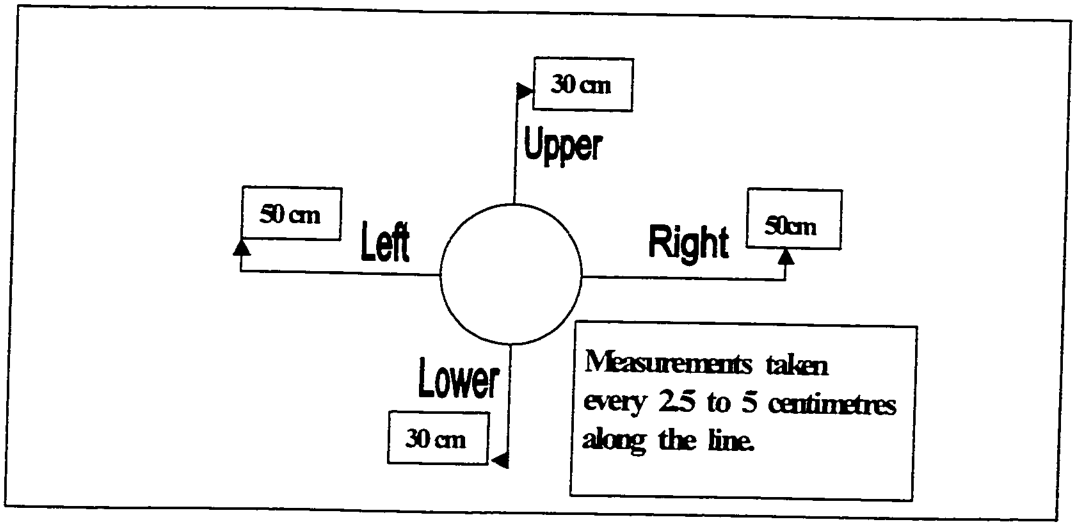

Figure 5-51 Pocket Penetrometer Test Layout

5.4.1 Shear Strength Comparison

The shear strength values that were measured and recorded included readings within the annular space and readings outside the annular space into the surrounding native soil. While performing the test on both areas it was quite evident that there was a difference in shear strength between the raw annulus and the native soil. Because the annulus was composed of a slurry, it was expected that the immediate shear strength of the annulus would be lower than the native soil. In Figure 5-52, a comparison between the annulus of the 100mm pipe and the surrounding native soil is made. The values that make-up the graph are derived by taking all the recorded shear strength measurements within the annular space (from the specified cross-sectional excavation) and averaging them, as well as taking all the surrounding shear strength points and averaging those numbers. What results is a comparison between the first day post-excavation to the four-week post excavation.

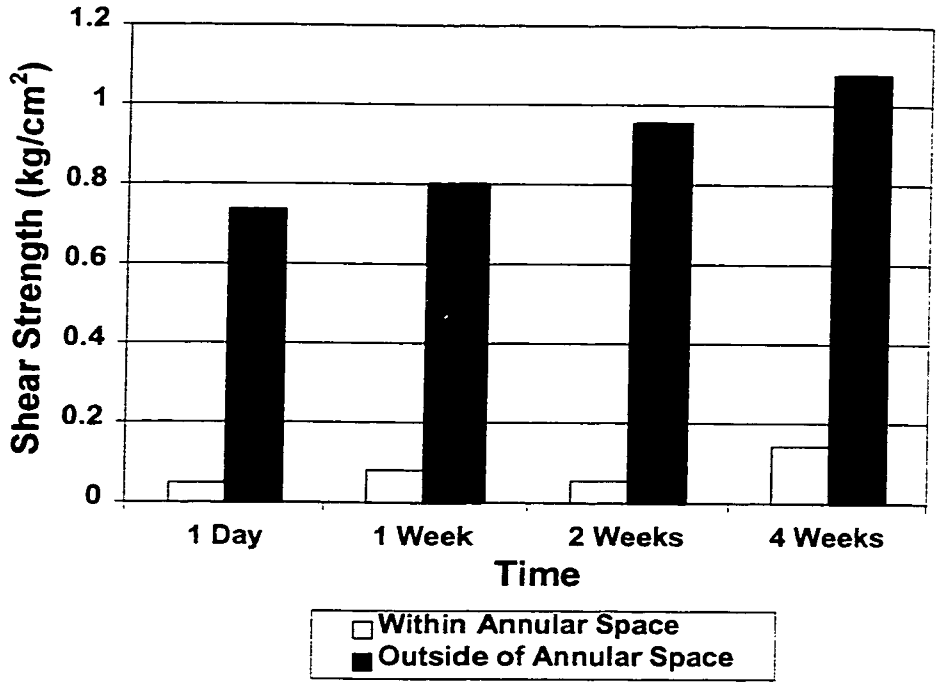

Figure 5-52 Comparison of Average Shear Strength in Clay between the 100mm Pipe Annulus and the Surrounding Soil

As illustrated in Figure 5-52, the shear strength of the native soil is greater than the shear strength of the annulus through all four time periods. The shear strength of the annulus is affected greatly by the large composition of water that makes up the drilling fluid. With the presence of water, the shear strength of a soil will lessen. The shear value was expected to be low for the first day cross-sectional excavation but it was uncertain how the shear value would change in the annulus for the subsequent excavations. The chart illustrates that there is a slight change upwards from the first day to the fourth week in the annulus, but it is still substantially less than the native soil. Furthermore, focusing only on the native soil results, a peculiar trend was noticed. The trend was that the shear strength of the native soil near the 100mm installation continually went upwards through each cross-section. A possible explanation for this may be the fact that as time progressed, the drilling fluid that may have escaped into the native soil could of dried up thereby possibly increasing the shear strength of the native soil. It is very difficult to be absolutely certain because an important point to remember is that the native soil is non-uniform. Because it is non-uniform each cross-sectional stratum may naturally exhibit different shear strength values and the reason that the shear strength may have risen was due to the natural characteristics of the native soil. Although, to possibly lessen this effect, a large number of sample points were taken at each cross-section thereby producing a more realistic average. All in all, the shear strength of the annulus in clay through a period of four weeks is less than that of the native soil.

5.4.2 Shear Strength within the Annulus

An important step into understanding the annulus is calculating its shear strength through subsequent time periods. By studying these results, a possible pattern or trend may be identified. In Figure 5-53, the results of the pocket penetrometer test for all the clay installations are presented. However, only those values that are within the annular space are represented in the chart and all other values are not included. The values within the annular space are once again averaged for each pipe installation at each cross-section. Therefore, this chart is a representation of the unconfined shear strength of the annulus for all installations.

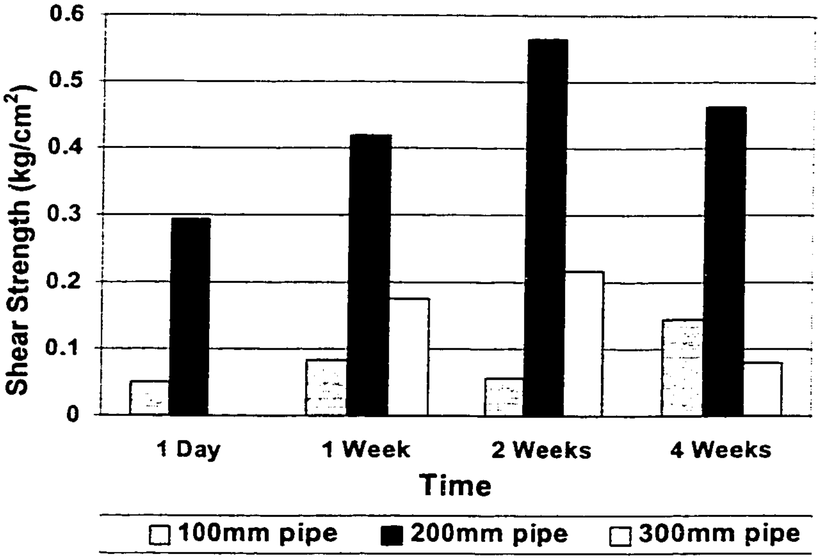

Figure 5-53 Average Shear Strength of Annulus in all Clay Installations

At first glance of Figure 5-53, there are two very noticeable particulars about the chart. One is that the 200mm annulus exhibits a noticeably larger shear strength than the other two installations and two, on average the annulus for each installation is for the most part rising except for the four week test on the 200mm pipe and the 300mm pipe. The possible explanation for both these trends is as follows. The reason the 200mm pipe does exhibit a larger shear strength is the fact that the pipe was stuck for the last ten metres of the installation. Flow in the borehole was lost and the drilling fluid that was being pumped into the borehole was escaping through the large number of frac-outs that were present. Because there were no returns, the clay that would normally leave the borehole remained and 'packed on' to the wall of the borehole. Because this space was now being compressed by the insertion of the pipe and the subsequent compaction and possible swelling of the clay, the final ten metres of installation would be an abnormally long process. At the one-day cross-sectional dig-ups for the 200mm pipe and the 100mm pipe, it was quite obvious this was the case. The 100mm annulus at one day was still raw and exhibited flowable features while the 200mm annulus was substantially more compact and not at all flowable. Therefore, the 200mm pipe exhibited a greater shear strength due to the fact that there was a large presence of the native clay and less presence of the drilling fluid. Basically, because there was less water present, the shear strength of the annulus was greater. Furthermore, the reason the 200mm and 300mm installations went uncharacteristically lower in the final cross-section possibly can be related to the site conditions. When doing the four-week cross-sectional excavations there was a considerable difference between the 100mm installation and the other two installations. The 100mm cross-section did not exhibit anything different from the prior excavation but the 200mm and 300mm pipes were considerably different from the previous cross-section. The difference was the amount of water present. For no apparent reason other than having a non-uniform moisture level in the soil, the 200mm and 300mm installations both exhibited a large presence of water in the cross-section. This could be visually seen and felt throughout the cross-section (this was also verified in the calculation of the moisture content in Section 5.6). And, with the presence of water, the shear strength will lower, as was the case with both installations. If we remove these occurrences from the complete picture of Figure 5-53, what is visibly noticed is that the shear strength of the annulus in all installations increases with time.

In studying the shear strength of the annulus, there are definite variations between values from each side of the pipe. In Figure 5-54, the shear strength values for each installation are averaged based on the location of the test. For example, all values from the left side of the pipe within the annular space from the 100mm pipe installation, 200mm pipe installation, and 300mm pipe installation would be taken and averaged and then compared to other sides of the annulus at each cross-sectional excavation.

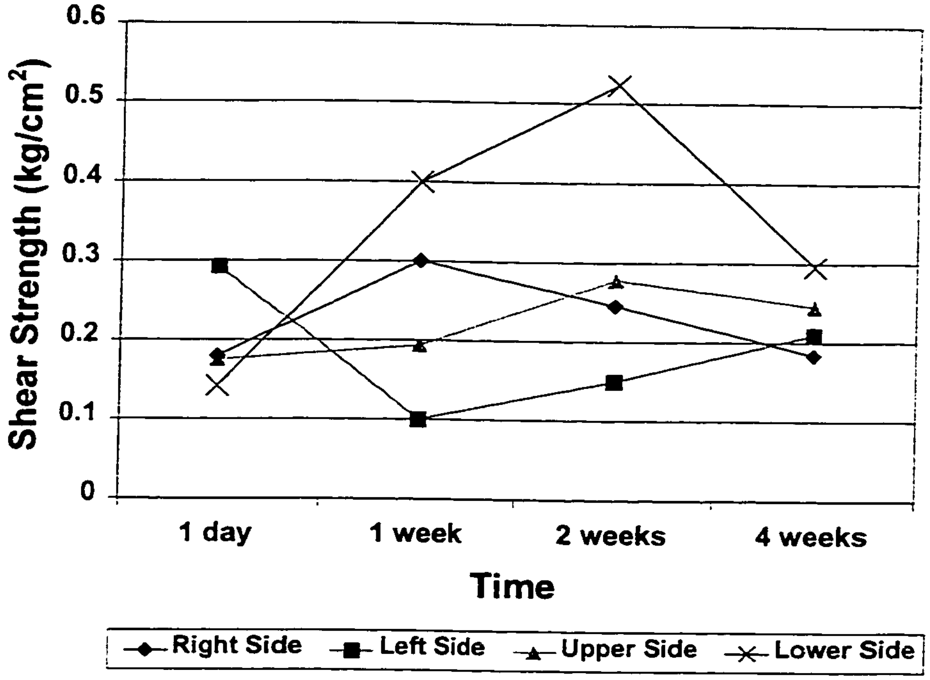

Figure 5-54 Average Shear Strength of Annular Regions in Clay

By averaging all the recorded data for each region through the 100mm, 200mm, and 300mm pipes in clay, it was discovered that through four weeks the right side exhibited the weakest shear strength and the lower region had the highest average shear strength. The upper side was just below the lower region and the left side was just above the right side. What may cause the lower region to have the highest average shear strength? It possibly may have to do with the weight of the pipe pressing down on the lower region. This may slightly compact the lower region, which may create more strength in that zone. Nevertheless, the values for each region do not differentiate greatly, and each zone on average is increasing in strength over time. As a side note, the effects of the water presence in the four-week cross-sectional excavations (as mentioned previously in the 200mm and 300mm pipes) is also displayed in Figure 5-56, where the 4 week values for most of the sections is lowered.

5.4.3 Comparing Maximum and Minimum Shear Strength

Through each increment, four shear strength values (for the upper, lower, right and left regions) are recorded for up to 30cm and two values (right and left) up to 50cm. By taking the lowest value and comparing it to the highest value, a zone of shear strength is revealed. In Appendix C, the values for the 100mm installation at one day through to four weeks are displayed. Comparing each, it can be seen that the zone, or the difference between the maximum and the minimum values, does tend to narrow through each subsequent cross-section. This signifies that the maximum and minimum values get closer as time progresses.

