University of Alberta

Productivity Improvement and Risk Reduction in Trenchless Pipe Replacement

by

Jason Sierzant Lueke ©

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To Mom and Dad

ABSTRACT

Trenchless pipe replacement, also known as pipe bursting, is an emerging field of construction utilized in the replacement of existing buried infrastructure with minimal need for excavation. It is the only rehabilitation method that allows for the complete structural replacement of an existing line with a new line of equal diameter or larger.

Presented in this thesis is a summary of research conducted in the trenchless pipe replacement industry to implement techniques in risk reduction and productivity improvement. Three research areas are developed resulting from: 1) the distribution and analysis of a contractor survey; 2) the development, programming and implementation of pipe bursting specific software applications; and 3) the implementation of a feasibility study to determine the effectiveness of using tilt meters to measure subsurface ground movements associated with the pipe bursting process. With improved understanding of the issues relating to the application of this technology, it is anticipated that increased utilization of trenchless pipe replacement may result.

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CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

As municipalities grow in size and population, increased demand is placed on existing underground distribution and collection networks. In established and developed communities, some underground utility lines have been in service since the early 1900's. As these cities continue to grow, additional lines and pipes are installed in and around the existing networks resulting in increased underground utility congestion. These underground systems deteriorate and require replacement or rehabilitation to maintain their functionality. When these lines deteriorate and fail, disruption of service can have considerable impact on the daily lives of the people affected by the inconvenience.

The repair and rehabilitation of existing lines is a continual task facing municipalities as they strive to provide the most cost effective and efficient service possible. Besides the direct cost of the replacement or rehabilitation, there are social costs that are generally difficult to quantify (McKim, 1997). These include the cost of closing roads on the businesses and residences located in the vicinity as a result of traffic redirection, increased noise pollution and aesthetically unpleasant activities, which typically are the result of open-cut construction processes. Additionally, as underground space becomes more congested, increased risks are inherent during any operation in which excavation is required. These concerns have initiated a new perspective on underground construction that eliminates or minimizes many of the risks and social costs associated with conventional trenching operations.

Trenchless pipe replacement, or pipe bursting, represents an emerging field of new construction that provides a practical alternative to conventional open cut construction. There are several advantages that pipe bursting presents over traditional pipe replacement and installation methods including: 1) reduced social costs and environmental impact; and 2) increased productivity and safety. Pipe bursting is recognized as the only method of trenchless pipe replacement or rehabilitation where an existing pipe can be replaced with a completely new pipe of equal diameter or larger, therefore maintaining or increasing the capacity of the current line. Additionally, the new line provides a complete structural replacement, which is independent of the existing or replaced line.

While pipe bursting has been employed in Europe since the mid-1980's, it has been slow in its acceptance in North America. Due to the many unknowns inherent to underground construction, there is certain risk and considerations associated with this construction alternative. As more municipalities become aware of this technique, and familiar with the effective risk management techniques that result through proper planning and design of pipe bursting projects, it is expected that the utilization of this method will increase. It is anticipated that, through the sharing of this knowledge and experience, the mysteries surrounding the pipe bursting technique will be made clearer to help promote this method as a viable alternative to traditional open cut pipe replacement.

1.2 RESEARCH SCOPE

There are many issues and concerns related to the trenchless pipe replacement construction technique. The industry is still very much in its infancy in North America, with many opportunities for research and development in equipment, applications, and techniques. In addition, there are many planning and implementation topics that need to be explored and analyzed to increase the awareness and utilization of the technology. The research scope includes the following:

- Determining the current profile of the North American pipe bursting industry through the distribution and analysis of a survey.
- A discussion and outline of the methods and techniques utilized in the industry to successfully implement pipe bursting projects.
- The development, programming and implementation of pipe bursting specific software applications for project tracking and estimation, equipment selection, and special purpose simulation.
- A feasibility study of the use of tilt meters in the collection of subsurface ground displacement data associated with the pipe bursting process, the discussion of the ground measurement results, and their comparison to established predictive models.

There are three methods of pipe bursting currently employed in the North American pipe bursting industry including the static, pneumatic and hydraulic expanding pipe bursting systems. The research contained here within focuses mainly on the static pipe bursting method, as a result of close industry ties with a static pipe bursting manufacturer based out of Calgary, Alberta. Subsequently, unless otherwise specified, the discussions contained in the proceeding chapters focuses on static methods of pipe bursting.

1.3 RESEARCH OBJECTIVES

Contained in this thesis is a summary of the research conducted and experiences attained by the author while working in the trenchless pipe replacement industry. Pipe bursting is a relatively new construction method in North America, with the majority of the knowledge and expertise held by the practitioners of the technology. Subsequently, few individuals are familiar with the industry, the various methods, practice and design issues, as well as the risks involved with this technology. The main objective of this research is to share the knowledge and experiences gained in the industry with the ultimate goal of reducing risk and improving productivity on trenchless pipe replacement projects.

The second objective of this research is to set the foundation for future research projects in the area of trenchless pipe replacement. Each chapter explores an issue related to the technology that can be expanded and further work conducted.

1.4 THESIS ORGANIZATION

Chapter 2 provides an introduction to trenchless technology and trenchless pipe replacement. This chapter provides background on pipe bursting, including the history, the various pipe bursting methods used in the industry, as well as procedures utilized to install various pipe materials for both main line and lateral replacement. Additionally, there is a comparison of pipe bursting to other trenchless and trenching methods of construction and rehabilitation. Issues relating to the practice of the pipe bursting method, pipe considerations, sequencing of replacement sections, soil movements, upsizing, and project risks are addressed. Additionally, three case studies are presented that illustrate specific methods to solving project specific challenges.

Chapter 3 presents the results of a survey conducted by the author, on the trenchless pipe replacement industry. Information from pipe busting contractors is analyzed and reported under four subsections: company profile; project information; bidding and cost estimation practices; and project planning and control of operations.

Chapter 4 summarizes research contributions in the development of computer applications designed specifically for trenchless pipe replacement. Three applications are discussed from concept to programming and implementation including: a project tracking data base developed for a pipe bursting manufacturer; an equipment selection program to determine appropriately sized equipment based on project characteristics; and the application of simulation in pipe bursting projects.

Chapter 5 summarizes research and analysis conducted on subsurface ground movements associated with pipe bursting. The first half of the chapter focuses on field work conducted in Naniamo, British Columbia, where a project was instrumented to measure the subsurface ground movements associated with the replacement of a 325 mm diameter asbestos cement pipe with a 675 mm high density polyethylene line. Additionally, the use of tilt meters as a method to measure these movements is evaluated against more conventional measuring techniques. The remainder of the chapter presents a comparison of ground movement prediction models to data collected by tilt meters and linear potentiometers. The author, in conjunction with industry support from a pipe bursting contractor and consultant, conducted the work and analysis presented in this chapter.

Chapter 6 contains conclusions from the research conducted as well as recommendations for future areas of related research in the area of trenchless pipe replacement.

CHAPTER 2 BACKGROUND AND PRACTICE

2.1 INTRODUCTION

With increased demands on existing underground urban infrastructure, new methods and a new perspective are required when considering rehabilitation or replacement. Trenchless methods of construction provide a viable alternative to more conventional trenching methods. Trenchless pipe replacement, or pipe bursting, is a new underground construction method that has proved effective in the replacement of defective and under capacity pipes. Experience has shown that, in almost all circumstances, pipe bursting provides a less expensive alternative to traditional open cut replacement, while increasing overall productivity.

This chapter provides an introduction to trenchless pipe replacement and issues related to the practice of this technology. Topics relating to trenchless technology, the history and development of pipe bursting, the various pipe bursting systems, pipe replacement techniques, and a comparison of trenchless and trenching projects are addressed to provide a background of this technology. This is followed by research related to issues faced in practice, including construction methods, pipe considerations, project risk, and site characteristics. Issues related to the application of this technology are complied from the author's experience in the trenchless construction industry.

While pipe bursting has been employed in Europe since the mid-1980's, it has been slow in its acceptance in North America. Due to the many unknowns inherent to underground construction, there are certain risks and considerations associated with this construction alternative. Through the analysis of three case studies of static pipe bursting projects, contained at the end of this chapter, several of these considerations will be examined to provide a summary of lessons learned. These lessons incorporate the aspects of pipe bursting that are lessor known to assist in the identification of circumstances in which pipe bursting may be a suitable method of replacement. It is anticipated that, through the sharing of this knowledge and experience, the mysteries surrounding the pipe bursting technique will be made clearer to help in promoting the method as a viable alternative to traditional open cut pipe replacement.

2.2 TRENCHLESS TECHNOLOGY

Trenchless Technology is an emerging area of construction involving innovative methods, materials, and equipment used for the installation of new and the rehabilitation or replacement of existing underground infrastructure with minimal or no need for open cut excavation. This technology provides an alternative to traditional methods of open trenching construction, which is often associated with major disruptions to surface activities. The North American Society of Trenchless Technology (NASTT) defines 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."

The extensive use of trenchless construction for the installation, repair, or replacement of underground utility infrastructure is a relatively recent development; however, the use of trenchless techniques dates back to the 1860's when Northern Pacific Railroad Company pioneered the use of pipe jacking techniques. By the 1930's, reinforced concrete pipe ranging in size from 1070 mm (42 in.) to 1830 mm (72 in.) in diameter had been installed using this technique. Thereafter, other methods of trenchless construction began being utilized including auger boring (1940), impact moling (1962), directional drilling (1971), microtunneling (1973), and pipe bursting (1980).

Trenchless methods can be classified as new construction methods or as rehabilitation methods. Generally, new construction methods are those in which new pipe is installed providing a new structural element. Rehabilitation methods include those processes that use the existing pipe as a "form work" during installation or require the existing pipe for structural support after the rehabilitation is complete. By these definitions the following table can be derived:

Table 2-1 Classification of Trenchless Methods

New Construction Methods	Rehabilitation Methods
Auger Boring	Grouting
Horizontal Directional Drilling	Lining of Pipe
Microtunneling	Pipe Scanning and Evaluation
Pipe Bursting	Robotic Spot Repair
Pipe Jacking	

2.3 TRENCHLESS PIPE REPLACEMENT

Trenchless pipe replacement is defined as the replacement of the host or original pipe by fragmenting the existing conduit and installing the product or new pipe in its place (CCET, 1991). Also known as pipe bursting, trenchless pipe replacement represents an emerging field of new construction that provides a practical alternative to more traditional open cut construction techniques. Pipe bursting is recognized as the only method of trenchless rehabilitation that can replace an existing line with a completely new pipe, providing a total pipe replacement. Additionally, pipe bursting allows for the replacement of existing pipe with a new line of equal or larger diameter, to maintain or increase flow capabilities. These are two distinct capabilities are unique to pipe bursting in comparison to other rehabilitation methods in the trenchless arena.

In general, pipe bursting is accomplished by the advancement of a cone shaped bursting head through an original, or host, pipe that due to its geometry translates forward thrust into radial expansion forces. These radial expansion forces overcome the host pipe's tensional and shear strength capabilities and subsequently bursts or splits the pipe. Attached to the rear of the bursting head is the new, or product, line that is simultaneously installed as the bursting head advances and bursts the pipe. To decrease the friction experienced by the product pipe during installation the bursting head is of slightly larger diameter than the outside diameter of the new line. This difference in diameters is commonly referred to as the over burst. The degree of over burst largely depends on the pipe material being burst as well as the soil conditions surrounding the existing line.

Pipe bursting is considered an on-line replacement technique, since it allows for the replacement of an existing utility using the existing host pipe or conduit as its guide. The advantages of on-line replacement, as highlighted in Kramer et al. (1992), include:

1. Avoiding finding a route through congested areas,
2. Providing a predetermined line to guide and direct the installation,
3. The replacement of damaged and deformed pipes,

4. Avoiding underground congestion caused by abandoned lines,
5. Capability of installing the cable or pipe size of choice, and
6. Allowing the upsizing of the line, depending on project characteristics.

Alternatively, some of the limitations of on-line replacement include:

1. Difficulty in maintaining service while replacement is conducted,
2. Limitations on pipe materials that can effectively be burst, and
3. Possible disturbance to adjacent lines.

One of the principal advantages that pipe bursting has over conventional methods of pipeline replacement is the minimal amount of excavation required to replace existing lines. Typical replacement pipe sizes range from 50 to 400 mm in diameter, and lengths between 100 and 200 m. Diameters up to 910 mm have been accomplished in St. Petersburg, Florida (Thomas, 1996), and lengths up to 470 m in Stockbridge, Massachusetts (Saccogna, 1997). Upizes are typically in the order of 30%, though upsizing up to 320% of the original pipe size has been accomplished (Fraser et al., 1992).

2.4 HISTORY OF PIPE BURSTING

Pipe bursting was first developed in the United Kingdom by D.J. Ryan and Sons in conjunction with British Gas for the replacement of small diameter, 75 to 100 mm, cast iron gas mains in the late 1970s (Howell, 1995). The process involved a pneumatically driven, cone-shaped bursting head operating by a reciprocating impact process. This original method of pipe bursting was patented in 1980.

The pipe bursting method of pipe replacement was originally used only to replace cast iron distribution mains. Soon after, this technology was applied to the replacement of sewer and water lines. In the mid 1980s, pipe bursting was further developed to install up to 400-mm outside diameter sewer pipe. While extensively used in the United Kingdom and Europe, it was not until 1990 when pipe bursting made its debut in North America. Unlike in Europe, most pipe bursting applications in North America have been in the replacement of sewer lines.

2.5 PIPE BURSTING INDUSTRY

There are several methods of pipe replacement that are classified as pipe bursting. In addition, there are a limited number contractors across North America that offer pipe bursting pipe replacement services. It is important to realize that pipe bursting is a patented method. And as a patented method, only persons or organizations that have the direct permission of British Gas can perform pipe bursting. British Gas permits the use of the pipe bursting method of pipe replacement to anyone who agrees to pay the royalty fees associated with the service. Typical royalty fees average around $23 per meter for pipe ranging between 50 – 700 mm or greater. Fees are lower for smaller diameter pipe and increase with respect to increasing pipe diameter. These fees are directly payable to British Gas and must be accompanied by a yearly report for all the pipe bursting performed for that year.

2.6 PIPE BURSTING SYSTEMS

Currently, there are three bursting methodologies utilized in the North American pipe bursting industry. These include the static, pneumatic, and hydraulic expansion systems. The main difference between each method is the manner in which force is generated and transferred to the host pipe during bursting operations. The selection of one method over another is influenced by the combination of soil conditions and host pipe material.

2.6.1 Static Method

Static methods burst the pipe using static forces, or forces that are not generated using potential energy. A large pulling force is applied to the cone shaped bursting head through rods, cable, or chain. The bursting head then is pulled through the pipe causing the pipe to fail in tension by the radial force applied to the pipe wall from the cone within the pipe. As the host pipe is burst, the bursting head pushes the broken pipe pieces into the soil as it displaces the surrounding soil, thus creating a cavity for the new product pipe.