5.4.4 Average Shear Strength

Taking the values for a specific increment (from the right, left, upper and lower) and averaging them, produces the average shear strength. This is a valuable number in trying to view the change in shear strength between subsequent cross-sections. In Figure 5-55, the average shear strength for all the 100mm pipe installation cross-sections is displayed.

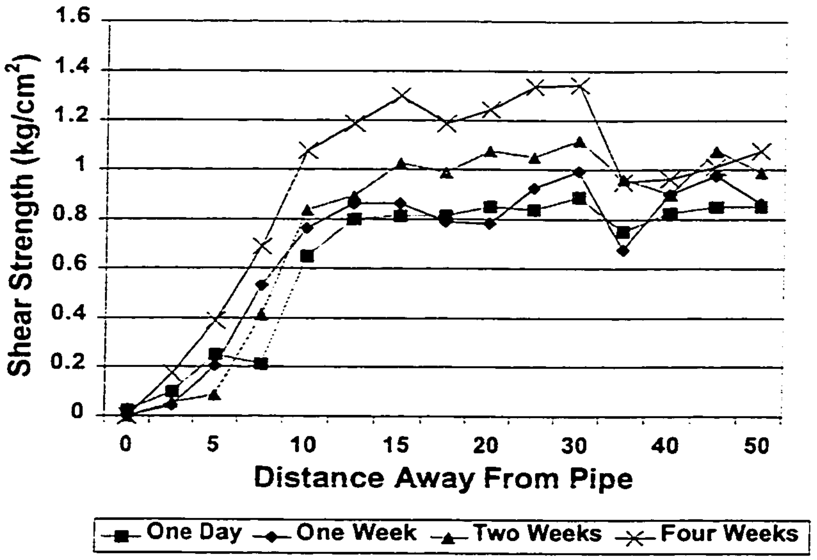

Figure 5-55 Average Shear Strength for 100mm Pipe in Clay

As displayed in Figure 5-55, the average shear strength increases as we move away from the 100mm pipe. This happens because as we move away from the pipe, we are also moving away from the annular space. Due to the amount of water in the annulus, it is the weakest area in the cross-section. It is evident from the 5cm mark (approximate edge of the annulus) to the 10cm mark there is a very noticeable difference in shear strength. Although, it is also important to point out that as time progresses, the average shear strength also increases. This occurs right from the edge of the pipe to 50cm away. Even though each cross-section follows a similar pattern, there is definitely more shear strength in the four-week cross-section than there was in the one day through each of the increments.

5.4.5 Summary of Pocket Penetrometer

The pocket penetrometer test was an important step in calculating the shear strength of the annulus. The test is simple to perform and produces results within seconds. Through the use of the pocket penetrometer, discoveries were made about the shear strength of the annulus and the native soil at the clay site. These discoveries were:

1. The shear strength of the annulus is lower compared to the native soil through the time span of 1 day to 4 weeks.
2. The shear strength of the annulus increases with time.
3. The lower zone of the annulus exhibited the highest shear strength over the span of 4 weeks.
4. The shear strength increases as the distance away from the installed pipe increases (up to 50cm).

5.5 Vane Shear Test

The vane shear test is another instrument used to calculate the shear strength in situ. As with the pocket penetrometer, the test is relatively simple to perform. The vane shear is carefully pushed into the stratum that is to be tested, and then a torque is applied gradually with the peak value being noted. The instrument used at our sites was calibrated to KPa.

The Vane Shear test was performed at the one-week, two weeks, and four weeks intervals. For each cross-section, three to four readings would be taken within the annular region and the average of those readings would be used to represent the shear strength of that cross-section. In Figure 5-56, the results of the clay installations are displayed.

Once again, the 200mm pipe exhibited the largest shear strength in clay. This was not surprising due to the same results in the pocket penetrometer. Although, unlike the pocket penetrometer results, the vane shear test does not have a rising trend. In fact, the 100mm and 300mm pipes have slightly lower results in the four-week results compared to the one-week. As well, throughout all the installations, there is no definite pattern to any of the installations. The results seem to slightly vary throughout. Therefore, what can be understood from the vane shear test in clay is that one, there is definite evidence of shear strength within the annulus through the span of 1 week to 4 weeks and two, four-weeks within the installation of the pipes is too minimal a time to compare weekly shear strength values derived from the vane shear test. The second point is true because the values do not change greatly and to see a possible change may require months or even possibly years. For our purposes, what can be interpreted is that there is considerable shear strength present in the annulus through most of the installations in clay.

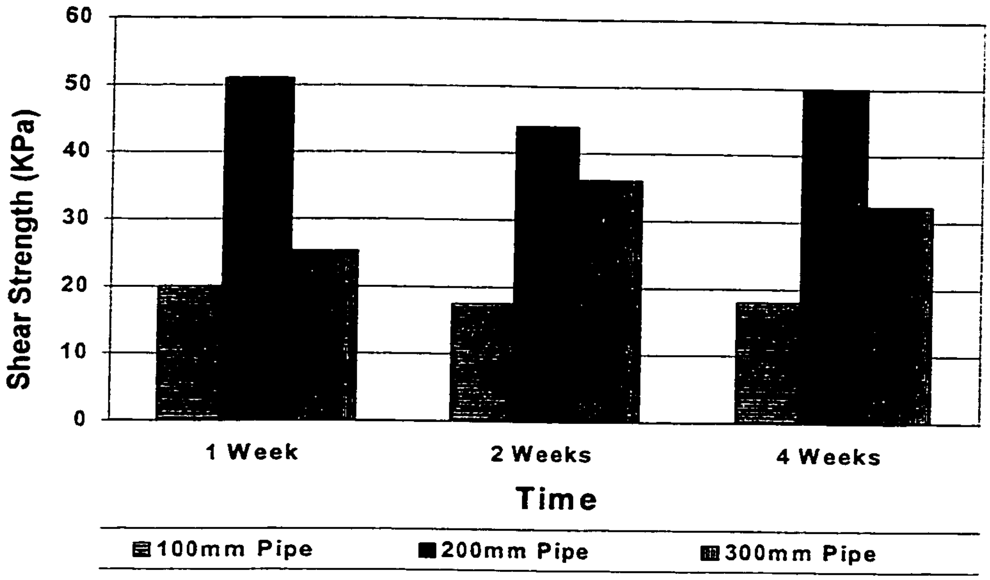

Figure 5-56 Vane Shear Results in Clay

The vane shear test in sand produced different results than that of clay. Figure 5-57 illustrates the results in sand.

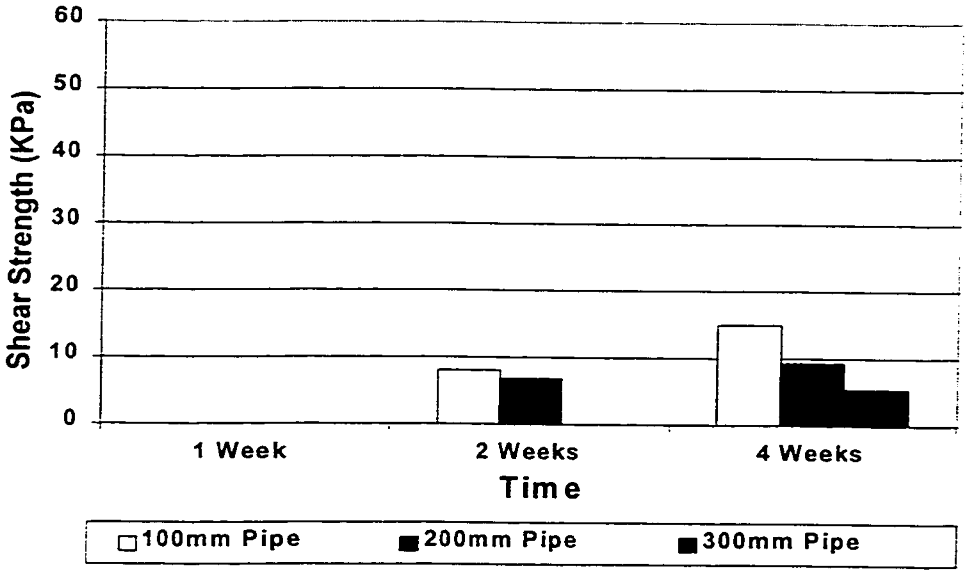

Figure 5-57 Vane Shear Results in Sand

As is evident, there is very minimal shear strength present in the sand installations. While excavating to these cross-sections it was apparent that the annulus still exhibited very fluid like properties. In fact, in many instances the slurry would flow right out of the annular region into the small pit created for visual observation. In the one-week test, the cross-sections all exhibited no shear strength due to the fluid like state of the annulus. It was only after two weeks did signs of shear strength evolve. In fact, it was only till the four-week cross-section that the 300mm pipe exhibited any signs of shear strength. Therefore, in the sand installations the immediate shear strength of all the installations was initially zero. It was only after a couple of weeks that the annulus did develop some shear strength. Unlike the clay installations, the early stage of the annulus in sand is still very volatile in that it exhibits fluid like properties. For it to reach a solid or more compact state, a much larger time frame is required compared to the clay installations. This is evident in Figure 5-58, where comparisons between the average of all the installations through each of the cross-sections in clay and sand are made.

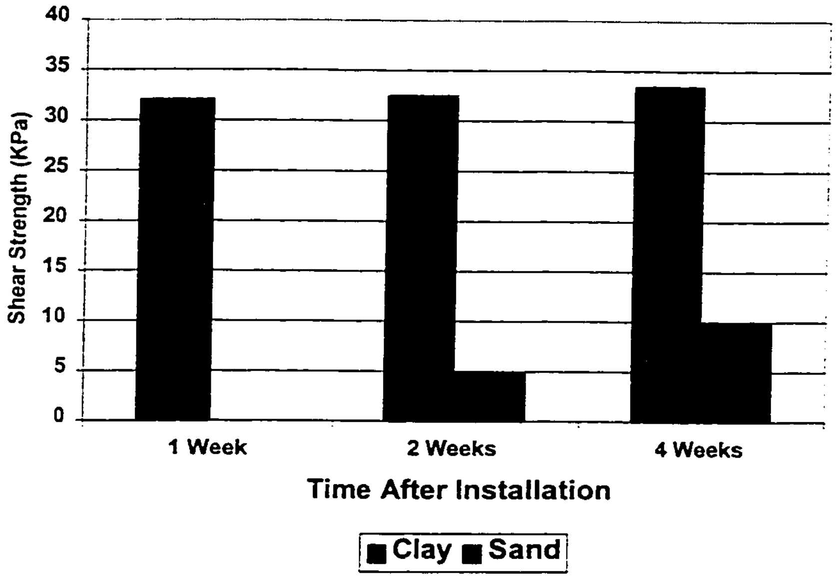

Figure 5-58 Vane Shear Average Results in All Installations

By viewing Figure 5-58, it is very clear that the clay installations exhibit much larger shear strength than the sand installations. Although, while the clay remains relatively the same through the four-week span, the sand installation does display a rising trend. This signifies that the state of the annular space in sand is rapidly changing or progressing to a higher strength state while the considerably higher developed clay annulus, is progressing at a slower rate. This is due to the fact that the clay annulus exhibits a much closer resemblance to the clay native soil properties than the sand annulus does with its native soil.

5.6 Moisture Content

The moisture content (m.c.) determines the amount of water present in a soil mass. It's defined as a ratio between the weight of the water to the weight of the solid particles. The location of the samples (to undergo m.c. calculation) were set at defined increments to the right side of the pipe. This was accomplished for all cross-sections from the one-week excavation to the four-week excavation.

In Appendix D, a table of the moisture content results is displayed. It is very apparent that there is a higher moisture content within the annulus than outside the annulus. This is to be expected with the insertion of the slurry into the annular region. Reinforcing this is Figures 5-59 to 5-60, which displays the comparison between the average moisture content within the annulus and outside the annulus for the clay and sand installations. All samples taken within the annulus for a particular cross-section were averaged as well as those samples outside the annulus.

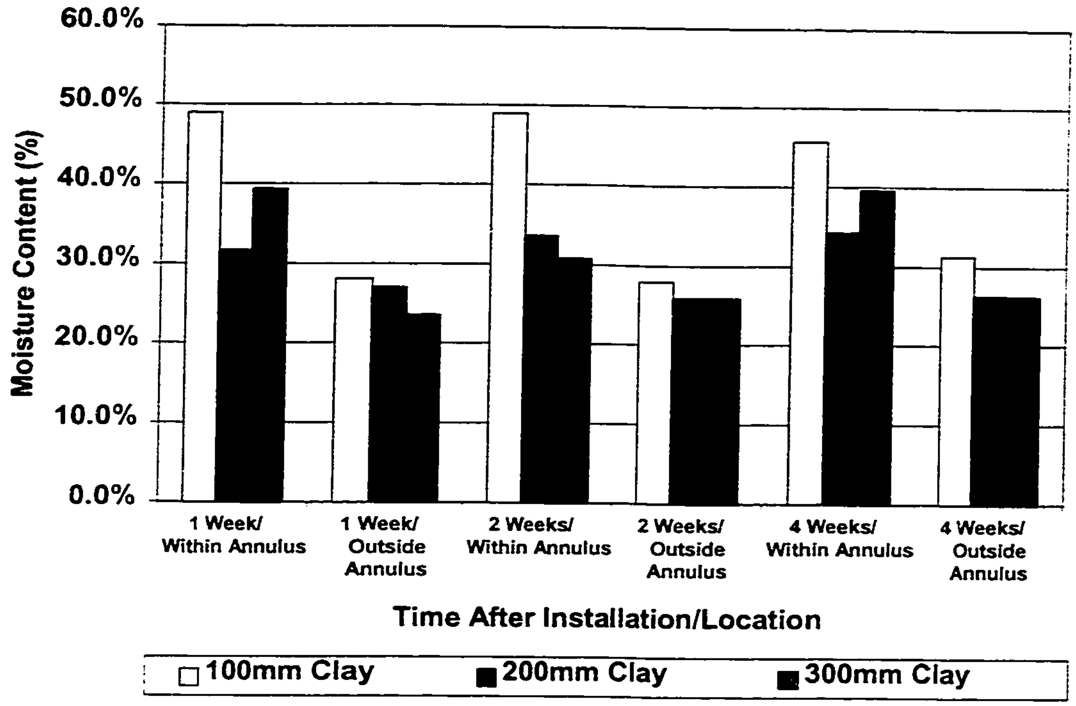

Figure 5-59 Average Moisture Content in the Clay Installations

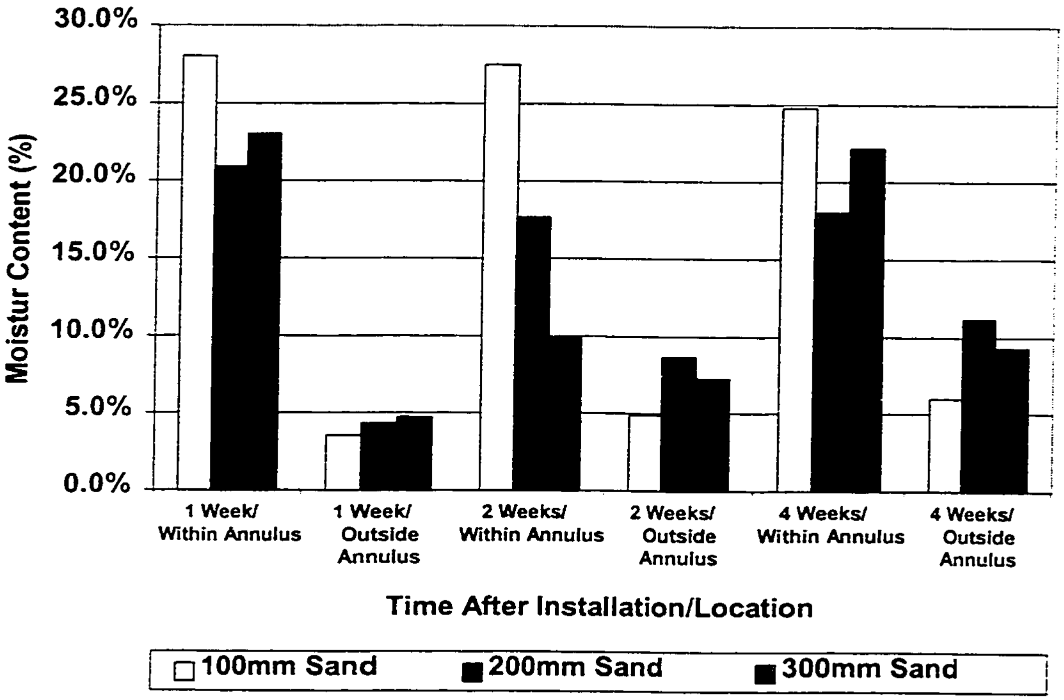

Figure 5-61 Average Moisture Content in the Sand Installations

It is very evident that there is a higher moisture content within the annulus than outside the annulus for all the cross-sectional excavations. The presence of water can effect the shear strength of the soil, which is evident when comparing the moisture content to the shear strength tests. Those tests comply with the fact that there is a higher moisture content within the annulus (resulting in lower shear strength) and a lower moisture content outside the annulus (resulting in higher shear strength). If we examine the moisture content for the clay installation a little closer (Figure 5-59) there are two definite trends that are noticed that can be related back to the shear strength tests. They are:

1. The 200mm pipe moisture content has values that are very close inside and outside the annulus (the lowest difference out of all the installations). This represents the fact that the annulus closely represents the native soil that surrounds it and which ultimately relates back to why the eight-inch exhibited the highest shear strength out of all the installations.
2. The dip in shear strength for the 300mm pipe installation, from the two-week to the four-week excavation, is evident as well by the increase in moisture content. Because there was an increase in moisture content for that cross-section, the effect of that was noticed when shear strength tests were done.

Furthermore, when comparing the difference between the native soil moisture content values and the annulus moisture content values for both installations, it is clear that the sand installation exhibits a very large difference between the two. The clay installations have a moisture content that is much closer in value to the native soil and this maybe why the clay installations have a higher shear strength value. The moisture content in the annulus for the sand installation carries values that are quite different than that of the native soil and this could relate to the short-term weakness of the annulus. The importance of moisture content is largely felt with the shear strength of the soil.

5.7 Conclusions

The first step of the analysis was taking visual observation of the annulus. The ability to view the annulus through different stages of post-installation allowed for a better appreciation and insight to the annulus. An important discovery was the fact that the annulus and placement of pipe varied through each section. This irregularity was caused from the machinery and the native soil that caused deviation within the drilling and backreaming. In addition, the existence of voids was present only in the sand installation. These voids were small but continuos gaps that were consistently adjacent to the side of the installed pipe. The next step of the analysis examined the drilling fluids. This section dealt with the components that make-up the drilling fluid as well as the properties that define the drilling fluid and subsequent slurry. The largest components that form the drilling fluid are water and bore-gel. Other components that can be added are used to improve the performance of the installation and alleviate any effects the native soil may impose. The properties of the drilling fluid/slurry that were examined include density, funnel viscosity, pH, sand content, gel strength, and filtrate/filter cake. These properties were examined and compared at different stages of the installation. Further along, the next sections focused on the strength of the annulus. A pocket penetrometer and a vane shear were used to calculate the shear strength of the annulus and surrounding areas. These tests were conducted at intervals of one day through to a span of four weeks. In the clay samples, the annulus, for the most part, exhibited some low shear strength initially but continued to rise as time progressed. In the sand samples, there were no recordings of shear strength within the one-day excavation and it was only until the second week that some low shear readings were measured with the use of the vane shear. Between the two, the clay installations exhibited an annulus which was more developed in terms of shear strength. The final section covered the moisture content of the annulus and adjacent areas. It was discovered that the moisture content within the annulus is higher than that of the adjacent areas. This also is directly related to shear strength, because the presence of water can reduce the shear strength of a soil stratum.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

The objective of this research was to analyze and assess the integrity of the annular space and develop an understanding into how it's shear strength may change through time. The objective was achieved through the installation of six HDPE pipes in two different soil sites. The pipes were successfully installed and subsequently underwent incremental cross-sectional excavations. These cross-sectional excavations would be the location where the visual assessment and testing of the annular space would occur.

Once a pipe was installed at either the clay or sand site, it would undergo post-installation cross-sectional excavations at one day, one week, two weeks, and four weeks (except for the 300mm pipe, which did not undergo the one day excavation). At each excavation, a pit would be excavated to allow for clear cross-sectional viewing of the pipe, annular space, and adjacent native soil. This is where the testing would begin and the objectives of the research fulfilled. The sequence of examination and testing would be as follows:

1. Visually assess the condition and state of the annulus.
2. Location of pipe in relation to the annulus.
3. Shape and extent (Zone of Influence) of the annulus.
4. Zone of Influence Ratio.
5. Existence of voids.
6. Pocket Penetrometer Test.
7. Vane Shear Test.
8. Moisture Content.
9. Drilling Fluid/Slurry Analysis (This happens during pipe installation).

Each cross-section had unique characteristics, but there were recognizable patterns or similarities within the clay installations and similarities within the sand installations. They are summarized and compared in Table 6-1. It is important to note that the details listed in Table 6-1 stem from the majority of cross-sectional excavations that were done and do not represent all the excavations. In addition, Table 6-1 is only an overview of some of the findings that were discovered during the cross-sectional excavations.

Table 6-1 Summary of Findings

Issue	Clay	Sand
Visual Assessment of the state of the annulus at 1 day.	Annulus shows signs of strength by holding in place during excavation but still fluid-like upon touch.	Annulus very fluid and weak. Annular composition flowing out of annulus during excavation of cross-section.
Visual Assessment of the state of the annulus at 4 weeks.	Annulus has improved substantially. No longer does it exhibit a fluid state but rather closer to a solid state.	Annulus still very fluid and weak although it does remain in the annulus during excavation.
Location of pipe in relation to the annular space.	Pipe remains centered in most of the cross-sections but there are a few cross-sections that are not centered.	Pipe is continually in the upper quadrant, either centered or off to a side.
Shape and Extent of Annulus (Zone of Influence)	Annulus is constantly changing in shape and extent. It is consistently larger than the backream size.	Annulus is constantly changing in shape and extent. It is consistently larger than the backream size.
Zone of Influence Ratio	Random – Indicating that the extent of the annulus is constantly changing vertically and horizontally	Under 1 – Indicating that the vertical Z.O.I. is consistently larger than the horizontal Z.O.I..
Existence of Voids	None detected.	Yes they did exist in some cross-sections.
Shear Strength of the annulus at 1 day	In most cases there was low values of shear strength	Zero.
Shear Strength of the annulus at 4 weeks	The shear strength increased considerably over the time period	There were very low values of shear strength detected.
Moisture Content Comparison	Higher within the annulus compared to adjacent native soil.	Substantially higher in annulus compared to adjacent native soil
Moisture Content within Annulus	Remained relatively the same during the 4 week span.	Remained relatively the same during the 4 week span.
Density of Drilling Fluid/Slurry	Density remained relatively constant at a value slightly higher than water (average approx. 8.8 lbs/gal).	Density was consistently higher in slurry samples than that of initial sample. (average approx. 12.3 lbs/gal)
Funnel Viscosity of Drilling Fluid/Slurry	The funnel viscosity of the samples increased slightly as installation progressed. Slightly lower than sand. (average approx. 47.1 secs/qt)	The funnel viscosity increased slightly as installation progressed. Slightly higher than clay. (average approx. 55.9 secs/qt)
pH of Drilling Fluid/Slurry	Remained consistently between 9-10.	Remained consistently between 9-10.
Sand Content of Drilling Fluid/Slurry	Very minimal readings.	Slurry samples consistently above 20%.
Gel Strength of Drilling Fluid/Slurry	Minimal readings.	Minimal readings.
Filter cake/Filtrate of Drilling Fluid/Slurry	Consistent low values.	Consistent low values.

In addition to Table 6-1, the annulus can be summed up by the following. The annulus is created as a by-product from the installation of a product pipe. It is a necessary component during the installation of a pipe to allow flow to exist in the borehole. Its size is directly related to the backreamer (which is 1.5 times the size of the pipe being installed) and the minor deviations created during installation. These deviations cause the annulus to constantly change slightly in shape and extent. The annulus is made up primarily of bentonite, water, and the native soil. The bentonite is used to create the outer cake layer and to suspend and remove cuttings from the drilling operation. The water is necessary to install the pipe and to create the flow needed. These two constituents along with the native soil reflect on the integrity of the annulus.

The properties of the native soil along with how it reacts with water will determine a large component of the annulus stature. As was evident between the clay and sand installations, the state of the clay annulus was far maturer than the sand installation. It exhibited strength and cohesive characteristics while the annulus in sand was very fluid and did not exhibit any shear strength initially. In addition, the sand installations did exhibit voids, which is another sign of non-cohesion. All in all, when it comes to the shear strength of the annular space, it is really dependent on the characteristics of the native soil and how it reacts with water. Even within the same soil site or even the same installation, there are differences between every cross-section. Because the soil naturally exhibits different stratums or pockets of compositions, strengths and moisture content, the annulus reflects this as well. The annulus was discovered to change in shape, texture, composition, shear strength, and moisture content from cross-section to cross-section. However, the primary and most important function of the post-installation annulus is to act like the native soil and provide security to the installed pipe. Through our quantitative tests and visual assessments, I believe this is accomplished. Even though the annulus is constantly changing in attributes within a pipe installation, it holds one common aspect throughout the cross-sections. That being, that the pipes that were installed were very secure in their locations and there was absolutely no signs or evidence of any potential movement. It is difficult to be absolutely positive that the future won't cause any displacements, however, from the six pipes installed and the twenty-two cross-sections that were excavated and inspected, it seems to support the notion that the annulus does provide the necessary attributes for the short term and long term success of a pipe installation using Horizontal Directional Drilling.

Recommendations for future research include expanding the scope of research to include other soil sites, sizes of pipe, types of pipe and lengths of pipe. In addition to changing the pipe, it would be beneficial to try different combinations of drilling fluid and different depths of installation. It would also be very beneficial to investigate the annulus over a longer period of time. This may bring validity to the long-term soundness of the installed pipe. Furthermore, more elaborate strength tests or other geotechnical in-situ or laboratory tests to measure properties of the annulus would be advantageous.