The majority of static pipe busting equipment is modeled after high-powered hydraulic jacks, mounted horizontally rather than vertically. The smaller units usually use two hydraulic cylinders to develop the required pulling force, while the larger units usually use four or more. Mounted in the center of the pistons is a mechanism to grab the chain or rod during the pulling operation (TRS, 1997). As the rod or chain is pulled by the machine, it is disconnected and the gripping assembly moves forward to grab another section of rod or link of chain. This process is repeated until the installation is complete. If cable is used it is usually pulled by a winch.

2.6.2 Pneumatic Method

The pneumatic method of pipe bursting is designed around a bursting head that displaces the soil using a hammering force developed from a compressed air system. Using compressed air, the bursting head is able to develop a hammering rate of 180 to 580 blows per minute (TT Technologies, 1997). The cone shaped bursting head is driven through the soil like a nail being driven into a wall. Each blow impacted by the bursting head into the pipe creates an impact load, applying a "hoop" stress into the pipe causing it to burst in tension. In addition, the hammering action creates force in the longitudinal orientation, causing failure in shear as the pipe is ripped. The shape of the head, combined with the percussive action, push the pipe fragments into the soil providing the space necessary for the installation of the product pipe.

With this method of pipe bursting, the bursting head is guided through the pipe with the use of a tensional cable inserted through the pipe prior to bursting. This cable is attached to the bursting head and provides constant pulling tension, through the use of a winch, to keep the bursting head in contact with the host pipe and aligned with its path, as well as assist in pulling the new host pipe into place. The main driving force that allows the progression of the bursting head through the pipe comes form the percussive hammering action of the head itself. Both the air compressor and the winch are set at constant pressure and tension which allows the operation to proceed with little operator intervention until the pipe section is complete. To power the bursting head compressed air lines must be run through the new product pipe

2.6.3 Hydraulic Expansion Method

This method of pipe bursting is defined by the mode in which the host pipe is burst. Rather than the pipe being burst from the transfer of a pulling or hammering force radial into the plane of the pipe diameter, the bursting head expands radially fragmenting the pipe from inside. Using hydraulic cylinders, the head expands to burst the pipe, then contracts to allow the winch to pull the cable and advance the head incrementally forward. The winch or pull on the cable does not assist in the bursting of the pipe, but pulls the head to help displace any residual soil formation, as well as pull the product pipe into the expanded cavity.

Like the pneumatic pipe bursting system, the hydraulic expanding bursting head requires a power source to provide energy to burst the pipe. In this case, a portable power unit on the surface provides power for the hydraulic cylinders, with hydraulic hoses run down the entire length of the product pipe.

2.7 REPLACEMENT PROCEDURES

Depending on the product being installed and nature of the host pipe, there are two main methods of installation associated with the static pipe bursting system. Typically, installations can be divided into continuous or sectional, based on the configuration of the product pipe as it enters the host pipe. Pipe materials such as high-density polyethylene (HDPE), polyvinyl chloride (PVC), and steel can be connected or fused to form continuous strings of pipe, this is termed as a continuous installation. This pipe string is typically as long as the section of pipe that is being replaced. Sectional installations use sectional pipe including clay, concrete, and fiberglass, and are generally installed using a push-pull method during installation. The installation progresses as each new section of pipe is added.

In general, the pipe bursting project is divided into sections or lengths that the bursting equipment being used can burst based on the geometry and layout of the total length of pipe being replaced. The length that can be burst is highly dependent on the type of pipe being burst, degree of upsize, soil conditions, geometry of the original installation, and the type of bursting equipment and method used. In addition, whether the installation is continuous or sectional has the greatest influence on the type of equipment required and the pit setup.

2.7.1 Continuous Pipe Installation

As previously stated, continuous installation procedures are used for pipe that can be connected or fused into continuous strings. This method is the preferred method of installation, as it minimizes the stoppage of the product line during the burst, and requires less equipment to perform the installation. The installation process usually begins with the excavation of access pits at each end of the pipeline to be replaced. On one end of the line, the machine pit is excavated into which the pipe bursting machine that pulls or directs the bursting head is located. Opposite the machine pit is the insertion pit through which the new or product pipe and bursting head are inserted into the existing or host pipe, as illustrated in Figure 2-1. Any services along the pipe route connected to the host pipe must be disconnected prior to the start of the burst, with access to the lateral connections achieved through service pits.

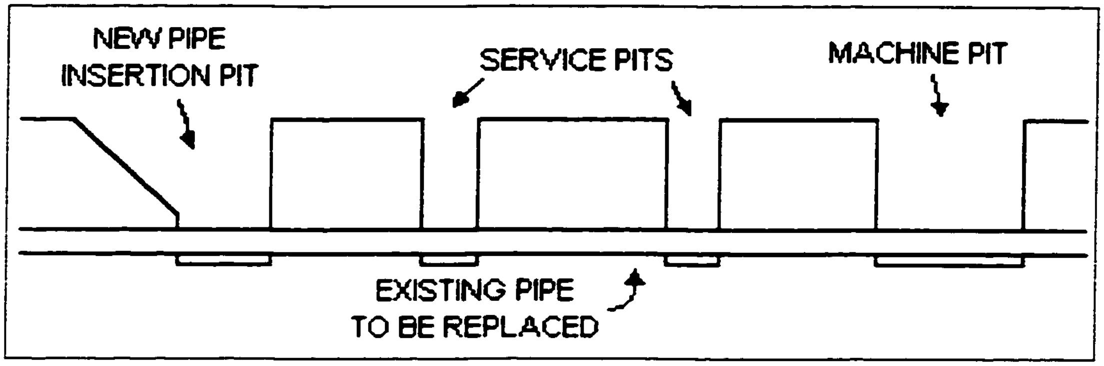

Figure 2-1 Continuous Installation Site Setup

The size of the machine pit depends on the size and type of pipe bursting equipment used. Machine pits used in static pipe bursting can range in size from 4 m by 2.5 m to the size of a manhole. Some types of bursting equipment only require the insertion of a mechanical arm or leg with a pulley into a manhole to direct and pull a cable or chain. Depending on ground conditions and depth of the host pipe, shoring may be required, though sloped walls are also an option. Generally, vertical walls are used to keep the footprint of the excavation to a minimum; this assists in minimizing surface disruption and the cost of restoration.

Insertion pits are generally smaller than the machine pits. As a rule of thumb, for static bursting methods using continuous pipe, the length of the insertion pit should be 12 times the diameter of the new product pipe. Additionally, a length to account for the slope depending on the depth of the excavation at a ratio of 1.5 to 2.5 run to 1 depth should be added. The slope ratio largely depends on the bend radius of the product pipe. The width of the pit depends on the amount of space required for crews to maneuver around the pipe in the pit to connect the bursting head. Generally, insertion pits need only be 1.2 m in width.

Service pits may be excavated with a minimal surface footprint. The size of pit depends on the depth of excavation and the maneuverability of the excavation equipment in the confined space of the pit. Generally, a service pit need only be 1.2 m in diameter to provide enough space for a worker to disconnect and reconnect the lateral. These pits may be shored using large diameter steel pipe sections, depending on the pit depth.

After excavation of the pits is complete, the bursting machine can be lowered and secured into the machine pit illustrated in Figure 2-2. Generally, the bursting machine is secured to the shoring in the pit to minimize lateral movement of the machine during pipe bursting. Additionally, the face of the excavation to which the bursting machine pushes against during the installation is reinforced with timber and steel plates to evenly distribute the bearing area. Once secure, the bursting machine pushes or "shunts" rods through the line to be replaced, to the insertion pit. These rods are specially fabricated drill pipes that are fashioned into 1.2 m long sections, with threaded connections on either end. As each section of rod is pushed into the host pipe, another section is connected until a continuous string of rods is in the host line. To assist the progression of the drill pipe string, a blunt nosed bullet head is attached to the first section of rod in the string. This head prevents the string from catching on pipe joints, as well as allows the pipe to push or bore through debris or sediment that may be in the original pipe.

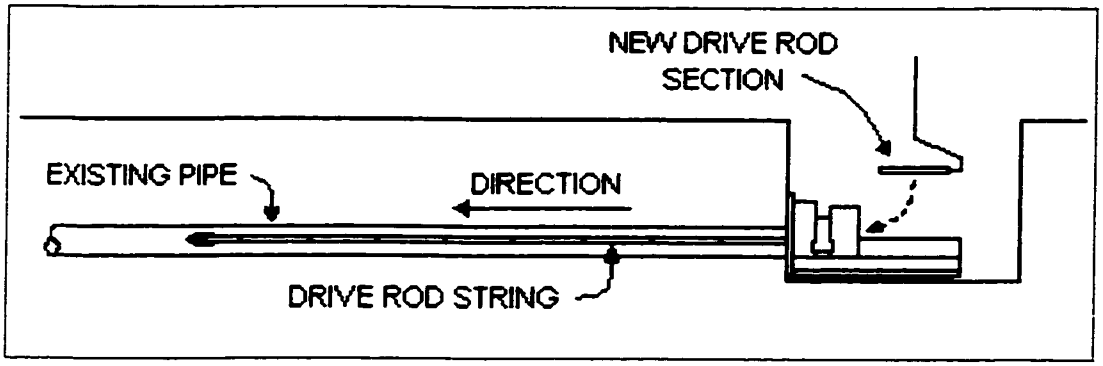

Figure 2-2 Continuous Installation Machine Pit

As the drive rods are advanced through the host pipe, the product line is placed at the insertion pit and prepared for attachment to the drive rod string. This generally requires the connection of the bursting head or tool to the front of the product pipe string, and placing the product line in the insertion pit to connect the bursting head to the drive rods. Once the drive rod string reaches the insertion pit, the product pipe is attached as illustrated in Figure 2-3. Adequate measures have to be taken to insure that the product line is not damaged as it enters the insertion pit. This can be accomplished with the addition of rollers or supports under the product pipe at intervals that keep the bend radius of the pipe within the manufactures recommended limits.

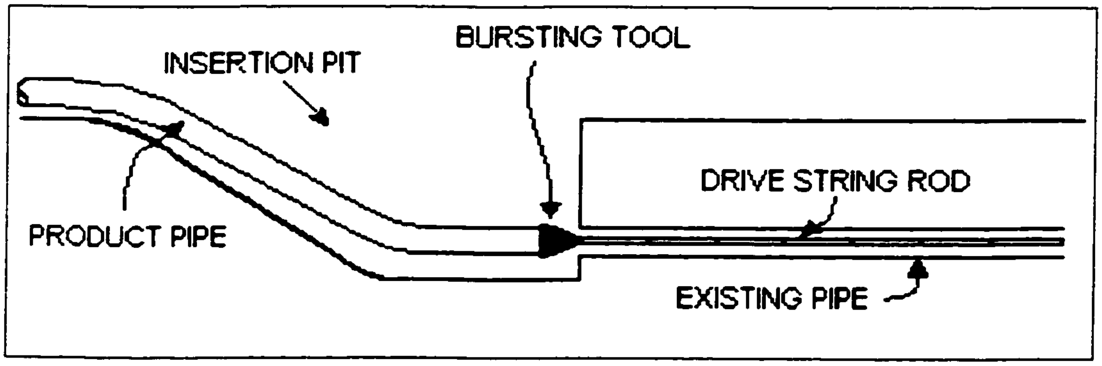

Figure 2-3 Continuous Installation Insertion Pit

After the bursting head is attached to the product line and drive string, bursting can commence. The bursting machine pulls the drive string and disconnects sections from the string as the burst progresses. As the bursting head advances, the host pipe is burst while the product line is simultaneously installed as shown in Figure 2-4.

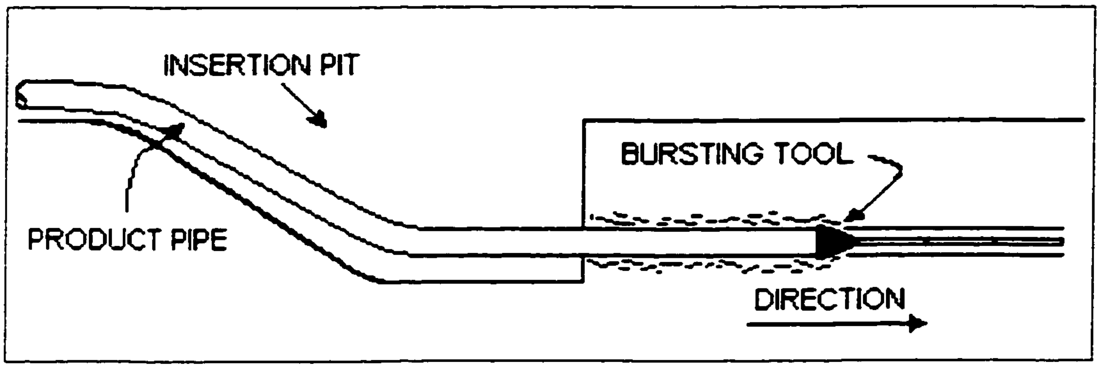

Figure 2-4 Continuous Installation Pipe Bursting

The head advances to the machine pit where it is disconnected from the product string. At this time, the product string is inspected for damage. If no damage is found, the new line is ready to be reestablished to the existing network. Generally, the new line is given time for any residual stresses from the installation to dissipate before any service connections are made or pit restoration performed. Once the product line is determined to have relaxed, generally within a 24 hour period, lateral services are reconnected and the site restored.

2.7.2 Sectional Pipe Installation

If sectional pipe is used as the product pipe for the installation, a slightly different setup is required. Again, access pits are excavated at each end of the line to be replaced, except in this case, both pits are considered machine pits as illustrated in Figure 2-5.

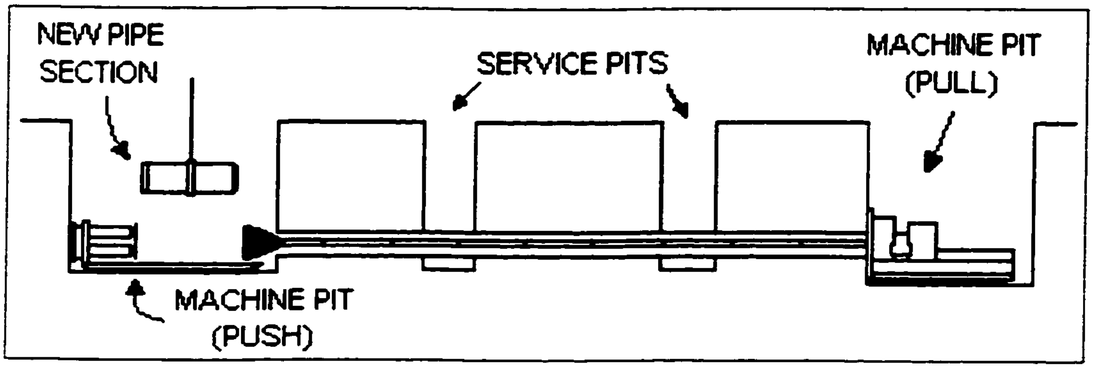

Figure 2-5 Push - Pull Installation Configuration

The installation of sectional pipe requires the application of a constant force to the pipe to keep the joints together during installation. This may be achieved by using a chain or cable run through the product line from the bursting head to a trailing plate on the last pipe section, or alternatively by using a push-pull setup. In the push-pull setup, the bursting head is pulled by one machine in the pulling pit, while in the opposite pit, the pipe section is pushed by another machine as illustrated on Figure 2-6. In this setup, a constant pressure is applied to the new pipe during installation by maintaining the push force slightly higher than the pulling force. This requires the synchronization of the machine forces; however, allows for larger diameter installations to be achieved. One such installation occurred in St. Petersburg, Florida, where 230 m (770 ft) of 900 mm (36 inch) diameter vitrified clay pipe was successfully replaced with Hobas pipe (Thomas 1996).