CHAPTER 7 REFERENCES

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Appendix A

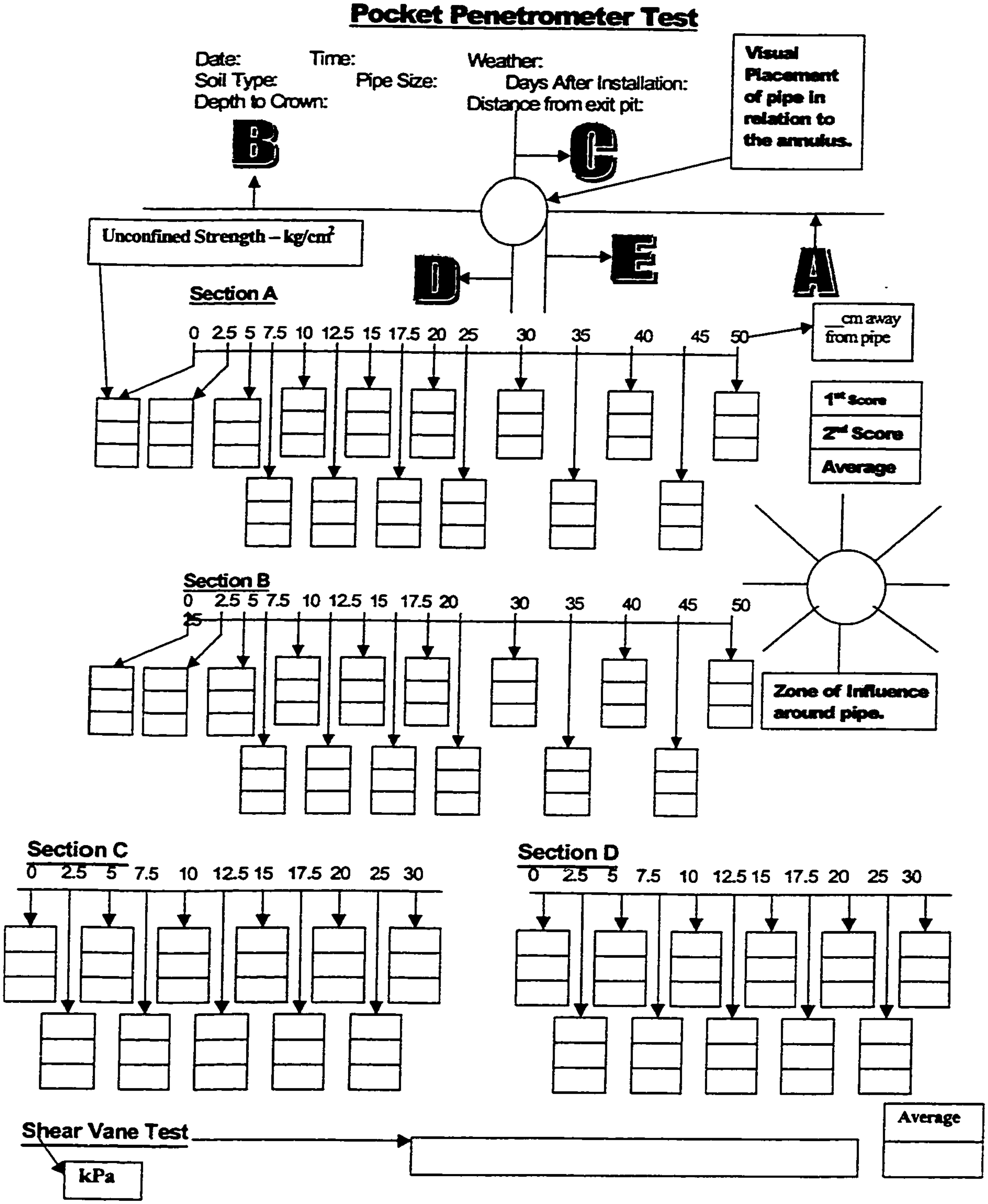
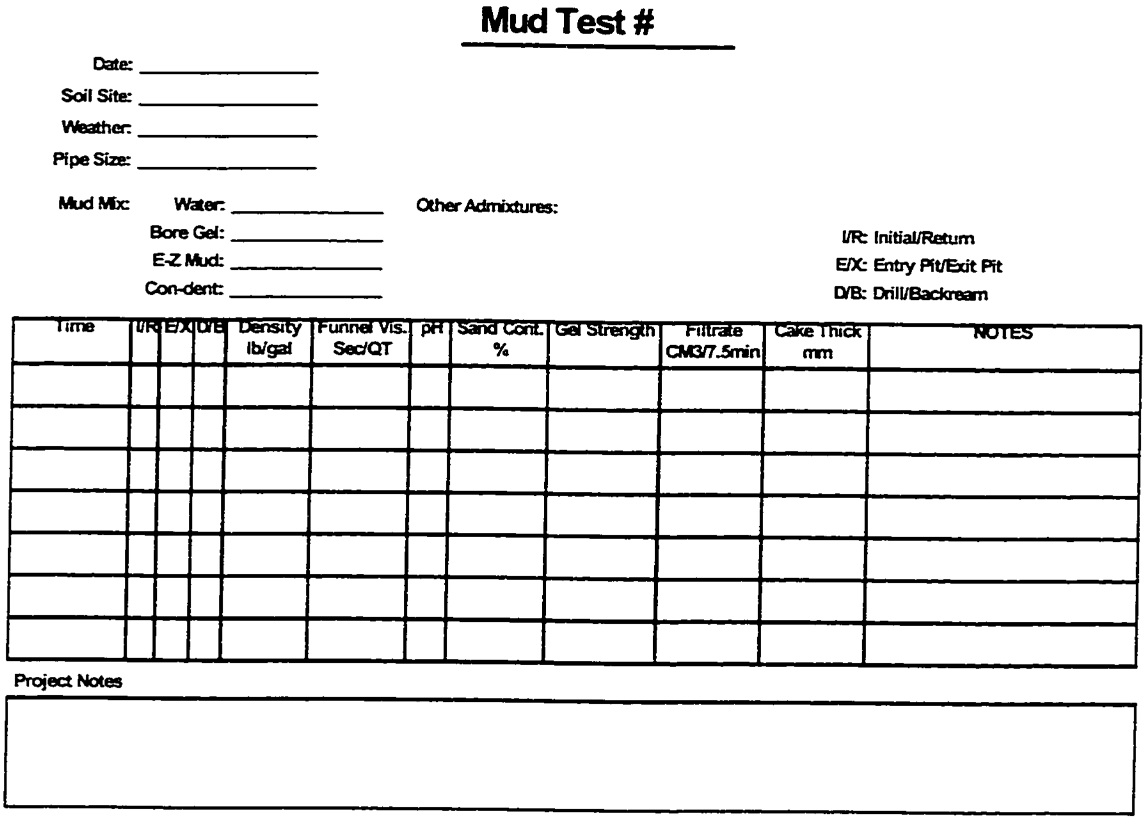


Figure A-1 Pocket Penetrometer and Vane Shear Field Data Sheet



Mud Test # ____________

Date: ____________
Soil Site: ____________
Weather: ____________
Pipe Size: ____________

Mud Mix: Water: ____________ Other Admixtures:
Bore Gel: ____________
E-Z Mud: ____________
Con-dent: ____________

I/R: Initial/Return
E/X: Entry Pit/Exit Pit
D/B: Drill/Backream

Time	I/R	E/X	D/B	Density lb/gal	Funnel Vis. Sec/QT	pH	Sand Cont. %	Gel Strength	Filtrate CM3/7.5min	Cake Thick mm	NOTES

Project Notes

Figure A-2 Drilling Fluid Analysis Field Data Sheet

Appendix B

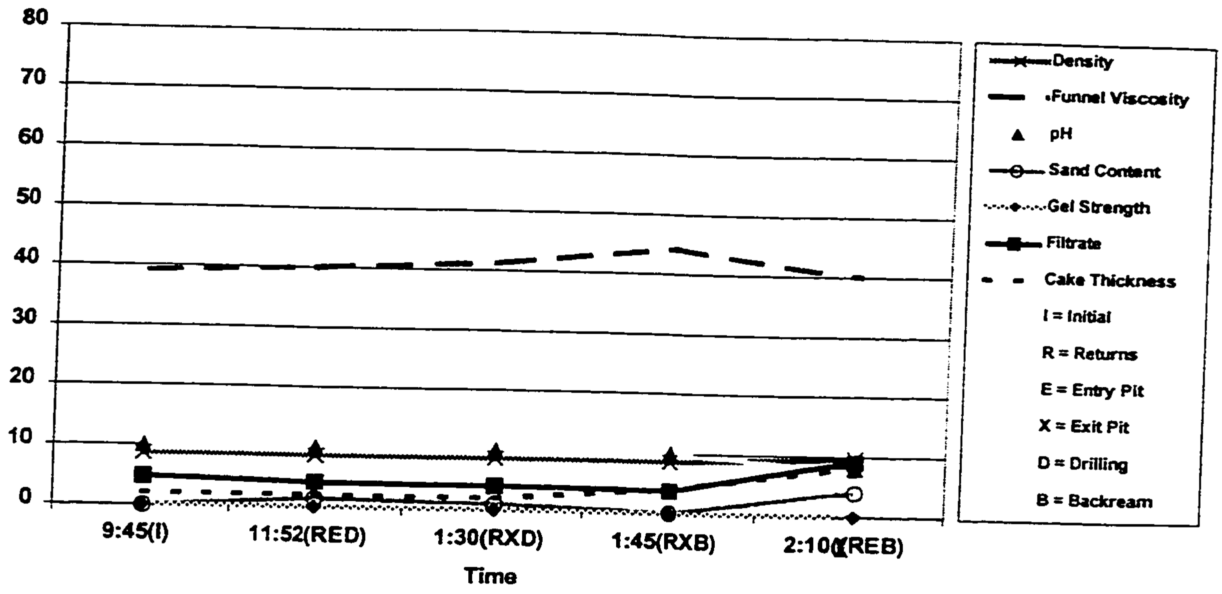


Figure B-1 Drilling Fluid Summary – 100mm Pipe in Clay

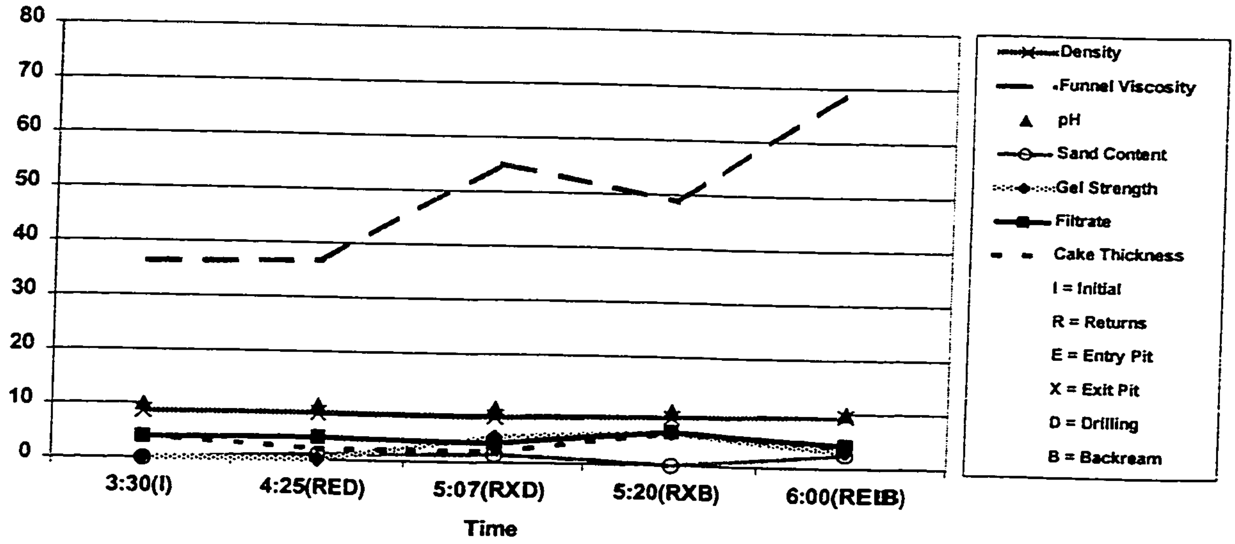


Figure B-2 Drilling Fluid Summary – 200mm Pipe in Clay

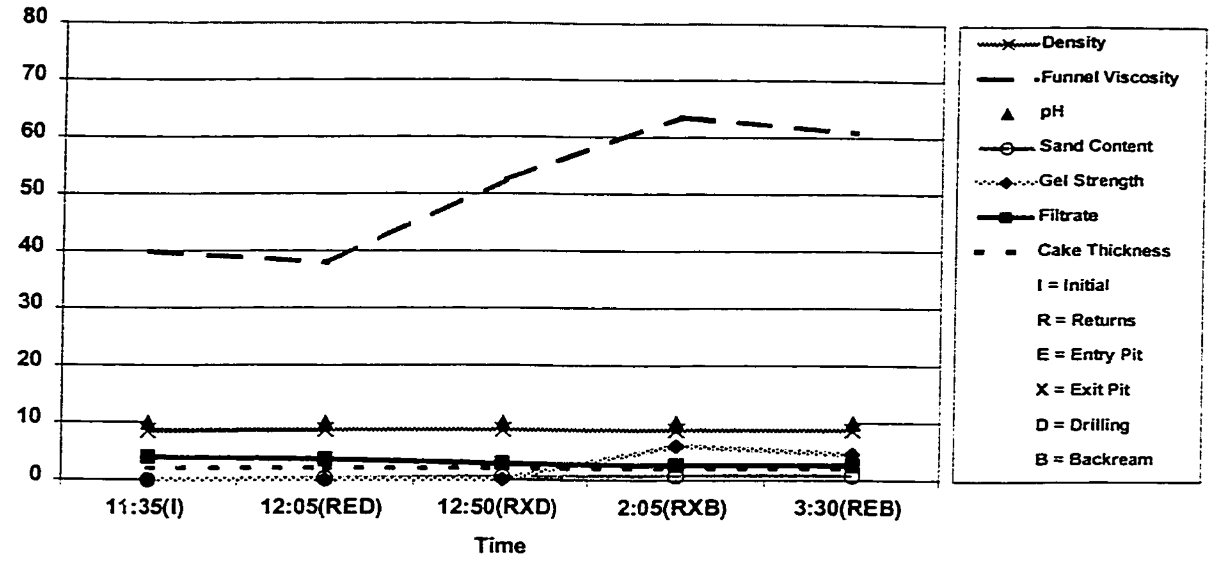


Figure B-3 Drilling Fluid Summary – 300mm Pipe in Clay

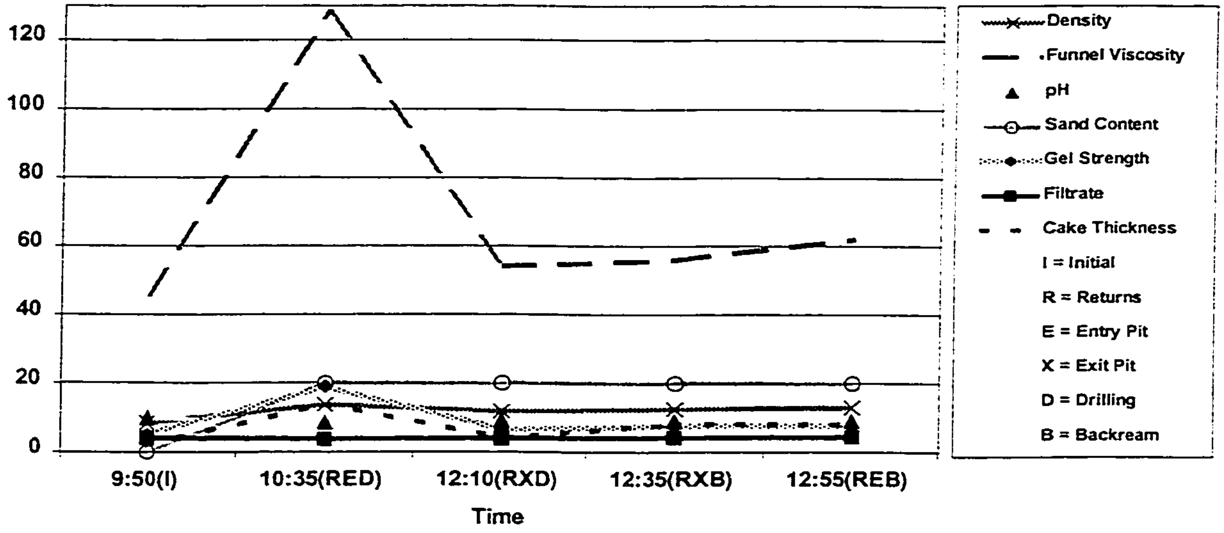


Figure B-4 Drilling Fluid Summary – 100mm Pipe in Sand

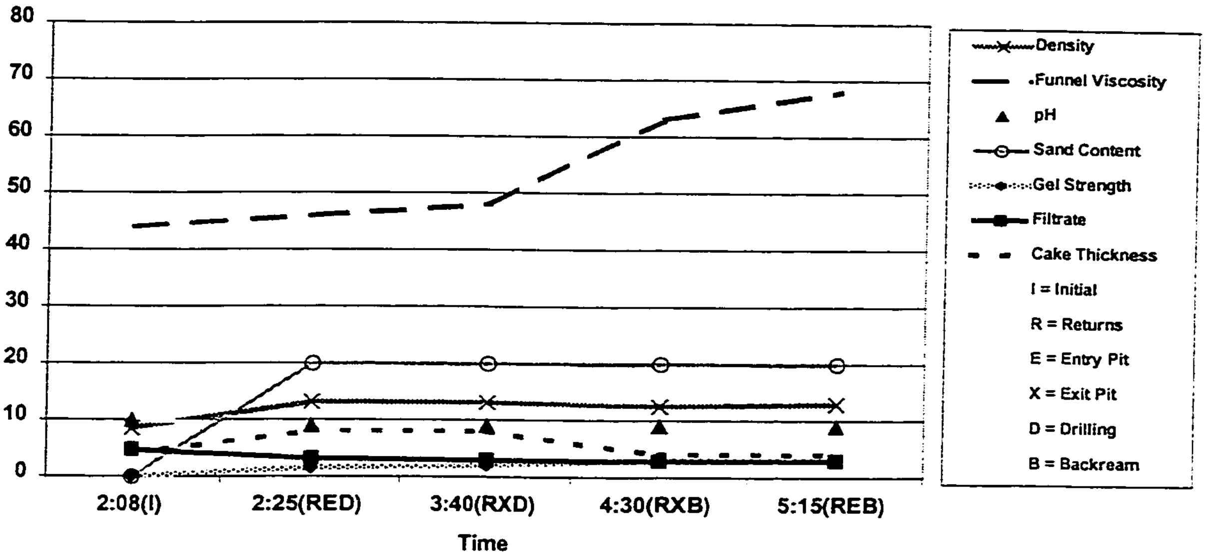


Figure B-5 Drilling Fluid Summary – 200mm Pipe in Sand

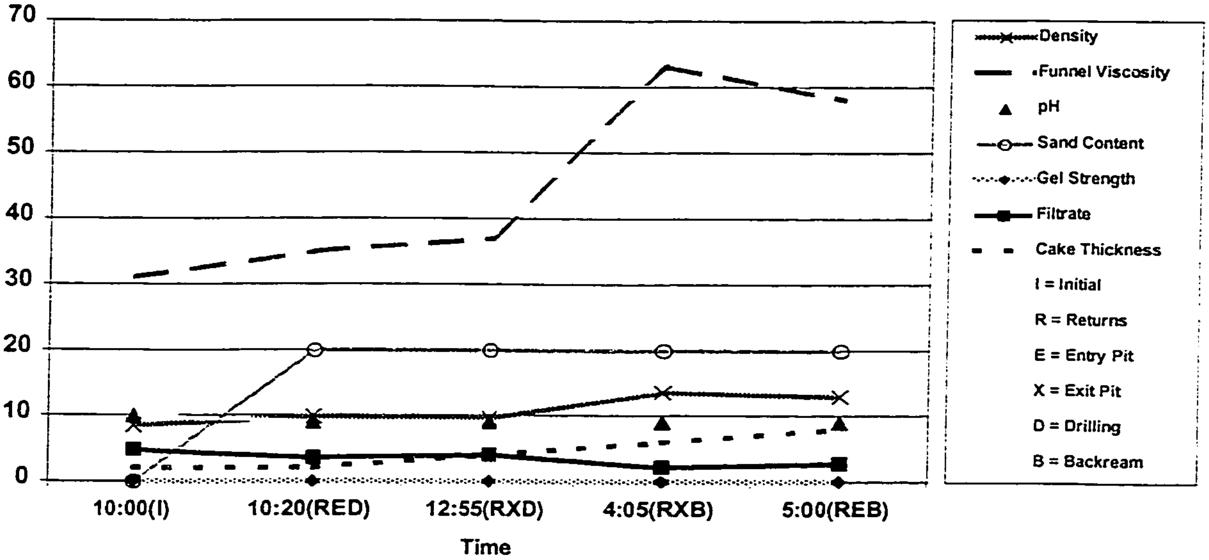


Figure B-6 Drilling Fluid Summary – 300mm Pipe in Sand

Table B-1 Summary of Drilling Fluid/Slurry Sampling

Pipe Size (inches)	Soil	Time	Density (lb/gal)	Funnel Viscosity (Secs/Qt)	pH	Sand Content (%)	Gel Strength (lb/100ft2)	Filtrate (cc/7.5min)	Cake Thickness 32nd's of an inch
4"	clay	9:45(I)	8.6	39.2	10	0	0	4.8	2
4"	clay	11:52(RED)	8.6	40.1	10	1.5	0	4.2	2
4"	clay	1:30(RXD)	8.6	41.3	10	1	0	4.1	2
4"	clay	1:45(RXB)	8.6	44.3	10	0.1	0	3.8	4
4"	clay	2:10(REB)	9.6	40	8	4	0	9	8
8"	clay	3:30(I)	8.6	36.3	10	0	0	4	4
8"	clay	4:25(RED)	8.6	36.7	10	1	0	4.2	2
8"	clay	5:07(RXD)	8.4	55.1	10	1.5	4.7	3.6	2
8"	clay	5:20(RXB)	8.8	48.7	10	0	6	6.2	6
8"	clay	6:00(REB)	9.5	70	10	2.5	3	4.3	4
12"	clay	11:35(I)	8.6	39.9	10	0	0	4	2
12"	clay	12:05(RED)	8.7	38	10	0.25	0	3.6	2
12"	clay	12:50(RXD)	8.7	52.4	10	0.5	0	2.8	2
12"	clay	2:05(RXB)	8.7	63.6	10	0.75	6	2.6	2
12"	clay	3:30(REB)	8.7	60.8	10	0.75	4.5	2.6	2
4"	sand	9:50(I)	8.4	46	10	0	5	4.1	2
4"	sand	10:35(RED)	13.7	128	8.5	20	19	3.8	14
4"	sand	12:10(RXD)	11.7	54	9	20	6.5	4	4
4"	sand	12:35(RXB)	12.4	56	9	20	7.5	4.2	8
4"	sand	12:55(REB)	12.9	62	9	20	7.5	4.4	8
8"	sand	2:08(I)	8.45	44	10	0	0	4.8	4
8"	sand	2:25(RED)	13.1	46	9	20	1.5	3.2	8
8"	sand	3:40(RXD)	13.05	48	9	20	2	3	8
8"	sand	4:30(RXB)	12.5	63	9	20	3	2.9	4
8"	sand	5:15(REB)	12.9	68	9	20	3	3	4
12"	sand	10:00(I)	8.45	31	10	0	0	4.8	2
12"	sand	10:20(RED)	9.8	35	9	20	0	3.6	2
12"	sand	12:55(RXD)	9.5	37	9	20	0	4	4
12"	sand	4:05(RXB)	13.5	63	9	20	0	2.2	6
12"	sand	5:00(REB)	12.9	58	9	20	0	2.8	8

Table B-2 Summary of Annular Flow Velocity (backream)

Pipe Size (inches)	Soil Type	ID Hole	OD Drillpipe	Pump Rate (Barrels per minute)	Annular Velocity (feet/minute)
4(100mm)	clay	6”	2.375”	0.905	23.00
8(200mm)	clay	12”	2.375”	0.905	5.05
12(300mm)	clay	18”	2.375”	0.905	2.194
4(100mm)	sand	6”	2.375”	0.905	23.00
8(200mm)	sand	12”	2.375”	0.905	5.05
12(300mm)	sand	18”	2.375”	0.905	2.194

Appendix C

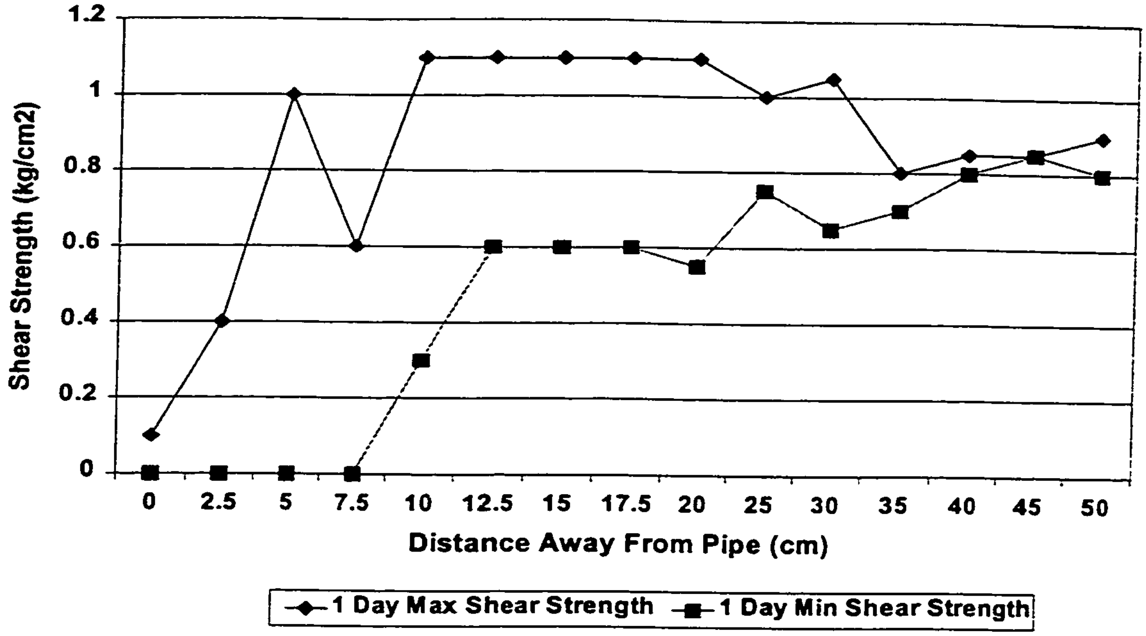


Figure C-1 Maximum versus Minimum Comparison for the 100mm Pipe in Clay (One Day Excavation)