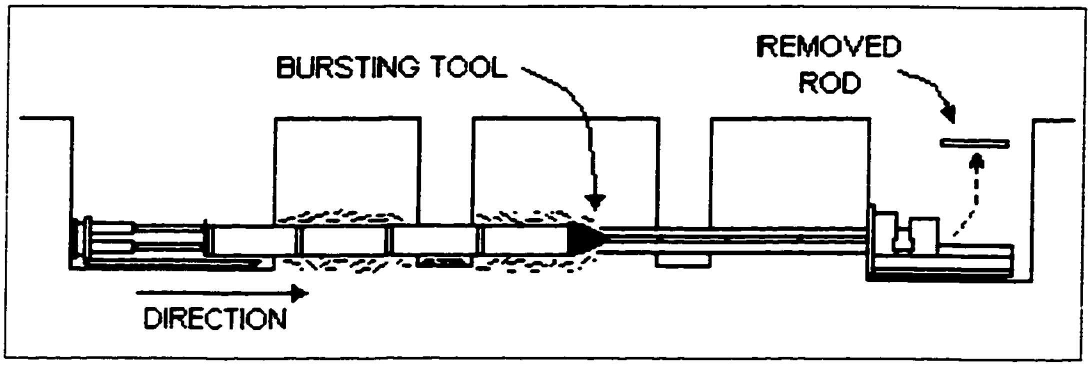

Figure 2-6 Push - Pull Installation Pipe Bursting

With sectional pipe installations, the push or insertions pit length will depend more on the length of one section of pipe with allowance for worker space to aid in the placement of the pipe. Width, like the length, depends more on the space required for the handling while the pipe is lowered into the pit.

2.7.3 Lateral Replacement

In more mature and established neighborhoods, the replacement of buried infrastructure can cause considerable disruption. This is evident when the laterals or services to individual businesses or residences need replacement. In this situation, there may be considerable disturbance to valuable landscaping and inconveniences due to the lack of access to a property with conventional cut and cover replacement options. Pipe bursting offers a unique solution to the replacement of service laterals that allows for minimal disruption to the property under consideration.

To replace a lateral using pipe bursting, excavation is required only at the connection of the lateral with the main distribution or collection line, as illustrated in Figure 2-7. Additionally, access to the location where the service enters the property is required.

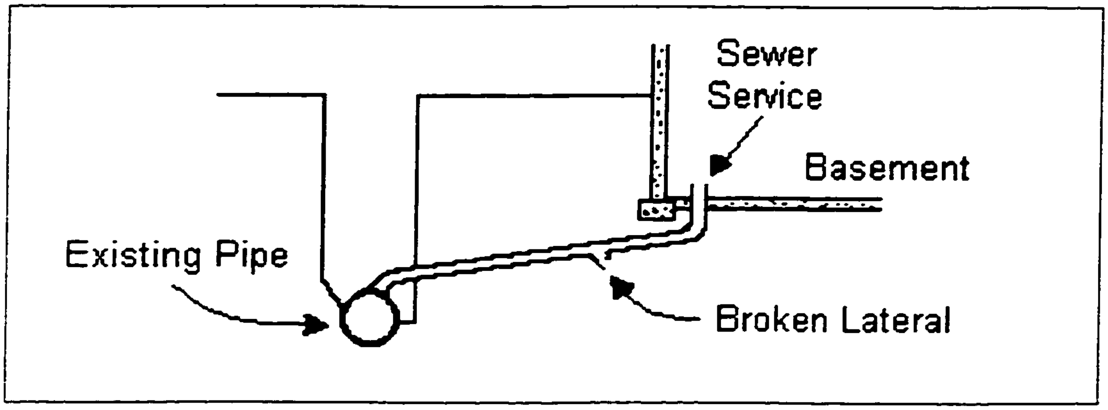

Figure 2-7 Lateral Replacement Configuration

To facilitate the replacement of the defective lateral, it must first be disconnected from the main line, and preparations must be made to improve access to the location where the lateral enters the property. In the case of a residential structure, a small area of the concrete floor around the lateral must be removed to increase the available space for the pulling of the new product line into the host. Most lateral replacements are conducted using a cable or chain pulling system as this allows the greatest flexibility for the limited space available. The product pipe is typically of continuous nature and is inserted through from the basement of the residence as illustrated in Figure 2-8. Since a cable or chain is used in this installation, a winch system is used to advance the bursting head through the host line.

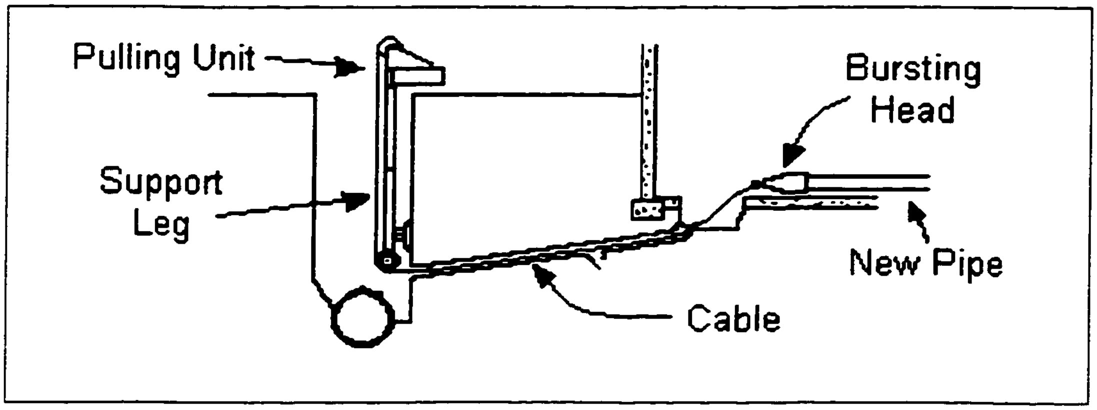

Figure 2-8 Lateral Replacement Setup

In Figure 2-9, a pulley and mechanical leg setup are used to direct the cable to the surface of the excavation where a winch pulls the cable to burst the pipe. After installation is complete, the line is relaxed to reduce any residual strains from installation prior to reconnection to the main line. Restoration to the site and basement can then be performed.

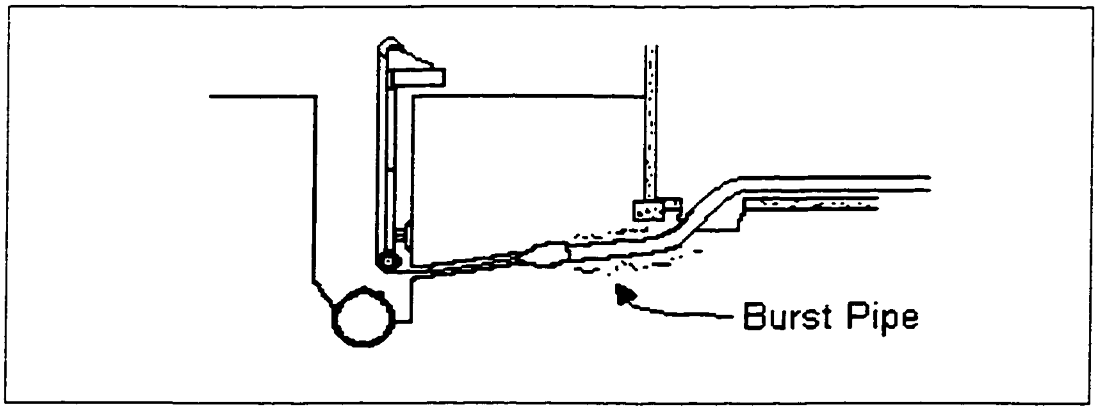

Figure 2-9 Lateral Replacement Pipe Bursting

In general, lateral replacements conducted in this fashion can be completed in less time and with less disruption to the owner than conventional open cut methods.

2.8 COMPARISON OF TRENCHLESS & TRENCHING METHODS

In comparison to conventional open cut techniques of pipe replacement, pipe bursting has many advantages. From experience, it has been shown that in almost all circumstances, pipe bursting has cost less that open cut alternatives, completed the installation in less time and, as a result, been a more efficient construction method. The main advantage pipe bursting has over open cut methods is that, in pipe bursting, a minimal amount of excavation is required. This especially comes into play when one compares the cost of open cut excavation to that of pipe bursting. As shown in Figure 2-10, as the depth of installation increases, the cost of installation using pipe bursting almost remains constant. In comparison, the cost of open cut excavation increases greatly as the depth of the installation increase. This is largely due to the increased need for dewatering, shoring and extra excavation required during open excavation operations.

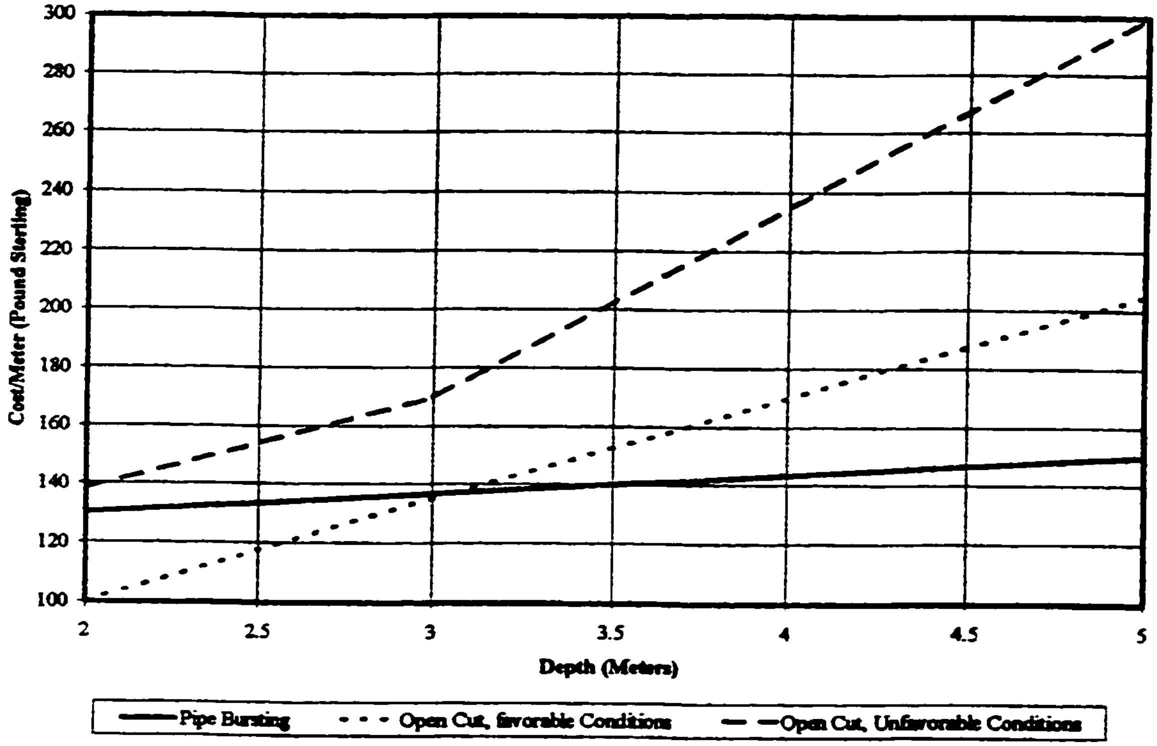

Figure 2-10 Pipe Bursting Feasibility Comparison (Poole et al., 1985)

There are also social costs to consider when one compares pipe bursting to open cut excavation. Social costs include the intangibles that one can not accurately quantify using financial terms. These costs include the loss of access to a driveway or garage, or the closing of sidewalks and parking areas in a down town business district. This is where pipe bursting has a distinct advantage over open cut, especially in urban centers or non-green field applications. To replace a line using open cut methods, the entire line must be excavated where with pipe bursting, only a machine pit and insertion pit need be excavated. This minimizes the interference with street traffic, reduces noise pollution, reduces environmental disturbance and reduces ground settlement, as there is minimal pore pressure reduction in the soil strata. A typical pipe bursting replacement can be performed using only a one-lane right of way thus maintaining the flow of traffic on the road. These are significant reasons why trenchless pipe replacement is more advantageous to implement than conventional open cut techniques.

In general, the selection of pipe bursting as the replacement option can be attributable to situations where restoration costs are high, such as beneath roads or highly landscaped areas. Additionally, if the authorities prohibit the use of open cut methods in environmentally sensitive areas, or in locations of high traffic, pipe bursting becomes a favorable replacement method. And perhaps, the situation where pipe bursting becomes a viable if not only option for replacement, when the pipeline right of way is inaccessible due to structures or obstructions. These situations make the utilization of pipe bursting much more economical than conventional cut and cover techniques.

Unlike traditional vertical or horizontal construction projects where project planning and management is a constant task throughout the project, the majority of the planning for a pipe busting project occurs prior to the actual bursting process. Subsequently, the bursting component plays a relatively minor role in the overall project. The main contrasts between trenchless and open cut projects are presented in Table 2-2. The table compares several planning elements that are common for the rehabilitation or installation of subsurface utilities.

Table 2-2 Comparison of Project Elements for Trenchless and Non-Trenchless Projects

Planning Element	Trenchless Construction	Conventional Open Cut
Schedule	Hours/Days	Days/Weeks
Excavation	Depending on method – minimal or none required	Entire length of installation must be exposed
Traffic Control	Minimal - if any	Usually required
Utility Support	Typically not required	Often required
Site Restoration	Depending on method – minimal or none required	Major resurfacing or restoration required
Worker Experience	New technology – limited pool of skilled workers	Proven method – many skilled workers
Safety	Only pits required	Trenches required

This illustrates many of the advantages that trenchless construction has over more conventional open cut methods that have been used for pipe installation and rehabilitation. In most cases, due to the reduction of excavation and spoil handling, site restoration, and speed of the operation, pipe bursting methods can complete the rehabilitation of pipes in a shorter time and with reduced social costs than open cut methods (TRS, 1997). The issue of traffic control is of great concern when working in areas of high vehicular and pedestrian usage. In many situations the closing of a route or street due to construction activities causes disruption to the businesses and residences in and around the closed road. Loss of access for customers, increased traffic due to detours, and noise are the effects of construction activities. Through the utilization of trenchless construction methods many of these problems can be minimized or eliminated.