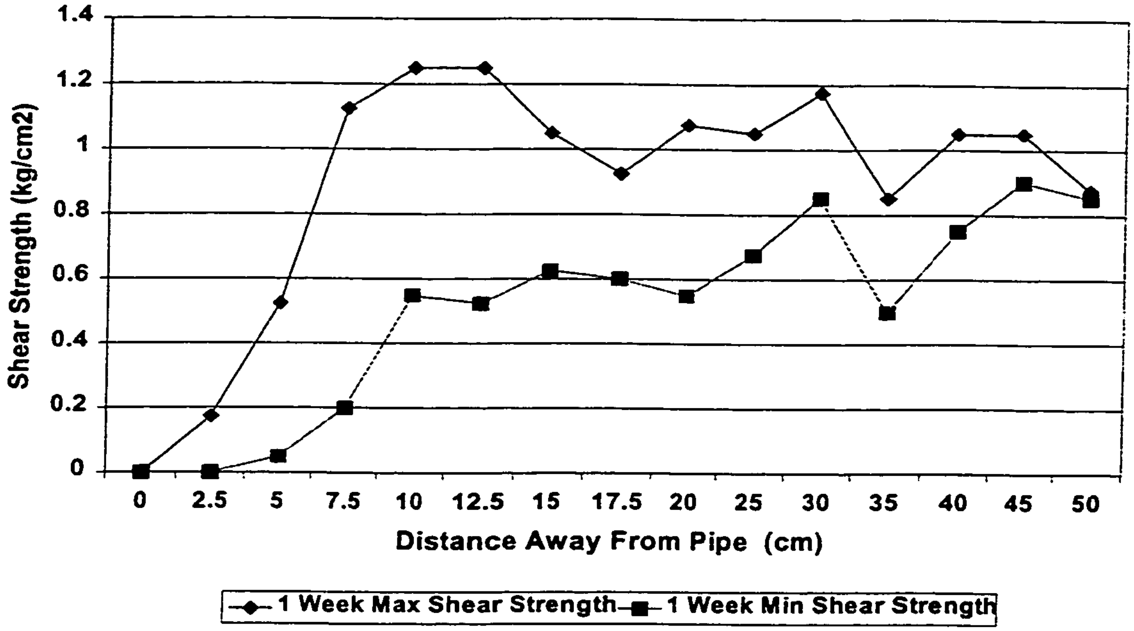


Figure C-2 Maximum versus Minimum Comparison for the 100mm Pipe in Clay (One Week Excavation)

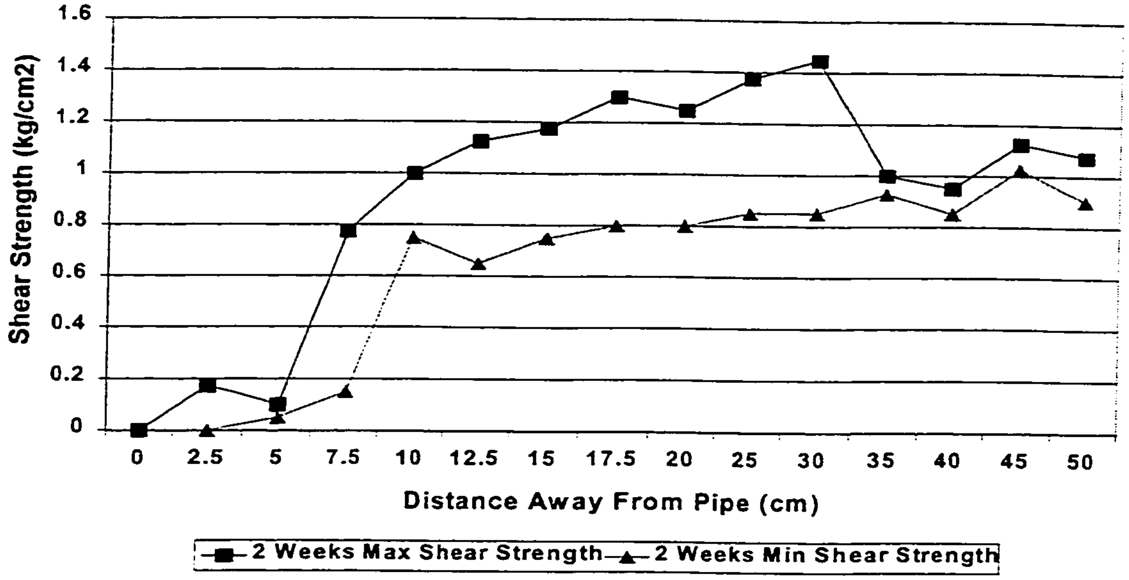


Figure C-3 Maximum versus Minimum Comparison for the 100mm Pipe in Clay (Two Week Excavation)

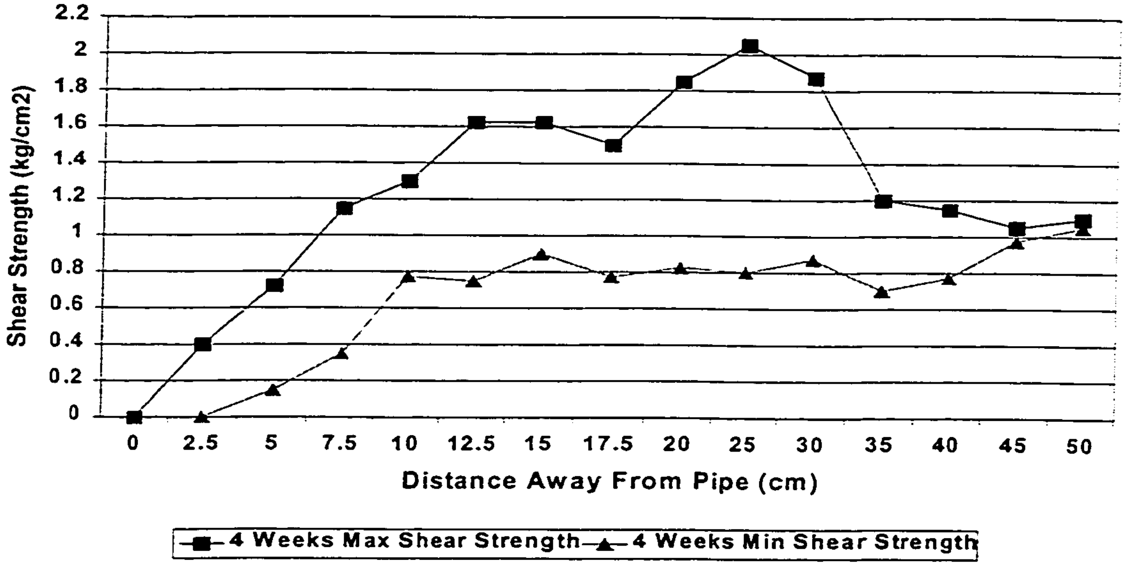


Figure C-4 Maximum versus Minimum Comparison for the 100mm Pipe in Clay (Four Week Excavation)

Table C-1 Pocket Penetrometer Results for the 100mm Installation in Clay

Right

Distance Away	1-Day	1-Wk	2-Wks	4-Wks
0	[illegible]	[illegible]	[illegible]	[illegible]
2.5	[illegible]	[illegible]	[illegible]	[illegible]
5	1	[illegible]	[illegible]	0.15
7.5	0.6	0.425	0.525	0.65
10	0.6	0.6	0.85	1.025
12.5	0.6	0.85	1.125	1.025
15	0.6	0.75	1.175	1.15
17.5	0.6	0.75	0.95	1.075
20	0.55	0.75	1.175	0.95
25	0.75	1	1.1	0.8
30	0.65	1.05	1.175	1.05
35	0.7	0.5	1	0.7
40	0.8	0.75	0.95	0.775
45	0.85	0.9	1.125	0.975
50	0.8	0.875	1.075	1.05

Upper

Distance Away	1-Day	1-Wk	2-Wks	4-Wks
0	[illegible]	[illegible]	[illegible]	[illegible]
2.5	[illegible]	[illegible]	[illegible]	[illegible]
5	[illegible]	0.525	[illegible]	0.725
7.5	0	1.125	0.775	1.15
10	1.1	1.25	1	1.3
12.5	1.1	1.225	0.975	1.625
15	1.1	1.05	1.125	1.625
17.5	1.1	0.925	1.3	1.4
20	1.1	1.075	1.25	1.85
25	1	0.975	1.375	2.05
30	1.05	1.175	1.45	1.875

Left

Distance Away	1-Day	1-Wk	2-Wks	4-Wks
0	0	0	[illegible]	[illegible]
2.5	0	0	[illegible]	[illegible]
5	0	0.1	[illegible]	0.075
7.5	0	0.375	0.15	0.35
10	0.3	0.55	0.75	0.775
12.5	0.8	0.525	0.65	0.75
15	0.7	0.625	0.75	0.9
17.5	0.75	0.6	0.8	0.775
20	0.8	0.55	0.8	0.825
25	0.8	1.05	0.85	0.95
30	0.85	0.85	0.85	0.875
35	0.8	0.85	0.925	1.2
40	0.85	1.05	0.85	1.15
45	0.85	1.05	1.025	1.05
50	0.9	0.85	0.9	1.1

Lower

Distance Away	1-Day	1-Wk	2-Wks	4-Wks
0	[illegible]	[illegible]	[illegible]	[illegible]
2.5	[illegible]	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	[illegible]
7.5	0.25	0.2	0.2	0.6
10	0.6	0.65	0.75	1.2
12.5	0.7	0.825	0.825	1.35
15	0.85	1.025	1.05	1.525
17.5	0.8	0.875	0.9	1.5
20	0.95	0.75	1.075	1.35
25	0.8	0.675	0.875	1.55
30	1	0.9	1	1.575

Distance Away	--Distance Away From Pipe Edge
Shear Strength Values	--Average Values (kg/cm2)
▨	--Within the Annulus

Table C-2 Pocket Penetrometer Results for the 200mm Installation in Clay

Right

Distance Away	1-Day	1-Wk	2-Wks	4-Wks
0	[illegible]	[illegible]	[illegible]	[illegible]
2.5	[illegible]	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	[illegible]
7.5	0.3	[illegible]	[illegible]	[illegible]
10	0.25	0.4	[illegible]	[illegible]
12.5	0.4	0.7	0.9	0.9
15	0.5	0.45	0.8	0.85
17.5	0.5	0.7	0.8	0.9
20	0.8	0.85	0.85	0.85
25	1	0.65	0.8	0.85
30	0.75	0.55	0.85	0.9
35	0.8	0.75	0.85	1.25
40	1.2	0.65	1.05	0.85
45	0.9	0.9	0.95	1
50	0.7	0.9	1.1	1

Upper

Distance Away	1-Day	1-Wk	2-Wks	4-Wks
0	[illegible]	[illegible]	[illegible]	[illegible]
2.5	[illegible]	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	[illegible]
7.5	[illegible]	[illegible]	[illegible]	[illegible]
10	[illegible]	0.95	[illegible]	1.25
12.5	1	0.8	1.1	1.15
15	0.85	0.9	1.3	1.15
17.5	0.95	0.9	0.9	0.95
20	0.9	0.9	1.15	0.85
25	0.55	0.95	1.15	1.15
30	0.75	1.1	1.2	1.3

Left

Distance Away	1-Day	1-Wk	2-Wks	4-Wks
0	0.25	[illegible]	[illegible]	[illegible]
2.5	0.25	[illegible]	[illegible]	[illegible]
5	0.35	0.2	[illegible]	[illegible]
7.5	0.45	0.25	[illegible]	[illegible]
10	[illegible]	0.45	[illegible]	1.1
12.5	0.8	0.6	0.75	1.1
15	0.65	0.7	0.9	0.9
17.5	1	0.65	0.8	0.75
20	0.8	0.45	0.9	0.85
25	0.7	0.65	0.85	0.7
30	0.7	0.65	0.7	0.85
35	0.9	0.7	0.75	0.65
40	0.65	0.75	0.85	0.7
45	0.9	0.8	0.9	0.7
50	0.5	0.8	0.7	0.75

Lower

Distance Away	1-Day	1-Wk	2-Wks	4-Wks
0	[illegible]	[illegible]	[illegible]	[illegible]
2.5	0.25	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	1.15	1.05
7.5	0.5	1.05	1.15	1.15
10	0.75	0.85	1.15	1.2
12.5	0.85	0.95	1.2	1
15	0.9	1.2	1.2	1
17.5	0.75	1.2	1.1	1.1
20	1	1.2	1.1	1.1
25	0.95	1.6	0.85	1.1
30	1	1.2	1.2	0.8

Distance Away	--Distance Away From Pipe Edge
Shear Strength Values	--Average Values (kg/cm2)
▨	--Within the Annulus

Table C-3 Pocket Penetrometer Results for the 300mm Installation in Clay

Right			
Distance Away	1-Wk	2-Wks	4-Wks
0	▨ [illegible]	▨ [illegible]	▨ [illegible]
2.5	▨ [illegible]	▨ [illegible]	▨ [illegible]
5	▨ [illegible]	▨ [illegible]	▨ [illegible]
7.5	▨ [illegible]	0.3	▨ [illegible]
10	1.2	0.3	▨ [illegible]
12.5	1.3	0.3	0.15
15	1.3	0.85	0.4
17.5	1.3	0.8	0.7
20	1.25	0.85	0.95
25	1.4	0.95	0.85
30	1.35	0.8	0.75
35	1.4	1	0.95
40	1.25	0.95	1
45	0.8	1.15	1.25
50	1.35	1	1.1

Upper			
Distance Away	1-Wk	2-Wks	4-Wks
0	▨ [illegible]	▨ [illegible]	▨ [illegible]
2.5	▨ [illegible]	▨ [illegible]	▨ [illegible]
5	▨ [illegible]	0.1	▨ [illegible]
7.5	▨ [illegible]	0.85	▨ [illegible]
10	▨ [illegible]	0.8	0.7
12.5	▨ [illegible]	0.9	1
15	▨ [illegible]	1	1
17.5	▨ [illegible]	0.9	1.1
20	▨ [illegible]	0.95	1
25	0.95	0.95	1.2
30	0.75	1.1	1.15