One of the main advantages of pipe bursting in the replacement of pipes beneath roads is that only one lane is required to situate the equipment necessary to perform the replacement. Subsequently, traffic flows can be maintained along the site in question minimizing the impact on the surrounding area.

Most trenchless pipe replacement techniques generally require some amount of excavation to be performed to complete the installation. The amount of excavation required on a pipe bursting project is substantially less than that that would be required on an open trench project for the replacement of the same pipe or conduit. This translates into reduced risk due to minimizing the time required for crews to work in excavations, as well as minimizing the ground disruption around buried utilities and building foundations.

In comparison to other trenchless methods, the decision to use pipe bursting over another rehabilitation or new construction method is determined by the present and future needs of the infrastructure system. In situations where the capacity of the line needs to be increased, pipe bursting provides the only trenchless alternative. In comparison to lining methods, where the original pipe must be structurally sound to provide an effective rehabilitation, pipe bursting provides a complete structural replacement independent of the original condition of the line. Additionally, if a new line or grade is required, pipe bursting is incapable of changing these conditions and therefore directional drilling, auger boring, microtunneling or pipe jacking would be better alternatives. Lastly, consideration must be given as to whether the existing pipe requires a complete replacement, complete or partial lining, or only spot repairs to fulfill the existing and future service requirements. These considerations will determine how pipe bursting compares to other trenchless rehabilitation and new construction methods.

2.9 PIPE CONSIDERATIONS

Pipe bursting has been successfully accomplished on a variety of host pipe material types (Poole et al., 1985; Everett, 1997). In general, host pipes can be grouped into two categories based on how the pipe fails in the bursting operation: brittle and plastic. Brittle pipe includes cast iron, clay tile, reinforced and non-reinforced concrete, and asbestos cement materials. Plastic pipe includes polyvinyl chloride and high-density polyethylene pipes. The main difference between these two categories is how failure occurs; brittle pipe fails more in tension while plastic pipe fails more in shear and usually requires larger deformations.

By failing in tension, brittle pipe develops high tensile "hoop" stresses around the circumference of the pipe. When the pipe fails the failure is sudden and the fragments are jagged and sharp. When brittle pipe bursts, a sound similar to that of popcorn popping can be heard on the surface in the vicinity of the bursting head beneath. Alternatively, plastic failures are more characterized as "ripping" the pipe apart. This pipe will tend to fail and expand along a seam. As a result, contractors usually assist the bursting of plastic pipe by cutting a notch in the pipe to provide a stress concentration area for the tear seam to start. In general, pipe that fails in a brittle manner requires less force to burst than plastic pipe. The only exception is heavily reinforced concrete pipe that still bursts in a brittle manner. One such burst of a reinforced concrete pipe occurred in Phoenix, Arizona, where 158 m (521 ft) of 610 mm (24 inch) diameter reinforced concrete pipe was burst using the static pipe bursting method and replaced with sectional vitrified clay pipe 610 mm (24 inch) in diameter (Holstad and Webb 1998; Miller 1998).

In general, the conceptual relationship in linguistic terms between the force required to burst plastic and brittle pipe types in relation to the soil surrounding the pipe is illustrated in Figure 2-11. This graph was compiled through interviews with several static pipe bursting contractors and a manufacturer of static bursting equipment. As the composition of the soil changes from granular to more finely grained, the amount of force required to displace the soil increases. Typically soils with higher void ratios will more readily be displaced or compacted as the bursting head progresses through the pipe (Swee and Milligan 1990).

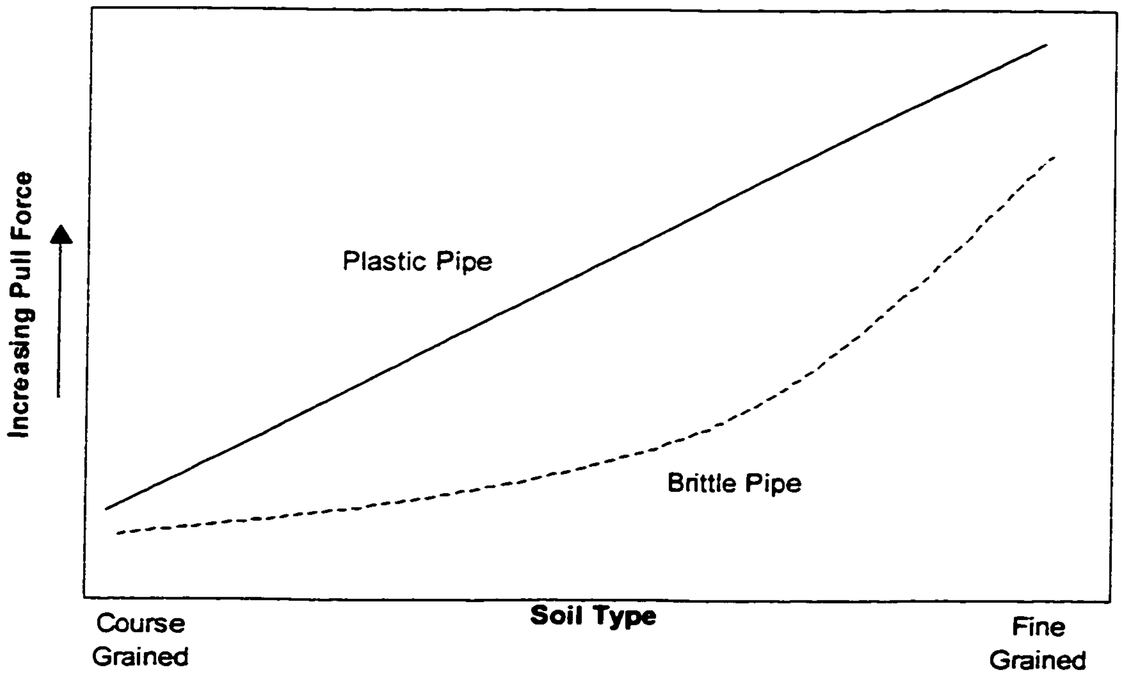

Figure 2-11 Relationship between Soil Composition and Pull Force Required for Bursting Plastic and Brittle Pipe Types

The additional force required to burst plastic pipe may be attributed to soil interaction with the remaining burst pipe. Brittle pipe, when burst, may fragment into several pieces, whereas plastic pipe will generally stay intact though may split into several sections along longitudinal seams in the pipe. The remaining lengths of pipe act as a beam to distribute the active earth pressure against the bursting head, thus more evenly distributing the radial expansion force. Alternatively, the fragments from a brittle pipe behave independently and consequently are easier to displace into the soil as the active earth pressure resisting the movement of each fragment is much less. The behavior of the pipe fragments results in higher burst forces being required for plastic pipe.

For product pipe material, there are a number of choices available ranging from sectional concrete or clay, polyvinyl chloride, steel, or high-density polyethylene. Virtually any type of pipe can be installed using the pipe bursting method. Consideration must be given to whether the product pipe is sectional or continuous. It is generally preferred to use continuous pipe for installations since the operation can proceed without stopping to add a section of pipe.

Typically, high-density polyethylene pipe is used for continuous installations (Howell 1995). It is the preferred material for pipe installation due to its high tensile strength, flexibility and its acceptance by municipalities and industry. HDPE pipe is safe to use for fresh and wastewater transport as well as pressurized gas. It is also easy to handle and transport due to its lightweight, and is easily connected into a continuous string using butt fusing processes.

2.10 BURST SEQUENCING

Consideration must be given to the arrangement of the machine and insertion pits, since the most time consuming operation in the pipe bursting process is the setup of the machine and the excavation of pits. Therefore, the number of setups and amount of excavation should be minimized. Prior to bringing equipment on site, the planner must consider the arrangement of pipe sections and manholes. It is best to use machine pits more than once to minimize moving the equipment and setting up the power plant. If a section of pipe that is being burst is a continuation or is in line with another section of pipe joined with a manhole, that manhole should be a machine pit. With this arrangement after the first section of pipe is burst, rather than the rods or chain being disconnected as they are pulled, the rods can be shunted (or chain pulled) down the next section of pipe to be burst. This increases the productivity of the operation by shunting rods (or chains) down one section of pipe while bursting another, eliminating removal and reconnection of rods for shunting them down the next line segment.

For example, if the line between manhole (MH) 93 and 98 (Figure 2-12) was replaced by pipe bursting, the machine and insertion pits would need to be located such that they could be used more than once during the burst. For this scenario, the line is considered to be a concrete gravity storm sewer, flowing from west to east. During the installation of the line, it is best to pull the pipe down the grade to keep the proper grade when complete. This project would be best setup by making MH 98 an insertion pit, MH 97 a larger machine and insertion pit, MH 96 a machine pit, MH 95 an insertion pit, manhole 94 a machine pit and MH 93 an insertion pit. Using this setup the machine need only be transported and setup three times, while minimizing the total excavation.

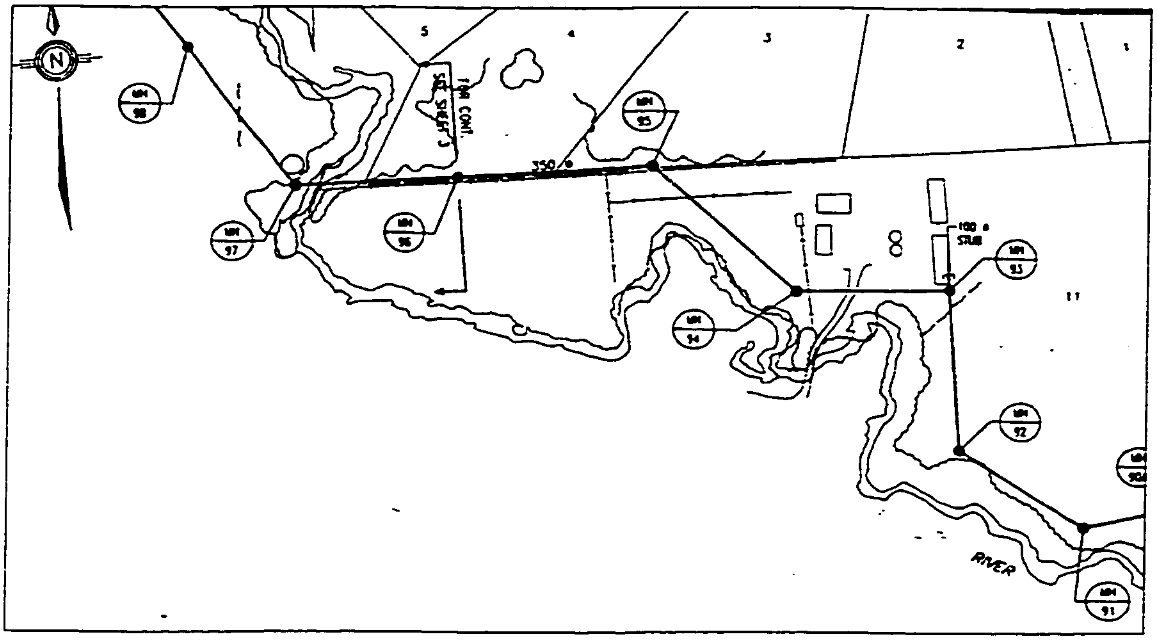

Figure 2-12 Example Pipe Bursting Project

The installation would begin by inserting the new pipe at MH 98 and pulling the pipe through to MH 97. Manhole 97 would be used as a machine pit for the first section, then as an insertion pit to install the second section. Next the pipe bursting equipment would be transferred to MH 96, where it would pull the pipe in through the insertion pit at MH 97, while simultaneously shunting the rods or pulling the chain or cable to MH 95. This is done so that the machine can be turned around and the next section installed without shunting rods or chain again. The product pipe can now be pulled from MH 95 to 96.

For the next installation, the machine would be moved to an excavation at MH 94, and pipe pulled from MH 95 and then MH 93 would complete the installation. In this situation, rods could not be shunted through the section between MH 94 and 93 due to the change in alignment of the line. Alternatively, if chain or cable were used, they could be pulled to MH 93 to facilitate that insertion of pipe. Using this setup procedure the total installation time can be reduced by minimizing equipment setup time.

2.11 SOIL MOVEMENTS

One of the primary concerns associated with pipe bursting is the interaction of the displaced soil with surrounding utilities and the surface. These soil movements have the potential of damaging existing buried lines and structures around the line being burst. All methods of pipe bursting displace soil in the process of bursting even if the replacement pipe is the same size as the existing pipe. Soil displacement can be attributed to the larger diameter of the bursting head as well as the thickness of the existing pipe wall. If the host pipe is upsized, the amount of soil displacement is greatly increased. In general, the soil properties and installation characteristics of the original pipe determine the magnitude and effect of ground movements.

Though numerous studies have been performed in various ground conditions and with varying utility configurations, it may be best to exercise caution when bursting in close proximity to buried utilities. Perhaps the best method to protect utilities that cross the bursting operation is to spot excavate at the planar intersection of the pipe and remove the soil from around the utility. In this manner, localized stress concentrations can be dissipated and the burst more confidently performed. A more detailed discussion and analysis of ground movements is presented in Chapter 5.

2.12 UPSIZING

One of the primary reasons one would favor pipe bursting over other methods of pipe rehabilitation is its ability to upgrade the capacity of the line by increasing its diameter. The degree to which a line can be upsized is related to the soil conditions, geometry of the installation, and the amount of soil that must be displaced and compacted. As the upsize factor increases, the amount of soil that must be compacted increases. Subsequently, this increases the amount of force required to push or pull the bursting head through the host pipe. Additionally, as the length and diameter of the new product line increases, so does the amount of force or energy to pull in the product pipe to overcome the friction of the soil around the pipe (Gokhale et al., 1996). As the length of the installation increases, the factor to which the host pipe can be expanded decreases as shown in Figure 2-13.

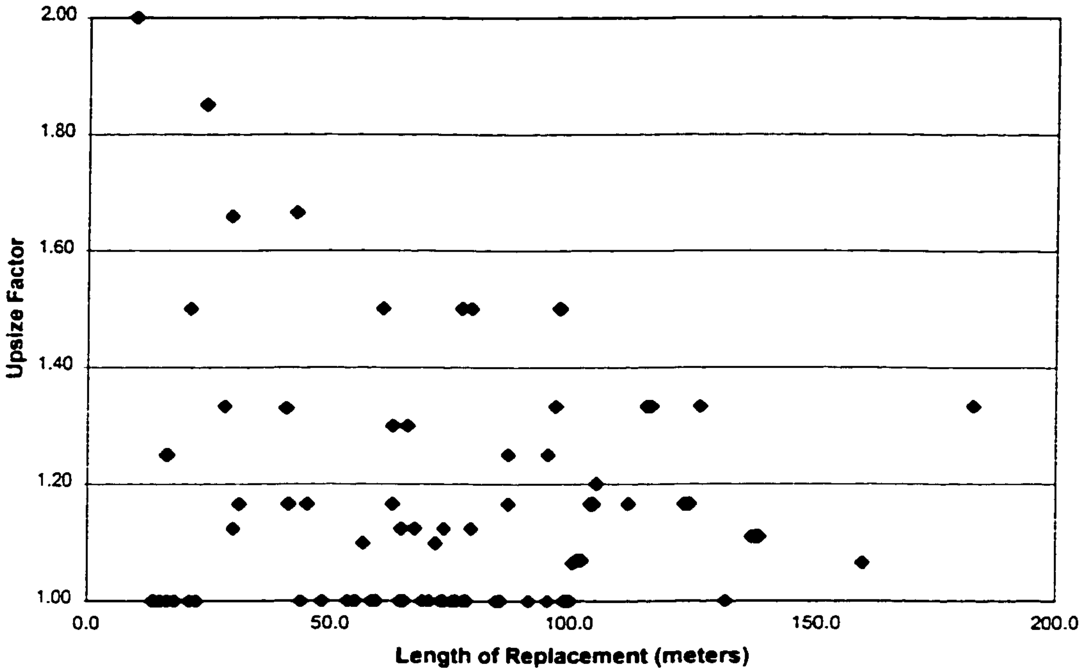

Figure 2-13 Relationship between Upsize and Installation Length

Data collected from 85 installations performed using the static pipe bursting method demonstrate the trend illustrating that the upsize factor greatly influences the length that can be installed. For example, if one were interested in bursting 100 m (300 ft) of pipe, it may be expected that the upsize be less than 1.5 times that of the original pipe diameter. Subsequently, if only 50 m (150 ft) were to be burst, one may expect to achieve an upsize close to 1.7. Soil conditions, original diameter of the host pipe, and material are major contributing factors in determining the degree to which a pipe may be upsized. Therefore, Figure 2-13 is only intended to provide pre-design guidance. Additionally, installation lengths over 200 m may be accomplished with project specific engineered design.

2.13 PROJECT RISK

The effective handling and controlling of risk is essential to the successful and safe completion of a project. Since trenchless construction projects require some degree of excavation and work below the ground surface, they essentially have many of the same risks associated with more conventional open cut installation procedures. Additionally, pipe bursting projects have risks that are specific to the bursting process that must also be considered, these are illustrated in Figure 2-14.

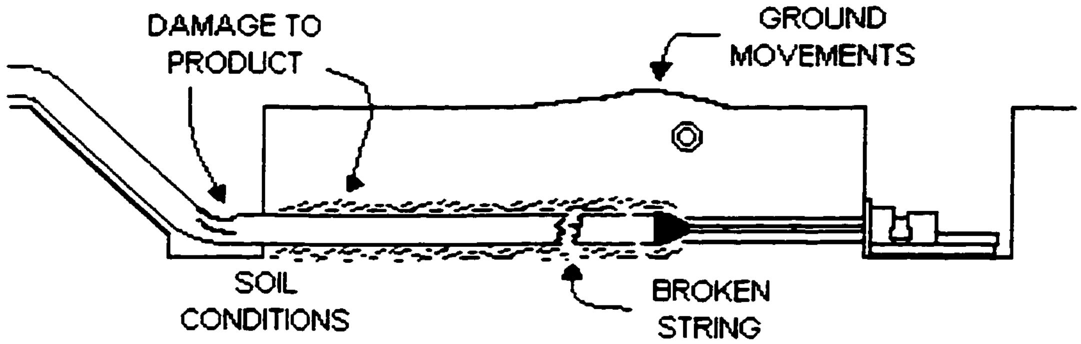

Figure 2-14 Risks Associated with Pipe Bursting

2.13.1 Damage to Product

During the installation of the new product line, one must be aware of the nature of the pipe that is being installed. It is essential that bend radius specifications for continuous pipe, in particular for HDPE pipe, be followed such that localized pipe buckling or collapse does not occur as the product sting is pulled into the insertion pit during installation. If this occurs, it would be necessary to stop the installation and repair those sections that have experienced localized failures. Additionally, these localized deformations may weaken the integrity of the pipe, and subsequently contribute to the product line failing in tension during the installation.

As the original pipe is burst and the cavity expanded for the installation of new product line, the fragments and remainder of the host pipe remain in the soil. These fragments are in direct contact with the wall of the product line as it is pulled through the ground. This presents the possibility of damage occurring to the surface of the new host pipe. The pipe materials most susceptible to this type of damage are high-density polyethylene and polyvinyl chloride pipes. Subsequently, cast iron and concrete pipes are most likely to initiate this type of damage due to the nature of their fragmentation. Interviews with several contractors and manufacturers indicate that most surface damage does not penetrate more than 10% of the wall thickness of the new product pipe. Therefore, to mitigate the risk of reducing the pipe wall thickness during installation, it may be necessary to increase wall thickness on pulls in which cast iron or concrete pipes are burst.

2.13.2 Breaking of Product Line

One of the most undesirable occurrences during the installation of new product line is the breaking of the product string. This usually occurs when the pull force required for installation exceeds the strength of the pipe. In general, failures of this type occur where localized damage has occurred from improper handling of the pipe. Increased friction on the pipe from the soil may additionally contribute to the damage. When the product string breaks, it is either necessary to excavate to the location where the broken pipe is suspected and continue the installation using conventional methods, or alternatively pull the remainder of the product line out of the cavity and re-try the burst.

2.13.3 Ground Movements

Perhaps the greatest impediment in the adoption of pipe bursting to main stream pipe replacement is the uncertainty associated with ground movements. Regardless of whether the host pipe is replaced size for size, or with a larger pipe, the ground around the original pipe cavity will ultimately move. Therefore, care must be exercised whenever bursting in close proximity to buried utilities and conduits. Ground movements may also occur on the surface if the depth of cover above the pipe being burst is too shallow. The minimum depth of cover is dependent on soil conditions, installation geometry, size of host pipe, and degree of upsize. The vertical ground movement will manifest itself as surface heave. Depending on the cover, this surface heave may cause permanent damage to pavements or foundations above the bursting operation.

With proper identification of the utility right of ways around the host pipe, measures can be taken to reduce the effects of the ground movements on these utilities. To reduce the effects of surface heave, it may be possible to place additional load on the surface in areas of concern while the burst is conducted. The additional weight on the surface may assist in redistributing the ground displacement more in a lateral direction, therefore reducing the surface effects.

2.13.4 Soil Conditions

Another factor that can affect the burst is the nature of the soil. In general, soils that are best suited for open cut excavation are also well suited for pipe bursting. Problems may occur when bursting in dry granular soils such as sand. In particular, as the burst progresses, vibration from the operation can assist in the compaction and constriction of the sand around the product line. This redistribution of the sand may increase the friction caused by the soil, therefore increasing the force required to pull the new product line in place. Regardless of the soil around the pipe, the amount of force required to pull the product line increases with the length of installation. Subsequently, if the sand is closely packed around the pipe, as the length of pull increases, the force necessary to complete the pull my exceed the capabilities of the equipment being used on the project. This emphasizes the importance of proper site investigation to determine the composition of the soil around the pipe and consequently to ensure that properly selected equipment is used to complete the installation.

2.14 CASE STUDY #1: PIPE BURSTING IN PHOENIX, AZ

2.14.1 Background

In 1992, the City of Phoenix, AZ undertook a condition assessment program to determine the condition of its large diameter concrete sewer pipes. From this study, it was discovered that some sections of this infrastructure required maintenance and, in some cases, replacement. The City of Phoenix does not allow the use of high density polyethylene in buried sewer applications due to soil and sewer flow characteristics, but rather prefers to use clay or vitrified clay pipe (VCP) for these direct bury applications

(Holstad and Webb, 1998). In a process to evaluate the feasibility of pipe bursting compared to slip lining and other cured-in-place lining methods, a section was designated to test the pipe replacement technique for the installation of VCP.

The section to be burst consisted of a 158 m length of 600 mm diameter reinforced concrete pipe with 2.75 m of soil cover comprised of a clayey sand with weak cementation. To preserve flow capacity, the replacement pipe diameter was maintained at 600 mm. Working with the City of Phoenix Water Services Department, Albuquerque Underground Inc. was awarded a contract to attempt the burst using a static bursting push and pull technique that facilitated the installation of sectional VCP pipe (Miller, 1998). The length was sub-divided into two smaller lengths as per the geometry of the pipe alignment. The first section to be burst was 56 m in length and was designated as the test section to determine if the remaining 102 m was feasible to finish with the pipe bursting technique.

2.14.2 Difficulties and Solutions

As the burst progressed on the 56 m section, the bursting head advanced to the first service pit. It was observed that the pipe and bursting head were offset in vertical alignment. In addition to this, there was substantial surface heave occurring directly above the crown of the pipe resulting in tension cracks opening along the road surface. The surface upheaval was a direct consequence of the bursting head being out of vertical alignment.

Prior to the burst being conducted, it was anticipated that there was sufficient soil cover to prevent surface heaving and keep the bursting head at the correct line and grade.

After some investigation, it was determined that the invert of the reinforced concrete pipe was not breaking as the bursting head progressed, thus acting as a wedge and subsequently, pushing the bursting head towards the surface. In addition, the geometry of the installation for the original pipe also assisted in the movement of the soil upward during the burst. It was determined that in all probability the original pipe was installed in a vertically walled trench with the invert of the pipe placed directly on the base of the trench. With the vertical walls on the original trench, there was less resistance to soil displacement towards the surface than laterally or to the trench floor. Therefore, as the burst progressed, the displaced soil took the path of least resistance causing the soil mass to shear at the trench wall and backfill interface pushing this soil to the surface resulting in surface upheaval. These concepts are illustrated in Figure 2-15, with the left diagram illustrating the original installation configuration, and the right diagram showing the soil movements resulting from the pipe configuration during the burst.

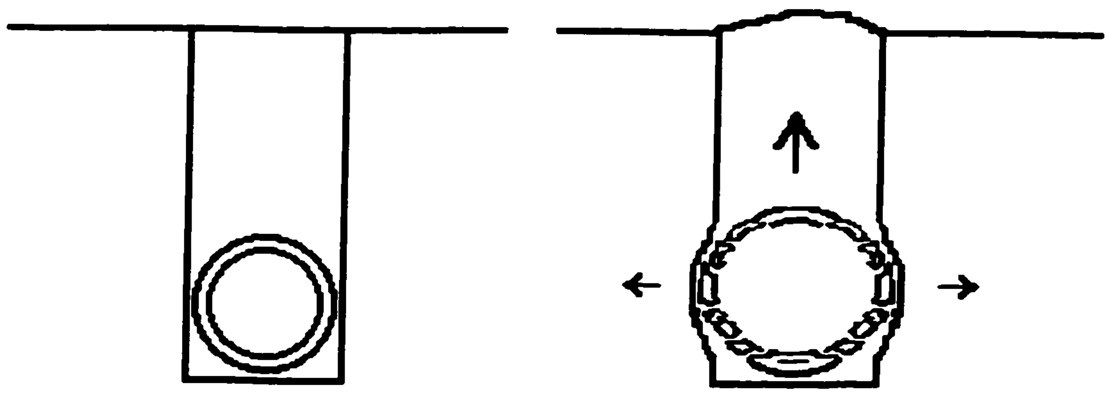

Figure 2-15 Original Pipe Installation and Resulting Ground Movements

To solve the problem of the surface upheaval and keep the proper flow characteristics of the sewer, two issues had to be addressed. First, it was required that the line and grade of the pipe be maintained by increasing the stability of the bursting head and second, to insure the proper vertical alignment, the pipe at the invert had to be burst or split. If the stability of the bursting head could be increased, the second problem would resolve itself. To increase the stability and downward pressure of the bursting head, it was elongated to take advantage of a longer lever arm to assist in guiding the head. The leading and trailing edges of the bursting head were lengthened such that there was a longer section of the bursting head in the original pipe as well as a longer tail behind. This resulted in a larger surface area above the bursting head and a leading edge that would insure that the bursting head maintained the proper grade and level throughout the pull. In addition, a cutting fin was added to the bottom of the head to break the pipe at the invert. With the additional downward pressure, the cutting fin would be able to break the invert and keep the new pipe at the same grade as the original pipe along the floor of the trench.

After the modifications were completed, the second section was burst with success. Surface heave was eliminated and it was estimated that the combination of lengthening the bursting head and adding the fin resulted in the pipe being installed at or near the original floor of the trench (Holstad and Webb, 1998).

2.15 CASE STUDY #2: PIPE BURSTING IN RENTON, WA

2.15.1 Background

Pipe bursting has been used to burst a variety of pipes with success, though some types of pipe material are very difficult to burst due to their configuration. In particular, corrugated metal pipe (CMP), or culvert, has been difficult to burst due to its configuration. During bursting of CMP, it tends to stretch and rather than burst or split, compresses in an accordion-like manner. This often creates a very densely packed and thick walled pipe mass. Additionally, the method in which sections of CMP are joined typically doubles the pipe wall thickness and, with some joints, a much heavier tension band or hoop constricts the joint to maintain the joint integrity. These clamps or hoops on the joints are designed to resist much higher hoop tensile forces than the rest of the pipe. As a result, most bursting methods experience difficulty bursting corrugated metal pipe.

In September of 1996, Debco Construction Inc. was awarded a project in the City of Renton, Washington to burst corrugated metal pipe. The project consisted of the replacement of approximately 300 m of 450 mm diameter storm sewer line at a depth of 3 to 4 m in wet blue clay. The CMP was to be replaced with 450 mm diameter high-density polyethylene pipe. Due to the geometry of the project and the difficulty of the burst, the project was subdivided and burst in three sections of approximately 100 m in length.

2.15.2 Difficulties and Solutions

From previous experience, Debco knew that, in order to successfully burst corrugated metal pipe, one had to ensure that the pipe spit or tore to prevent the pipe from collapsing during the burst. Additionally, it was imperative to prevent the pipe from being pulled with the bursting head. Subsequently, this contributed to the pipe collapsing closer to the bursting equipment in the machine pit. With the soil conditions on this project being a wet clay with considerable amounts of silt, preventing the pipe from slipping and being pulled along with the bursting head was a major concern. To successfully burst the pipe, it would need to be cut or split first, prior to expanding the cavity for the installation of the product line.

On previous bursts involving corrugated metal pipe, Debco made modifications to the bursting process in an attempt to successfully burst the pipe. This included adding cutting fins to assist in splitting the pipe ahead of the bursting head. Debco, using a static bursting method with the bursting head pulled by rods, added cutting fins to a rod section approximately 1 m ahead of the bursting head. The cutting fins spread out from the rod with an ultimate diameter greater than the diameter pipe being burst. This method worked well initially; however, as the burst progressed, the fins ceased cutting and began to elongate the pipe along the axis of the cutting fins making the burst more difficult to conduct. Therefore, when presented with a similar situation on the project in Renton, a new solution had to be found.