Left			
Distance Away	1-Wk	2-Wks	4-Wks
0	▨ [illegible]	▨ [illegible]	▨ [illegible]
2.5	▨ [illegible]	▨ [illegible]	▨ [illegible]
5	▨ [illegible]	▨ [illegible]	▨ [illegible]
7.5	▨ [illegible]	▨ [illegible]	▨ [illegible]
10	▨ 0.05	▨ 0.2	▨ 0.5
12.5	0.15	0.85	1.05
15	0.15	0.8	1.1
17.5	0.4	0.8	0.85
20	0.3	0.7	1.2
25	0.65	0.75	1.2
30	0.9	0.75	0.95
35	1.1	0.75	1.2
40	1.2	0.75	1.1
45	1.15	0.85	0.9
50	1.25	1	1.1

Lower			
Distance Away	1-Wk	2-Wks	4-Wks
0	▨ [illegible]	▨ [illegible]	▨ [illegible]
2.5	▨ [illegible]	▨ [illegible]	▨ [illegible]
5	1	▨ [illegible]	▨ [illegible]
7.5	1.55	▨ [illegible]	▨ [illegible]
10	1.65	▨ [illegible]	▨ [illegible]
12.5	1.75	▨ 0.45	0.75
15	1.4	▨ 1.25	0.85
17.5	1.65	▨ 0.9	0.95
20	1.45	1.4	1.2
25	1.25	1.25	1.4
30	1.5	1.35	1.35

Distance Away	--Distance Away From Pipe Edge
Shear Strength Values	--Average Values (kg/cm2)
▨	--Within the Annulus

Table C-4 Vane Shear Results

Pipe Size	Soil Type	Weeks After Installation	Vane Shear Readings	Max V.S.	Min V.S.	Average V.S.
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	clay	1	42,52,48,62	62	42	51
12	clay	1	28,20,28	28	20	25.3
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	clay	2	40,40,40,52,48	52	40	44
12	clay	2	32,40,38,34	40	32	36
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	clay	4	44,50,56	56	44	50
12	clay	4	31,22,38,38	38	22	32.3
4	sand	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	sand	1	-	-	-	-
12	sand	1	-	-	-	-
4	sand	2	6,9,9	9	6	8
8	sand	2	6,8,9,4	9	4	6.8
12	sand	2	-	-	-	-
4	sand	4	11,12,22	22	11	15
8	sand	4	8,9,11	11	8	9.3
12	sand	4	4,4,8	8	4	5.3

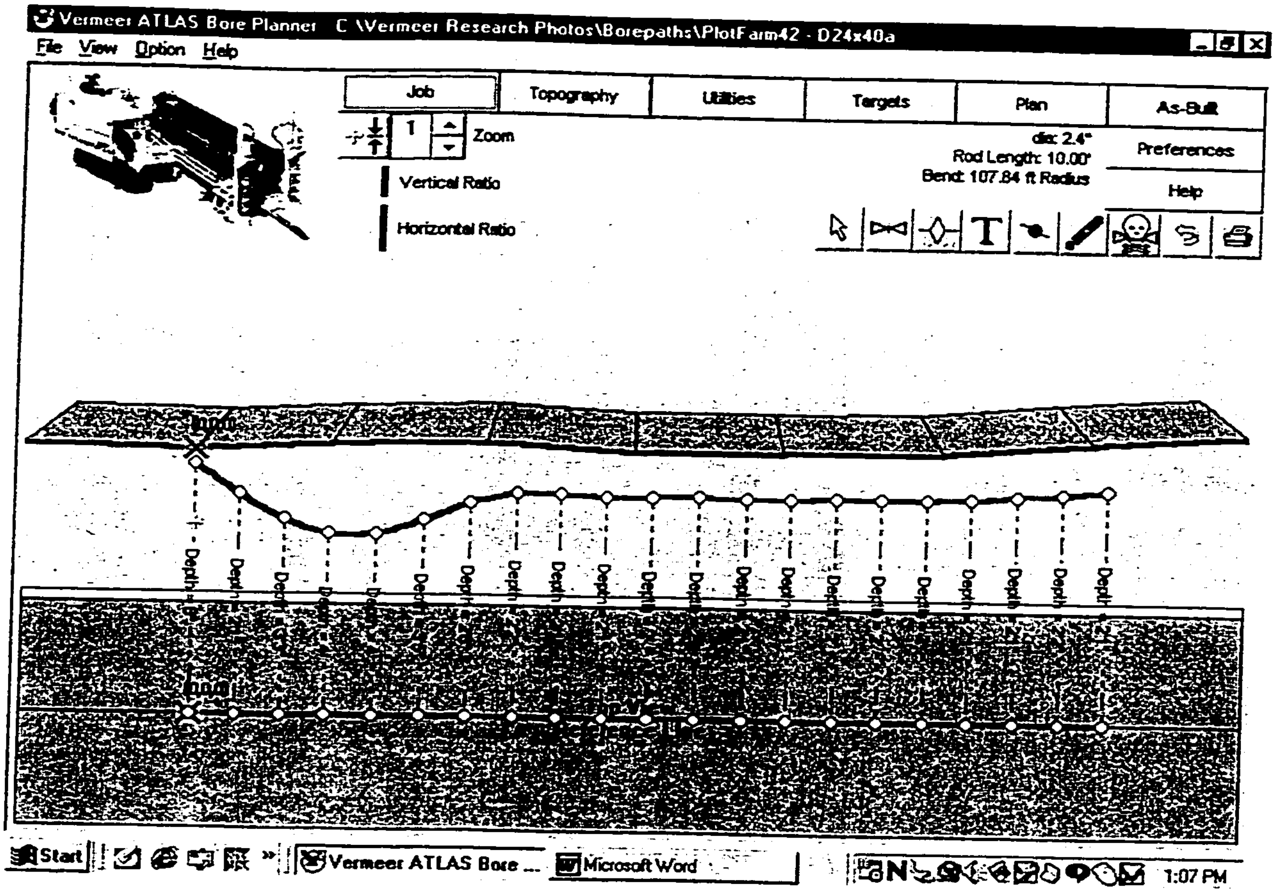
Appendix D

Table D-1 Moisture Content Results

Soil Type	Pipe Size	Distance Away From Pipe	M.C. - 1 Week	M.C. - 2 Weeks	M.C. - 4 Weeks
Clay	4	2.5	49.1%	49.1%	45.7%
Clay	4	5	33.3%	33.9%	33.4%
Clay	4	10	26.2%	25.6%	34.9%
Clay	4	20	26.5%	25.7%	26.3%
Clay	4	30	26.6%	26.7%	30.5%
Clay	8	2.5	32.4%	33.6%	34.9%
Clay	8	5	31.0%	27.0%	33.6%
Clay	8	10	27.9%	25.5%	25.9%
Clay	8	20	26.7%	25.6%	26.3%
Clay	8	40	26.6%	25.9%	27.1%
Clay	12	5	45.6%	30.8%	40.9%
Clay	12	10	33.1%	25.3%	38.4%
Clay	12	20	24.4%	25.5%	26.0%
Clay	12	40	23.7%	26.2%	26.2%
Clay	12	60	23.0%	27.1%	26.8%
Sand	4	2.5	28.0%	27.5%	24.8%
Sand	4	5	3.7%	7.8%	6.9%
Sand	4	10	3.6%	4.2%	5.8%
Sand	4	20	3.7%	3.7%	6.0%
Sand	4	30	3.1%	3.8%	5.2%
Sand	8	2.5	21.0%	17.6%	21.0%
Sand	8	5	20.8%	17.7%	15.1%
Sand	8	10	4.7%	11.4%	11.8%
Sand	8	20	4.2%	7.4%	13.2%
Sand	8	40	4.1%	7.1%	8.5%
Sand	12	5	22.9%	10.0%	22.8%
Sand	12	10	23.1%	9.8%	21.5%
Sand	12	20	5.3%	8.3%	13.7%
Sand	12	40	4.5%	8.0%	7.8%
Sand	12	60	4.3%	5.5%	6.3%

	–Values within Annulus

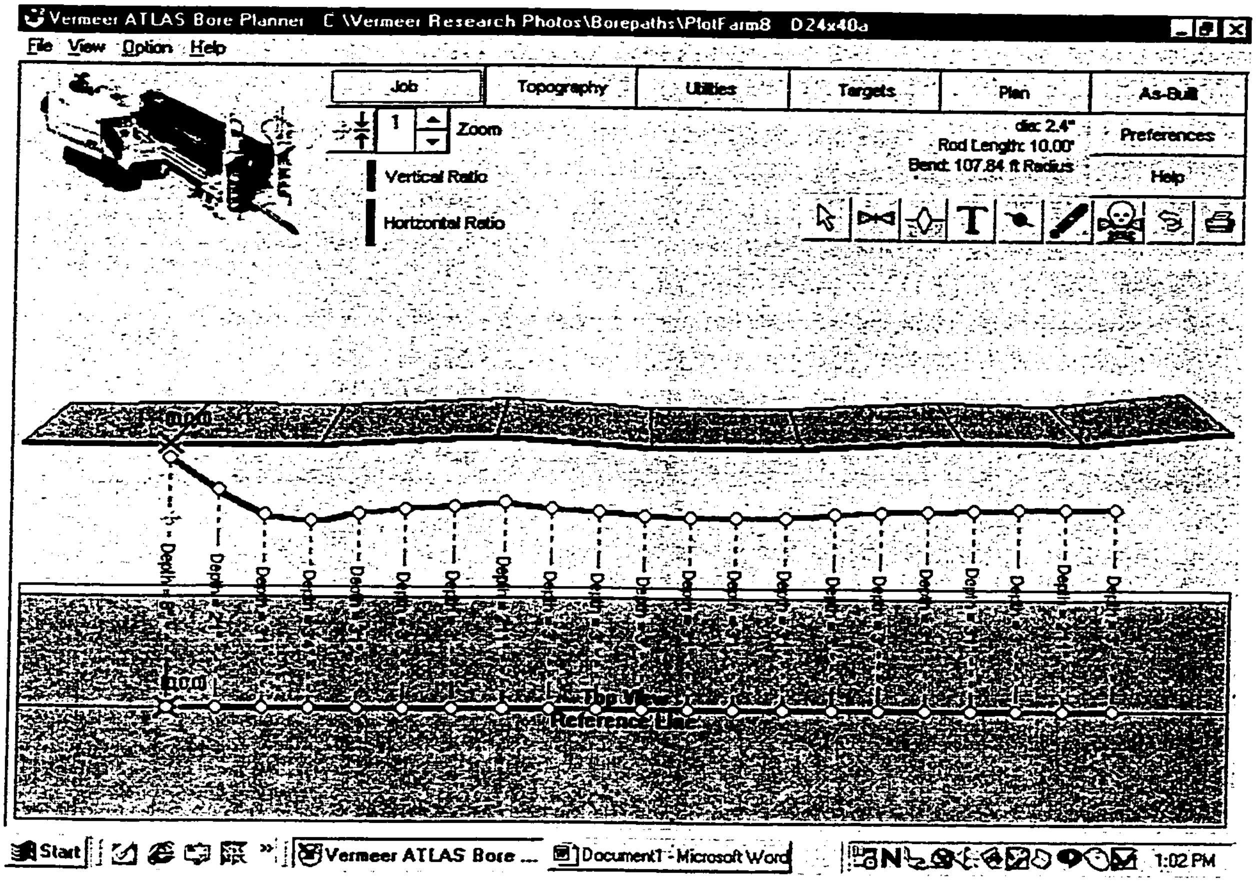
Appendix E



Vermeer ATLAS Bore Planner C:\Vermeer Research Photos\Borepaths\PlotFarm42 - D24x40a