To solve the problem, Debco developed a new process that used cutting wheels rather than fins. Using a 1 m length of steel pipe with a diameter slightly less than the inside diameter of the corrugated metal pipe, a series of cutting wheels were attached to the pipe wall to create a new cutting tool. The cutting tool was run approximately 1 m in front of the bursting head to cut the pipe and enabling the bursting head to displace the pipe and soil while installing the new pipe. The cutting wheels were approximately 150 mm in diameter and composed of a tough cutting grade steel to resist wear. By having the cutting wheels rotate while cutting, the potential problem of the pipe collapsing and being pulled along with the burst was eliminated. With the addition of this new tool, the contractor was able to successfully complete the 300 m installation. Both the old and new configuration of the bursting heads are shown in Figure 2-16.

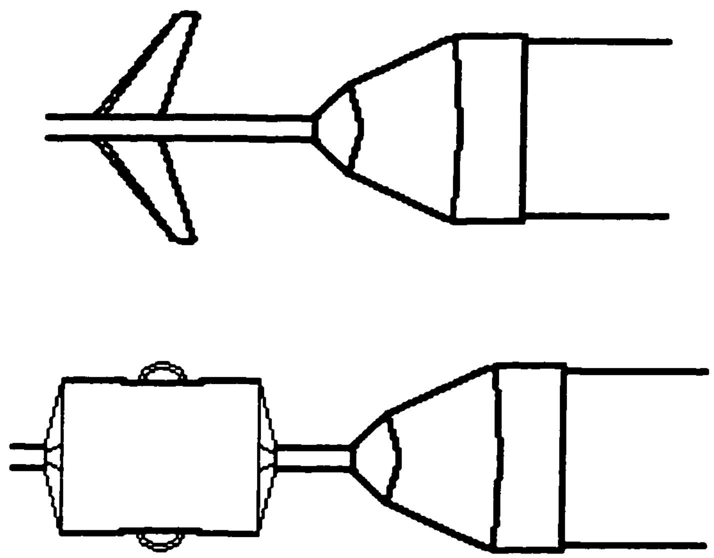

Figure 2-16 Bursting Head Configurations

2.16 CASE STUDY #3: PIPE BURSTING IN CALGARY, AB

2.16.1 Background

One of the main advantages trenchless construction techniques have over conventional open cut methods is in the reduction of social costs. Trenchless methods can minimize surface disruption, limit road closure, and minimize subsurface soil movements in situations where utilities are in close proximity to the pipe being rehabilitated or replaced. In 1997, the City of Calgary, Alberta was faced with the problem of an aging 30 mm diameter clay sewer line that ran beneath Centre Street in the city's downtown core. It would be next to impossible to close the street for even a block to replace the 70 meters of pipe by open cut methods. In addition, access was severely limited due to the density of underground utilities that ran along the street. Access to the line could only be achieved through one manhole and through a small access pit at one end of the pipe to be replaced. As a result, a trenchless construction process was the only viable option.

2.16.2 Difficulties and Solutions

Originally, the project was bid to use a trenchless lining method to rehabilitate the aging sewer line. This method could rehabilitate the line considering the inherent limited access to the line. Pre-construction videos revealed the line to be structurally intact and subsequently, the line was cleaned and prepared for the liner. Soon after, it was discovered that there was one pipe segment that was completely deteriorated, past the integrity that would facilitate lining. After experimenting with different lining and slip lining methods, it was deemed another process would have to be employed to replace this section of pipe.

Pipe bursting was chosen as the construction method to replace the line. Typically, when a section of line is burst, there is access pits at both ends of the line for machine and insertion pits. In this situation; however, due to the extreme utility congestion around the manhole at one end of the line, an access pit could not be excavated. As a result, Terraco Excavating Ltd., the bursting contractor for this project, had to employ a method that would facilitate the replacement of the pipe under these conditions.

To solve this problem, Terraco proposed that sectional pipe be used as the product line and be inserted through the manhole. They used a rigid polyethylene pipe that was specially manufactured into 1200 mm long sections for easy handling in the manhole. A high capacity pulling machine was inserted in the access pit at the opposite end and was used to pull the bursting head and the pipe segments simultaneously. To keep the pipe segments together, 1200 mm long rods from a smaller bursting machine were attached to the back of the bursting head and a backing plate attached to the rods in the product pipe to keep the joints of the new pipe together. Therefore, for each 1200 mm advancement of the bursting head, one section of rod and pipe were added through the manhole until the burst was completed. Due to the difficult soil conditions encountered, polymer was used to aid in the installation. Hose, containing polymer, was run through each new section of pipe prior to installation so as to facilitate the transfer of polymer to the bursting head through the backing plate. Terraco successfully completed the installation using this method.

2.17 CONCLUSIONS

Proper design and planning of construction operations can result in significant savings through increased productivity and reduced risk. The unique nature of pipe bursting requires special considerations that are unlike traditional open cut pipe replacement methods. Proper identification of host pipe composition and replacement pipe material greatly influences the method of bursting employed. The pull force required for bursting pipe depends on pipe composition, nature of the soil, and length of installation. In general, brittle pipes including concrete, cast iron, and clay tile tend to require less force to burst in comparison to plastic pipe. A major advantage that pipe bursting has over other methods of pipe renewal is its ability to increase flow capacity through upsizing. In general, the degree of upsizing is dependent on the original pipe diameter, soil conditions, and length of replacement. Site logistics planning, in conjunction with proper equipment selection, should result in improved productivity and successful installations.

In each of the three case studies presented, the contractor's ingenuity turned a potentially disastrous situation into a success. It is anticipated that, through the sharing of this knowledge and experience, the mysteries surrounding the pipe bursting technique will be made clearer and help in promoting the method as a viable alternative to traditional open cut pipe replacement. Subsequently, the utilization of this trenchless technology is expected to continue its growth in North America as more infrastructure managers become familiar with pipe bursting and its capabilities.

2.18 ACKNOWLEDGEMENTS

The author would like to acknowledge the invaluable contribution of Debco Construction Inc. of Snohomish, Washington; Terraco Excavating Ltd. of Calgary, Alberta; and Trenchless Replacement Services Ltd. of Calgary, Alberta in the preparation of this chapter. Additionally, the technical advice provided by Peter Strychowskyj and Lyle Laforge of StrykerForge Consulting Inc. of Calgary, Alberta is hereby acknowledged.

CHAPTER 3 PROFILE OF THE INDUSTRY

3.1 INTRODUCTION

Trenchless pipe replacement, or pipe bursting, represents an emerging field in pipe replacement and rehabilitation techniques. It is a relatively new technology that has not had significant academic exposure. To gain a better understanding of the industry it was deemed important to gather information from the practitioners of the technology. A survey was developed and distributed by the author to various pipe bursting contractors across North America. This chapter summarizes the information collected from this survey and discusses the significance of its findings. The results of the survey are reported under four subsections: company profile; project information; bidding and cost estimation practices; and project planning and control of operations.

3.2 SURVEY METHODOLOGY

The author, in consultation with contractors and a manufacturer of pipe bursting equipment, developed and conducted a survey of the North American pipe bursting industry. This survey consisted of 16 questions divided into four sections. The first section contained information pertaining to the contractor's business activities, location of operation, and equipment inventories. The second section covered work soliciting practices as well as the amount of projects the contractor had been involved with over the 1996-97 construction year. In the third section, issues pertaining to bidding and cost estimation were covered including typical costs and types of contracts undertaken. The final section contained questions related to productivity. The final section also provided a medium for respondent comments and discussion. A copy of the survey as distributed is contained in Appendix A.

In the summer of 1998, the questionnaire was sent to 24 pipe bursting contractors across Canada and the United States. The list to which the surveys were sent to was taken from the 1998 Trenchless Services Directory published by Trenchless Technology Magazine. Ten of the surveys were returned representing a response rate of 42%. All surveys were completed in full, resulting in the use of all the surveys in the analysis process. Responses were received from various contractors across both countries, providing a representation of contractors of various sizes, economic factors, and differing geologic conditions. Three of the ten contractors were from Canada, which still represents a good cross-section due to the limited number of experienced pipe bursting contractors across both Canada and the United States. In fact, at the time the survey was sent out there were only four licensed pipe bursting contractors in Canada.

3.3 COMPANY PROFILE

3.3.1 Region of Operation

The first question of the survey was to determine the regions in which the contractor conducted business and provided bursting services. Due to the limited number of responses some sections of the Unites States and Canada may not be represented in the survey. In actuality, many areas may not have a contractor that provides pipe bursting services, as a result of the limited number of qualified contractors. Additionally, the issue of regional licensees that some manufacturers have with their equipment may affect the distribution of the contractors. From experience, it can also be seen that many contractors that perform pipe bursting are not dedicated pipe bursting contractors. Pipe bursting is typically a side service or tool offered by these larger underground contractors, and for this reason, it is difficult to determine which contractors provide the service since they may not advertise themselves as bursting contractors. These are issues that are difficult to address in a survey of this nature, but should be kept in mind when considering the response rate. The distribution of surveys sent out by region and the representation of responses are presented in Table 3-1.

Table 3-1 Regional Representation and Distribution of Surveys by Region

Region of Operation	Represented	Number Distributed
Canadian Regions:		
Western Canada (BC, AB, YK, NWT)	Yes	3
Prairies (MB, SK)	No	
Central Canada (ONT, QUE)	Yes	5
Maritimes (NB, NS, PEI, NFLD)	Yes	
United States Regions:		
Region I (ME, VT, MA, NH, RI, CT)	No	1
Region II (NY, NJ)	No	1
Region III (PA, VA, WV, MD, DE)	No	2
Region IV (KY, TN, NC, SC, GA, AL, MS, FL)	Yes	1
Region V (OH, IN, IL, MI, WI, MN)	No	2
Region VI (OK, AR, LA, TX, NM)	Yes	5
Region VII (IA, NE, KS, MO)	No	
Region VIII (ND, SD, MT, WY, CO, UT)	Yes	
Region IX (CA, NV, AZ, HI)	Yes	1
Region X (WA, ID, OR, AK)	Yes	3

3.3.2 Projects and Experience

The number of projects completed by year and product pipe material is complied in Table 3-2. It can be seen that there has been a large increase in the number of projects and contractors involved in the installation of high-density polyethylene (HDPE) pipe. From 1994 to 1998, the percent of the number of total projects completed by the respondents using HDPE has increased from 27% to 79%. This trend may be explained by the fact that the number of contractors involved in the installation of HDPE has also increased from 3 to 8 over the same time frame. This could also suggest that the general awareness of pipe bursting has also increased over that time period.

Table 3-2 Number of Installations by Product Material and Year

		1994	1995	1996	1997	1998
Product Material	**HDPE**	10	19	43	58	50
	Clay Tile	6	2	2	3	3
	Ductile Iron	6	3	5	3	3
	Concrete	5	6	6	3	3
	PVC	10	12	9	8	4

The most frequent product pipe material installed is HDPE followed by PVC. In 1994, approximately 54% of the projects utilized HDPE and PVC product lines, while in 1998 this number had increased to approximately 86%. This may be accounted for by the ease of installation that these two pipe materials, as well as their acceptance by municipalities and owners.

Product pipe material types can be divided into three categories based on the installation procedures required. High-density polyethylene pipe is typically installed in lengths were the individual sections of pipe have been fused prior to installation to form a continuous string of pipe. Clay tile and concrete pipe types are usually installed using a push-pull combination method of installation, which requires two pieces of equipment to complete, as previously discussed in Chapter 2. Lastly, polyvinyl chloride and ductile iron pipe are installed using a backing plate installation method, which requires the insertion of a cable through the pipe string attached to the backing plate to form a continuous string that can be pulled by the bursting machine. Installations using HDPE pipe are typically simple to accomplish, while the push-pull installations are generally more labor intensive and technically challenging. This may account for the higher number of projects completed using HDPE pipe as the product line.

The use of a specific product pipe material is also influenced by individual restrictions provided or enforced by municipalities or the soil characteristics of an area. For instance, the City of Phoenix, Arizona, specifies that new installations be completed using clay tile pipe due to effluent and soil conditions. Additionally, the product carried by the pipe influences the pipe material used. For example potable water is typically distributed by PVC and ductile iron lines, while sanitary and storm water discharge is generally transported by concrete, clay tile, and HDPE pipe.

3.3.3 Clients

Survey results indicate that the majority of the projects undertaken by the respondents were for municipalities. On average, 83% of the projects undertaken were for city or municipal government clients, 10% for federal government clients, 5% for private owners, and 2% for state or provincial government clients. This suggests that pipe bursting is generally used in municipal applications.

3.3.4 Contracting Practices

In general, pipe bursting is a specialized technique that requires specialized equipment and project management techniques that are unlike those used on other underground construction activities. This may account for the fact that, on average, 80% of the projects undertaken had the respondent acting as the general contractor.

3.3.5 Equipment

The 10 contractors that responded to the survey indicated that they owned a total of 28 pipe bursting machines from various manufacturers. Bursting machines are classified by the pull tonnage utilized during the installation. These can be classified in three categories; equipment with pull capacities under 50 tons, mid sized equipment with pulls between 50 and 175 tons, and large machines with over 175 tons of pulling force. The survey was well distributed with all methods and manufacturers represented in the responses.

Three of the respondents indicated that they only owned one bursting unit, and two of these contractors indicated that these units were of the smaller variety. Three of the contractors indicated that they owned two bursting units, which in all cases consisted of one large and one mid sized bursting units. The remaining four contractors owned three or more bursting units, with the largest contractor owning seven bursting units. Those contractors that owned three or more units usually had equipment from all three size categories. In general, contractors used equipment from one manufacturer with 8 of the 10 contractors supporting this trend. Conclusions as to the distribution of manufacturer equipment could not be made due to the limited number of respondents.

3.4 PROJECT INFORMATION

3.4.1 Work Soliciting Practices

Projects in the underground construction industry are typically obtained through a competitive bidding process. From the results of the survey, the pipe bursting industry follows this practice. As presented in Table 3-3, 80% of the contractors surveyed obtained between 75% and 100% of their work through competitive bidding practices. The table also reveals that very little work in the pipe bursting industry is obtained through negotiation or contract extensions. This may be due in part to many of the projects undertaken being of specified scope. Most projects are for municipal clients requiring the replacement of pipe between specific locations; resulting in limited opportunity for contract extensions. Additionally, the limited amount of information available regarding the bursting process to municipal planners may result in bursting contractors having to bid against contractors using more traditional open cut methods of construction to obtain work.

Table 3-3 Work Soliciting Practices of Pipe Bursting Contractors

Percent of Total Work	Method of Obtaining Work		
	Bidding	**Negotiation**	**Contract Extension**
None	0%	50%	60%
Less than 25%	0%	40%	40%
25 to 49%	10%	10%	0%
50 to 74%	10%	0%	0%
75 to 100%	80%	0%	0%

3.4.2 Types and Diameters of Host Pipe Burst in 1996-97

One of the advantages pipe bursting has over other methods of pipe rehabilitation is that pipe bursting provides a total pipe replacement option. That is, the original or host pipe can be completely replaced with a new pipe with a new structural integrity. Almost any pipe material composition can be burst using the bursting process, though the actual capability of bursting may be limited by project characteristics. Many of the host pipe materials that are burst include asbestos cement; reinforced concrete (RCP); non-reinforced concrete (NRCP); cast iron; clay; corrugated metal pipe (CMP); and polyvinyl chloride (PVC) pipe. Additionally, ductile iron and steel pipes have been burst, though only in shorter sections and in optimal soil and project conditions.

As part of the questionnaire, the respondents were asked to indicate the length of pipe that they replaced in the 1996-97 construction year, by host pipe composition and diameter. The results from the survey are complied in Table 3-4. The contractors that responded rehabilitated a total of 13,925 m of pipe of various materials and diameters during the 1996-97 construction year.

Table 3-4 Breakdown of Host Pipe Burst by Diameter and Material

Diameter	Original Pipe Material								
	Asbestos Cement	**RCP**	**NRCP**	**Cast Iron**	**Clay**	**CMP**	**PVC**	**Total**	**Percent of Total**
50–100 mm	60 m	0 m	40 m	500 m	1219 m	0 m	600 m	**2419 m**	**17 %**
300–400 mm	339 m	0 m	1567 m	400 m	3488 m	0 m	0 m	**5794 m**	**42 %**
500–600 mm	663 m	0 m	595 m	500 m	1829 m	0 m	0 m	**3588 m**	**26 %**
600–1200 mm	0 m	340 m	1219 m	0 m	294 m	271 m	0 m	**2124 m**	**15 %**
Total	**1063 m**	**340 m**	**3421 m**	**1400 m**	**6830 m**	**271 m**	**600 m**	**13925 m**	
Percent of Total	**8 %**	**2 %**	**25 %**	**10 %**	**49 %**	**2 %**	**4 %**		

It can be seen that 49% of all the pipe replaced using the pipe bursting process during the 1997-96 construction year was clay pipe, with 69% of the clay pipe being of 200 mm diameter of less. Typically, clay pipe of that size is used for sanitary sewer and may have been installed before PVC pipe became more popular for sanitary services. The second most burst host pipe material type was non-reinforced concrete pipe accounting for 25% of the total length replaced. Also of note, cast iron mostly utilized in water distribution networks, accounted for 10% of the total replaced length. Asbestos cement with 8%, PVC with 4%, and reinforced concrete and corrugated metal pipe each with 2% accounted for the remainder of the replaced lengths.

According to the survey, approximately 85% of the total pipe replaced during the 1996-97 construction season was under 300 mm in diameter. In general, larger diameter pipe is more difficult to burst due to the increased amount of soil to be displaced or compacted to complete the installation. Even in size for size replacements over 300 mm in diameter, the pipe wall thickness increases and accounts for a large portion of the material that is required to be displaced to make room for the new product line.

3.5 BIDDING AND COST ESTIMATION

3.5.1 Cost of Installation

There are many factors that influence the cost of a pipe replacement using the pipe bursting process. Most of the costs associated with the bursting process are those associated with the excavation of machine, insertion, and service pits. The actual construction time to complete the replacement is quite small since most bursts can be completed in under half a day. The majority of the cost is in the setup and site restoration. Additional costs on a project can be incurred if a bursting head is specifically built, or if additional equipment is purchased for a given project.

In the survey, participants were asked to provide approximate unit costs for the replacement of a range of pipe sizes that were to be replaced with similar sized pipe, as well as for instances where the pipe diameter was doubled. The results from the survey are shown in Table 3-5. Values are shown as a unit cost per meter, and do not include the cost of the new pipe, mobilization and demobilization costs, excavation or restoration. Bracket values under the costs indicate the number of respondents providing data for that category. It was determined that the cost for size for size replacement can be approximated to be $0.75/mm diameter/linear m ($6.00/inch diameter/linear foot).

In general, as the diameter of the replacement pipe increases, the time required to complete the burst increase. Additionally, larger bursts may require lubrication to reduce the friction force on the bursting head and pipe being installed. This is especially predominating on bursts where the pipe is upsized, as friction increases substantially on large upsizes. Also contributing to the cost of larger installations, is the handling time and preparation time to ready the bursting head and to connect the pipe to the bursting head. All of these factors contribute to the cost of completing an installation using the pipe bursting method.

Table 3-5 Average Installation Costs for Selected Pipe Diameters

Original Pipe Diameter	Replaced In Kind	Diameter Doubled
50 mm	$89 [3]	$87 [2]
100 mm	$79 [5]	$124 [3]
150 mm	$82 [7]	$115 [4]
200 mm	$112 [10]	$184 [4]
250 mm	$144 [8]	$253 [4]
300 mm	$164 [8]	$315 [4]
600 mm	$341 [7]	
900 mm	$407 [6]	

3.5.2 Type of Contract

The survey indicated that the most common type of contract utilized in the pipe bursting industry is the unit price contract. All of the respondents indicated that they had undertaken work under the unit price contract. Unit price contracts are well suited for utility projects where the majority of the work is linear in fashion. Additionally, it provides the owner with the option of adding additional work to the contract if the initial stage goes well. On pipe bursting projects, the estimation would typically include prices for replacements of different diameters, upsize, and soil conditions. A summary of the percent utilization of various types of contracts is presented in Table 3-6.

The second most utilized contract in pipe bursting is the lump sum contract with 60% of the respondents indicating they had worked under that type of contract. Lump sum contracts work well on projects where the scope is well defined and established. For bursting projects, this is typically the case since as-built drawings provide information on the lengths of pipe that need to be replaced or rehabilitated. The combination of the lump sum and a schedule of unit rates is the third most utilized contract with 50% of the respondents indicating its use. This allows for the initial scope of the project to be completed and additional work added at the predetermined rate.

Of note is the number of contract types that were not used. These include the Per Diem, hourly, and cost plus percentage fee. Additionally, the cost plus fixed fee had only 10% utilization by the respondents. These types of contracts are typically utilized when project conditions are not known or where there is substantial risk that the project may not be completed successfully. This guarantees that the contractor will at least receive compensation for their efforts; however, in the replacement of pipe, an "attempt" at replacing or rehabilitating is not acceptable. Therefore, these contracts are typically not used. The other contracts by the hour, or day, are also not typically used since the time it takes to burst a pipe section is unpredictable.

Table 3-6 Percent Utilization of Various Types of Contracts

Type of Contract	Percentage
Unit price (rate per meter)	100
Per Diem (daily rate)	0
Hourly	0
Lump sum	60
Lump sum with schedule of unit prices	50
Cost plus percentage fee	0
Cost plus fixed fee	10
Other	0

3.5.3 Software Applications in the Pipe Bursting Industry

The use of software in the construction industry is ever increasing, and now is moving out of the office to the project site. Computers are particularly invaluable in the management and tracking of large projects. In the pipe bursting arena, there is currently no commercially available software that is pipe bursting specific. The survey asked respondents to indicate if they saw a need for the development of dedicated pipe bursting software in the areas of cost estimation, cost control, project planning and budgeting, project scheduling, and asset management.

From the survey results, it was shown that the responding contractors felt that the greatest need for dedicated pipe bursting software was in project planning applications, with 70% of the respondents indicating its importance as presented in Table 3-7. Project planning tools include decision support applications and simulation programs that can be used to more effectively make decisions on conditions that affect a project. This also includes models to predict ground movements and those to determine safe bursting distances between buried structures. The second most indicated application area was in cost estimation. Cost estimation applications can range from a specially designed spreadsheet to a fully programmed estimation application. These assist in the development of estimates during the project bidding stage.

The next potential areas for software development were in cost control and project scheduling. Once the project is underway, cost control comes to the forefront, and can be used to track where money and resources are expended throughout the lifetime of a project. Project scheduling programs including, Primavera and Microsoft Project are used to more effectively plan and coordinate the activities on a project by balancing and designating the use of project resources.

Finally, asset management applications were indicated as an area that required the least development. Asset management applications include those that track the equipment and hardware used by the contractor and assists in tracking equipment costs and maintenance schedules.

Table 3-7 Current Needs for Dedicated Pipe Bursting Software

Software Package	Yes	Somewhat	No
Project Planning/Tracking	50%	20%	30%
Cost Estimation	20%	50%	30%
Cost Control	40%	20%	40%
Project Scheduling	40%	20%	20%
Asset Management	10%	40%	50%

3.6 PROJECT PLANNING AND CONTROL OF OPERATIONS

3.6.1 Productivity

As in all construction activities, productivity determines the cost effectiveness of the operation. With pipe bursting, the productivity rate is influenced by several factors including the size of the replacement pipe in relation to the original pipe, soil conditions, and original or host pipe material composition. The survey attempted to collect data related to these factors in a series of questions regarding common soil conditions and host pipe types. The initial objective was to create productivity charts for different soils and original pipe materials, providing productivity rates for different upsize factors. As the data was collected, it became apparent that this could not be done since there were too many possible combinations of soils and pipe materials. For example, with seven soil types and eight host pipe materials, there are 56 possible combinations of soil and pipe materials. The survey was setup such that each respondent could provide one set of productivity rates for two combinations; however with only 10 respondents, there were too many possible combinations that made the data in that format unusable.

Subsequently, only the productivity sets were used in the determination of average productivity rates, independent of soil and host pipe material. These productivity rates are compiled in Table 3-8 and are based on an 8-hour working day.

Table 3-8 Average Productivity (m/day) by Upsize

Original Pipe Diameter (mm)	Replacement Pipe Diameter (mm)				
	50-100 (2 - 4")	150-200 (6-8")	250-300 (10-12")	350-600 (14-24")	650-900 (26-36")
50-100 (2 - 4")	399	106	96	0	0
150-200 (6-8")		148	88	0	0
250-300 (10-12")			166	74	0
350-600 (14-24")				152	0
650-900 (26-36")					255

It is important to recognize that these productivity rates may be slightly misleading. These rates reflect the lengths that are typically installed in one day, and with this comes some qualifying requirements. Firstly, generally the contractor will never stop a burst partially completed so as to prevent the soil from constricting the pipe and overpowering the bursting machine. Subsequently, the contractor will only burst lengths that can be completed in one day. Secondly, the actual bursting time for an installation can be very short. If one were to convert the rates listed in Table 3-8 to a rate in meters per hour based on an 8-hour day, one would find these rates generally too low. Typically, on a pipe bursting project, 5 to 6 hours is spent preparing the site, equipment, and pipe for a burst. Therefore, in actuality most burst times range from 2 to 3 hours.

These time values would provide more accurate determinations for hourly productivity values.

In general, it can be observed from the data that productivity decreases as the differential between the host and product lines increase. This trend is supported by interviews with several pipe bursting contractors. Additionally, a trend should be shown where the productivity decreases as the host pipe diameter increases. This trend may not appear in the data due to the limited sample size.

3.6.2 Future Growth in the Pipe Bursting Industry

Trenchless pipe replacement techniques have been in use since the early 1980's in the United Kingdom and Europe. Since then the industry has expanded into North America, with numerous contractors becoming licensees. It is difficult to gauge the number of actual pipe bursting contractors in North America since royalties must be paid to British Gas, and many contractors try to avoid enduring the additional costs of this procedure by operating illegally. If caught, these contractors are subject to legal ramifications. Subsequently, an accurate count of the number of contractors that use pipe bursting is difficult to achieve. It can be inferred from the relative obscurity of the bursting process among municipal planners, that there are many markets that are still available for a pipe bursting contractor to establish operations. This statement is supported by some of the comments supplied by the respondents of the survey, along with the fact that many of the contractors surveyed indicated they plan to expand their operations.

From the survey results, 70% of the respondents indicated that they are planning to increase the number of personnel and the amount of equipment utilized in their current operations. Additionally, 60% of the respondents indicated they wished to expand their area of business. This seems to indicate that there are many markets that are under developed in the industry, with room for additional contractors.

3.7 RESPONDENT COMMENTS

The opinions of the practitioners of the pipe bursting industry are considered very important in understanding the concerns of the industry. At the end of the survey package, the respondents were asked to provide overall general comments. Additionally, they were asked to provide their opinion of where they see the most potential for growth in equipment and in new applications of pipe bursting technology. Selected comments are stated below and in the same format as they were received.

Potential Growth in Equipment:

- Smaller manhole entry units to eliminate excavations.
- Smaller and more compact pulling machines about 60 to 125 tons of pull.

Potential Growth in New Applications:

- Replacement of gas mains.
- Large diameter replacements.
- Developing methods to pull from inside the pipe or above the manhole without damaging or moving the manholes.

Overall General Comments:

- Pipe bursting must gain greater owner acceptance
- Bursting is limited by the lack of knowledge of municipal engineers regarding the use of high-density polyethylene as a product pipe. Overcoming unfounded fears based on preconceived prejudices within the engineering and maintenance departments is the biggest challenge.
- Biggest part of pipe bursting is doing the excavations and back-filling and service reinstatements. The actual bursting of the pipe is quite simple.
- There is a need to promote pipe bursting in the municipal industry.
- First, the owners and engineers must be made aware of pipe bursting.
- There is little effort put forth in marketing pipe bursting.

3.8 CONCLUSIONS

The analysis of the survey revealed that the most common pipe material installed using pipe bursting techniques is high density polyethylene (HDPE). From 1994 to 1998, the percentage of all projects undertaken by the contractors surveyed increased from 54% to 86%. Installations using HDPE pipe increased since 1994, while other materials including clay tile, ductile iron, concrete, and polyvinyl chloride had remained constant or decreased slightly.

Most pipe bursting projects undertaken by the respondents were for municipal clients, with 83% of their total projects accounting for this area. Additionally, 80% of the projects undertaken had the respondents acting as the general contractor. As for work soliciting practices, the most common method of attaining work was through a competitive bidding approach. The survey indicated that 80% of the contractors obtained 75% to 100% of their work through competitive bidding. Very little work was attained through negotiation or contract extension. All contractors indicated that they employed the unit price contract, while 60% indicated that they utilized a lump sum contract.

In general, most contractors used equipment from the same manufacturer, and those that owned only one piece of equipment usually operated the smaller capacity bursting units. With larger contractors, they owned equipment from more than one manufacturer, and utilized several sizes of equipment.

The most common pipe replaced using trenchless pipe replacement in the 1996-97 construction year was clay tile, accounting for 49% of the total pipe replaced. Additionally, 85% of the total pipe replaced was under 300 mm in diameter. These values indicate that the most replacements involved sanitary or storm lines, which were typically collector pipes in the network. Additionally, the respondents indicated that they rehabilitated a total of 13,925 m or pipe in the same construction season.

Typically, installation costs increased as the size of the original pipe increased for size for size replacements. Costs for increasing the diameter of the pipe by 200% were generally close to double the cost for size for size replacements. The average cost for a size for size replacement can be calculated to be $0.75 / mm diameter / linear meter (approximately $6.00 / inch diameter / linear foot).

Software applications were seen as being somewhat important, 70% of the contractors indicated that they felt that the greatest need was in project planning applications. This was followed closely by cost estimation, cost control, and project scheduling applications. Contractors felt that the least need for pipe bursting specific software applications was in asset management.