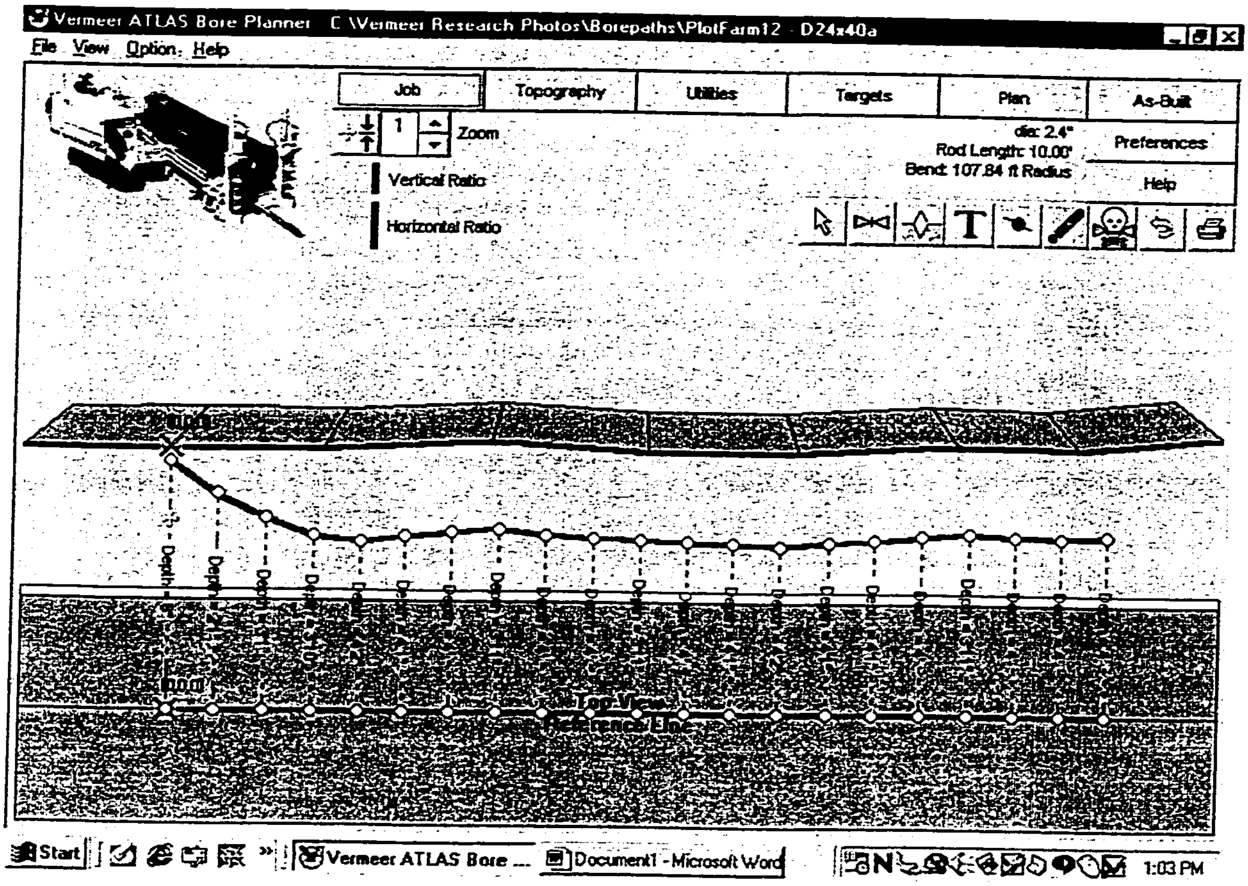
dia: 2.4"
Rod Length: 10.00'
Bend: 107.84 ft Radius

Figure E-1 100mm Pipe in Clay – Trajectory Plot (Vermeer Bore Planner)



dia: 2.4"
Rod Length: 10.00'
Bend: 107.84 ft Radius

Figure E-2 200mm Pipe in Clay - Trajectory Plot (Vermeer Bore Planner)



dia: 2.4"
Rod Length: 10.00'
Bend: 107.84 ft Radius

Figure E-3 300mm Pipe in Clay - Trajectory Plot (Vermeer Bore Planner)

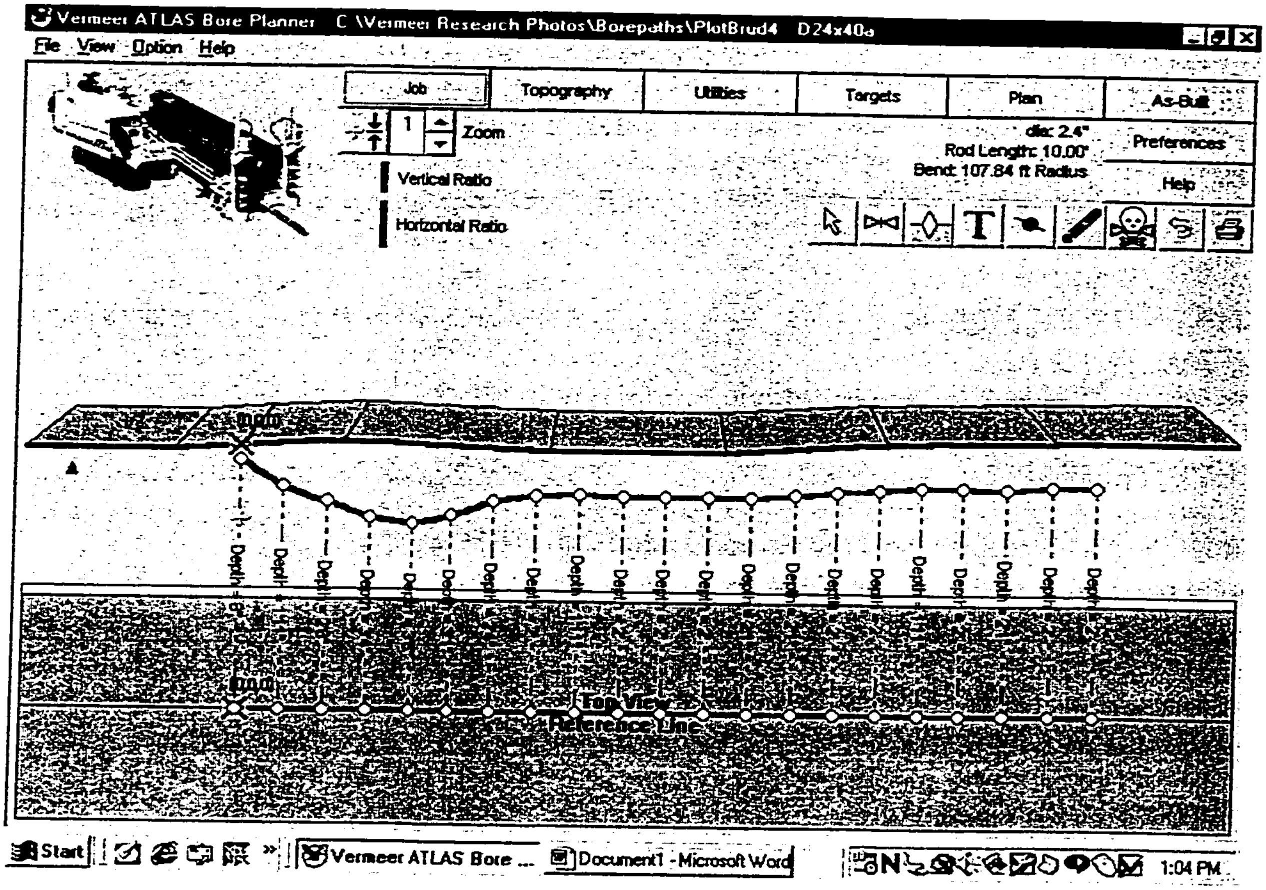
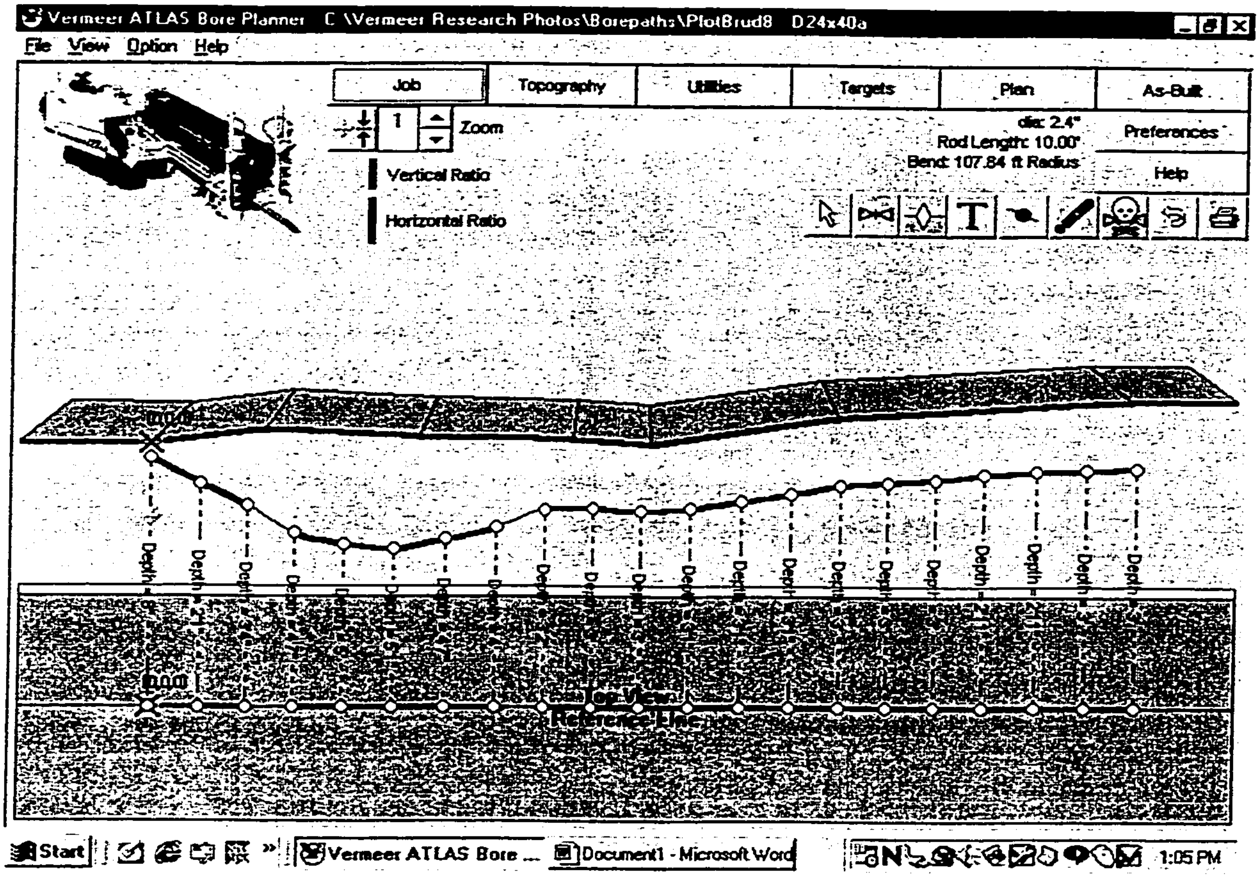


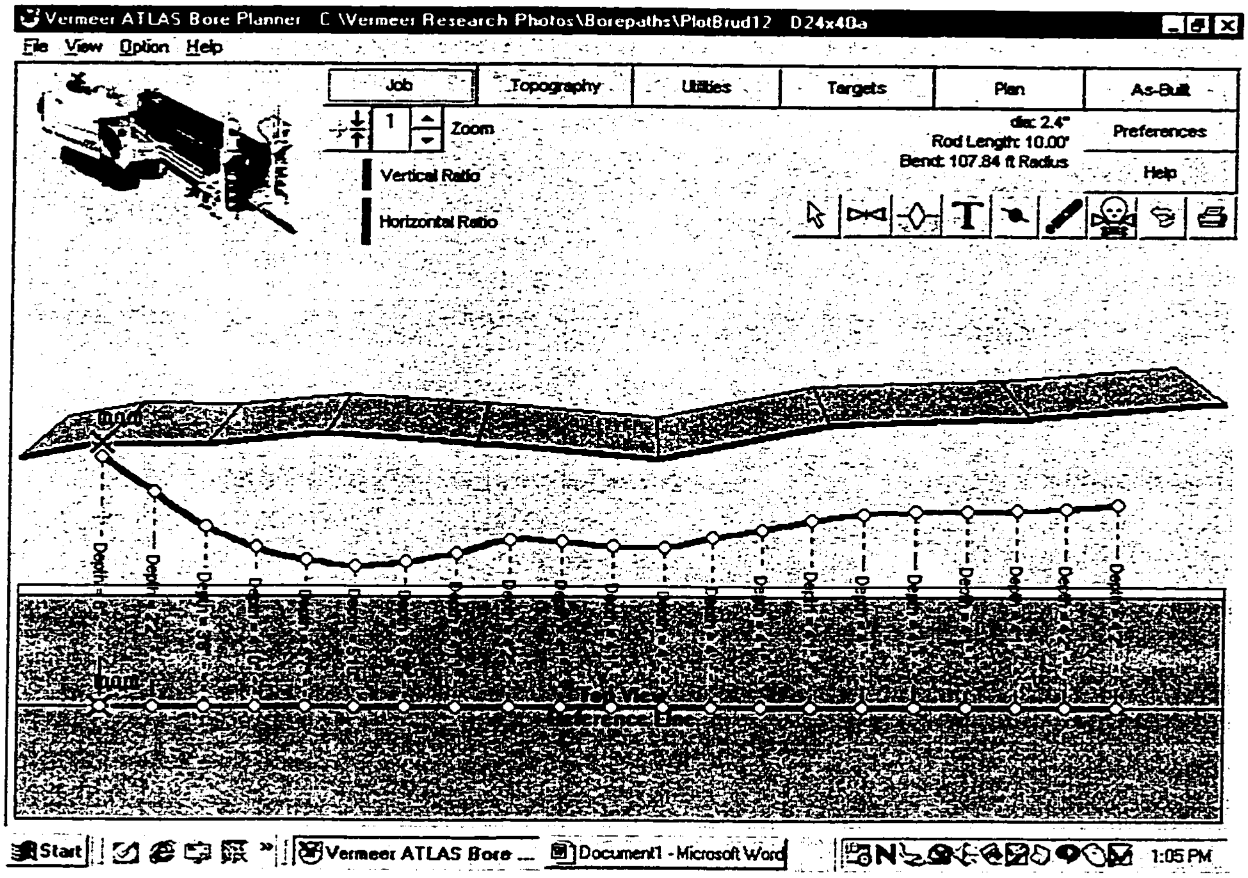
Figure E-4 100mm Pipe in Sand - Trajectory Plot (Vermeer Bore Planner)



Zoom 1

dia: 2.4"
Rod Length: 10.00'
Bend: 107.84 ft Radius

Figure E-5 200mm Pipe in Sand - Trajectory Plot (Vermeer Bore Planner)



dia: 2.4"
Rod Length: 10.00'
Bend: 107.84 ft Radius

Figure E-6 300mm Pipe in Sand - Trajectory Plot (Vermeer Bore Planner)