In terms of productivity, it was revealed that in general, as the original pipe size increases the replacement productivity decreases. Additionally, as the replacement pipe diameter increased, the productivity decreased as well. Productivity is greatly influenced by the pipe material burst, as well as the soil composition surrounding the pipe being replaced.

Finally the contractors were asked if they were planning future growth in their company and operations. The survey indicated that 70% of the contractors plan to increase the number of personnel and the amount of equipment utilized in their current operations. Additionally, 60% of the respondents indicated they wished to expand their area of business.

From the results of the survey, an indication of the typical pipe bursting contractor and the trenchless pipe replacement industry can be gained. Overall, it appears as if contractors are successful in the industry, and that it has grown and evolved over the past five years. All indications reveal that growth in the industry will continue, as more municipalities, contractors and consultants become aware of the technology.

CHAPTER 4 COMPUTER APPLICATIONS

4.1 INTRODUCTION

Perhaps one of the greatest impediments for the advancement of pipe bursting in the municipal marketplace is the limited amount of information on the pipe bursting method. The majority of municipal planners have limited knowledge of how pipe bursting could be applied to their particular rehabilitation needs. The inclusion of computers in the daily operations of a construction company has become common place, if not essential in the industry today. Computers are useful in all aspects of construction engineering, from design and planning to scheduling. As presented in Chapter 2, design and planning of pipe bursting operations is critical to ensuring the success of this emerging trenchless process. Presented in this chapter is the development of special purpose software applications to provide planners, engineers, and contractors alike with information and tools to more effectively plan pipe bursting operations.

This chapter describes the development of special purpose pipe bursting software based on research work conducted at the University of Alberta in collaboration with a static pipe bursting equipment manufacturer. All of the pipe bursting specific applications described within this research were developed, implemented and programmed by the author. Three different aspects of computer software applications are included. The first subject addressed is the development of a database for the tracking of pipe bursting projects for an equipment manufacturer with the ultimate goal of more effectively collecting equipment royalties. The second, is the application of a decision support system for the selection of equipment for pipe bursting projects, based on project and site characteristics. And lastly, the development of a simulation template using

Simphony, a simulation language developed at the University of Alberta. Preliminary designs and results, with future enhancements are included for all applications.

4.2 BACKGROUND OF DEDICATED PIPE BURSTING SOFTWARE

In a recent survey of pipe bursting contractors across North America, the respondents were asked to provide their opinion as to where they saw the greatest need for the development of software applications dedicated to the pipe bursting industry. As previously mentioned in Chapter 3, the results of the survey indicated that 70% of the contractors felt the greatest need for software development was in the application of project planning and tracking, and cost estimation. With contractors working on various projects and in several locations, it is useful to have a system to track project particulars. When working on a project in a similar location as one previously completed, having the tools to reference information from that completed project can provide valuable information on the site characteristics that could greatly influence the success of the current project. Being able to construct estimates in a timely fashion is also very important to the success of a contractor in any industry. The nature of the pipe bursting process is very different from other construction processes. Having an estimation application designed specifically for pipe bursting would greatly increase the efficiency of the estimation process.

Research and discussions with industry determined that, no commercially available software specifically designed for pipe bursting currently exists. This is not, however, the case for all trenchless technology methods. Currently, there are several dedicated horizontal directional drilling software applications available in the industry.

Applications such as Drill Path (Kirby et al., 1997), and Path Tracker (Onscreen Software Solutions, 1996), have been developed as bore-hole and installation design-aid software for directional drilling. Additionally, there are several software applications to assist in the prediction of horizontal well performance, for wells installed using directional drilling. One of the possibilities that may explain the lack of dedicated software for the pipe bursting industry is that in all applications of the technology, an existing pipe is replaced with a new line. In this situation, a pipe or conduit had existed in a known location and no real changes are being made to the alignment. Subsequently, owners and contractors know where the new line will be located; thus the path of the line or installation need not be planned like that of directional drilling. As-built drawings are also easy to create, as the alignment of the new installed pipe is known, or can be confirmed from visual or camera inspection.

The dedicated pipe bursting software that may exist in the industry would be those developed in house, suited to the particular needs of the contractor or manufacturer. Additionally, for estimation, cost control and scheduling, there are many general purpose programs, as well as simple spreadsheet applications in which templates can be created to assist in these tasks.

4.3 PROJECT PLANNING & TRACKING

Increased competition requires contractors to reduce cost and improve productivity to remain competitive. Through the use of computers, contractors can manage large quantities of project data for use on future projects and in the generation of tenders. With pipe bursting, record keeping is an integral part of the operation due to stringent patents on the process. In accordance with the British Gas license agreement, users of the pipe bursting technology are required to submit royalty payments on a regular basis based on the length of pipe burst and the diameter of the product line.

As part of this agreement, bursting contractors submit the length of pipe burst, diameter of the host and product lines, type of material burst, composition of the product line, soil conditions, and project location and ownership information. This information must be recorded for each project undertaken by the contractor and subsequently forwarded to British Gas along with the appropriate royalty fees. Computers are an appropriate tool to assist in the collection and storage of this information. If this data were collected and stored in a database, the information could be processed and used to prepare royalty reports and additionally, can be used to plan and estimate future pipe bursting projects. For example, when a contractor submits a quotation for a project near a location where a previous project was completed years earlier, the ability to retrieve information regarding soil conditions and other environment factors that may influence the bursting operation could prove to be invaluable in preparation of the bid.

4.3.1 Database Development

Because of the inherent advantages of having project information on pipe bursting projects readily available for estimation and planning purposes, the author and a pipe bursting manufacturer/licensor, Trenchless Replacement Services (TRS) Ltd., undertook the task of developing a project planning and tracking database. Initially, the database was constructed to track and record licensee information to improve data handling and reduce paper work; however, having these records available in a database format opened up the possibility of creating estimation and planning tools. Additionally, the database could be useful in developing programs, distributed to contractors, consultants, and owners, to assist in planning and estimating.

As part of the licensing agreement TRS has with British Gas, the original developers of the pipe bursting process, TRS has the capability of licensing its own contractors. These contractors used equipment that was patented by TRS, which used the bursting method patented by British Gas. Therefore, the TRS licensed contractors paid royalties to TRS, whom in turn paid a portion of these royalties to British Gas. Royalty payments are collected quarterly, and prior to the development of the database, records were tracked by hand and entered into the computer on an as need basis, primarily to provide a summary report. With the current setup of royalty report collection, the infrastructure was in place for data flow between the contractor and TRS, which could be modified slightly to collect the additional data required for the database.

To accomplish the goals of the database development, additional data was required to be collected form the contractors. The original royalty reports were functional, but had to be modified to obtain this additional information. A copy of the new Project Report form is included in Appendix B. This form was designed to replace the existing royalty reporting forms that the contractors currently used. The information collected on the report included information related to the project location, client and owner, information on the equipment used on the project, characteristics of the original and new pipes, as well as soil characteristics. Additionally, data was collected on the length, depth, and diameters of pipe, number of services and time required to complete each replacement length. With this data collected on each installation length, after several construction seasons there would be a substantial volume of data. This data could be used to estimate productivity under various project characteristics.

Using Microsoft Access, a database was constructed to facilitate the tracking of project and licensee data. The database consisted of six tables containing licensee information, royalty fees, project particulars, pipe information, and equipment specifications. Tables and their relationships are shown in Figure 4-1. For additional information of how the database was constructed and operates, refer to Appendix C for the database user manual.

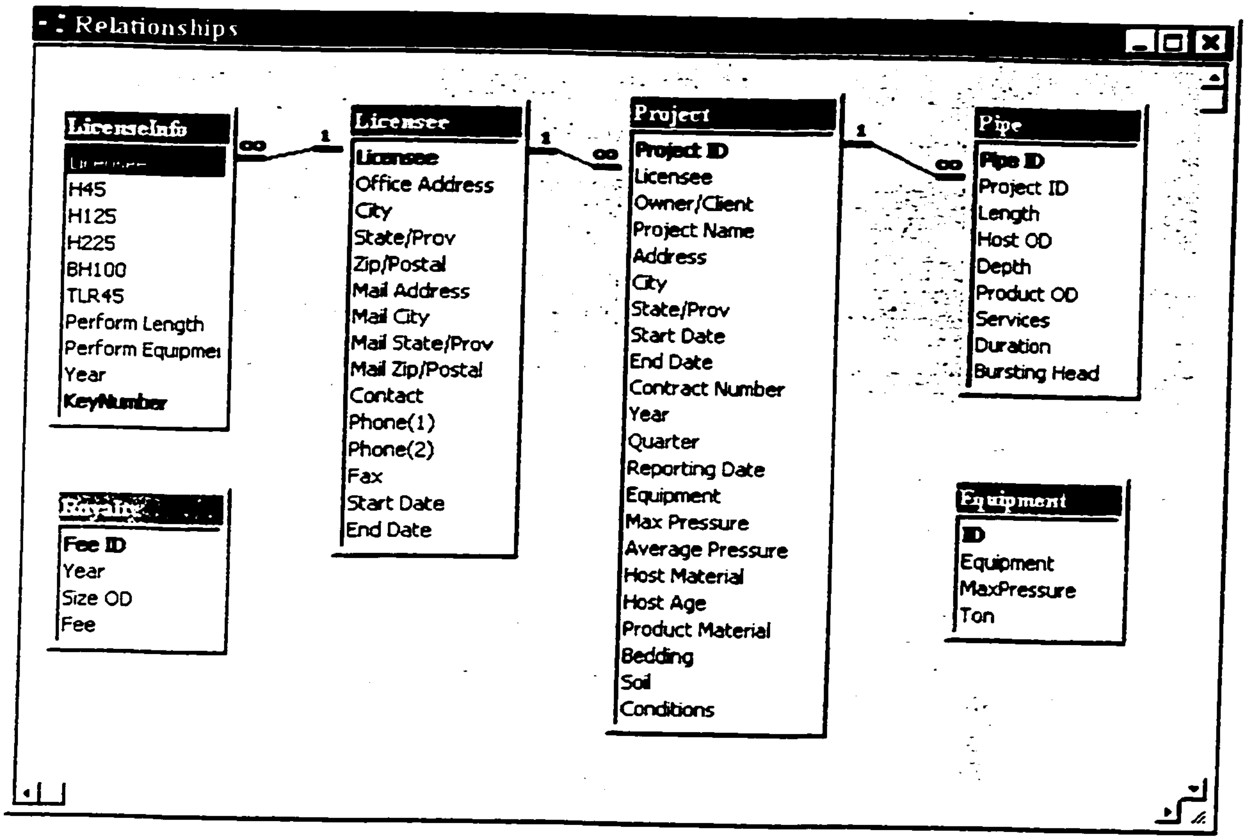

Figure 4-1 Database Table Relationship Diagram

As licensees submit royalty reports for a particular period, the data could be entered into the database, which would then sort and organize it to create royalty reports for British Gas and a historic record of all pipe bursting projects performed by the manufacturer's equipment. Entry was simplified by providing the user with a template that mirrored the contractor's royalty reports. Figure 4-2 illustrates the project information entry window in Access.

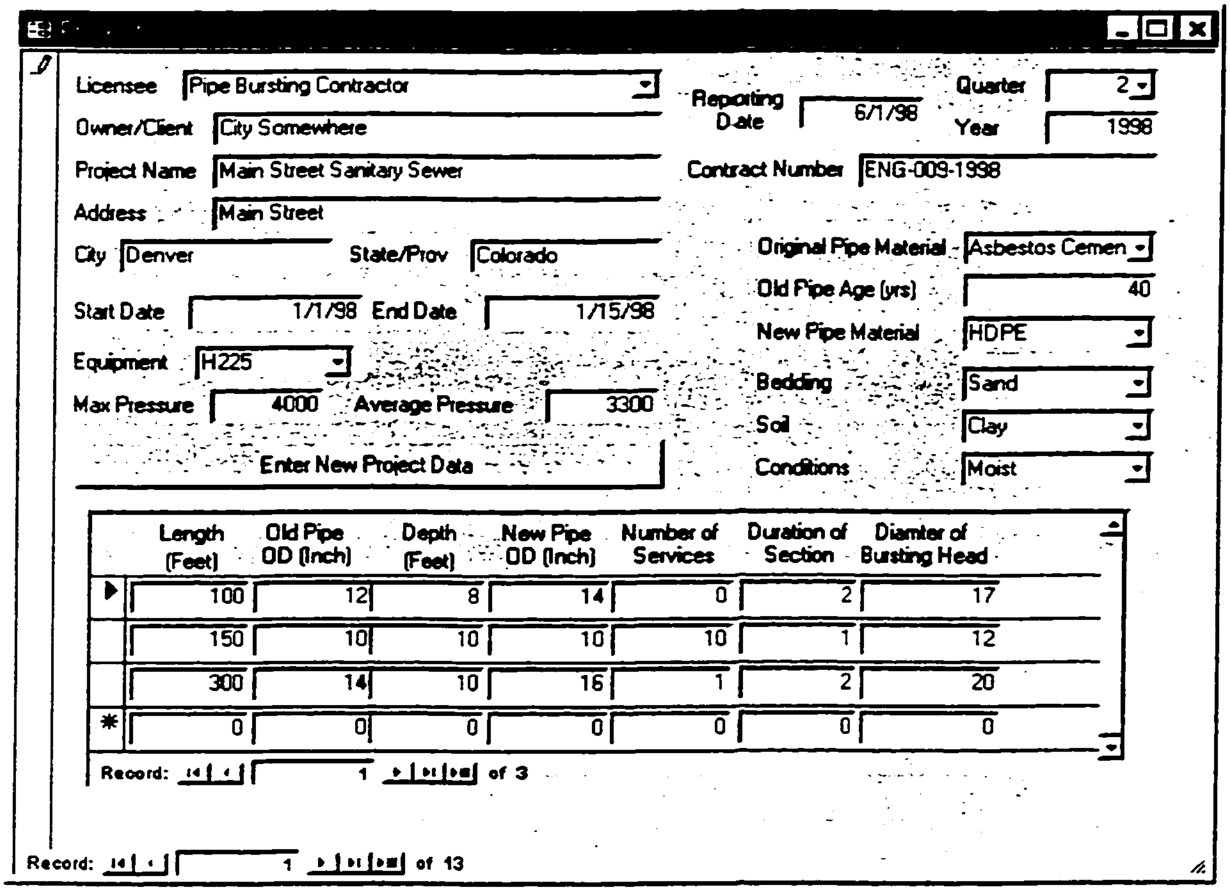

Figure 4-2 Project Information Entry Screen

Once the data has been entered into the database, reports on various aspects of the bursting operation conducted with the manufacturer's equipment may be generated.

These include reports that summarize projects by licensee, equipment, total pipe lengths and composition installed or burst, royalty reports by licensee and yearly totals, as well as total licensee information. A summary of the reports that could be generated is listed in Table 4-1. With these reports, royalties could be more conveniently recorded and the pipe bursting market better understood. Additionally, the manufacturer could use this information to make equipment and process modifications for specific applications in regions where ground conditions and pipe compositions dictate.

Table 4-1 Summary of Reports

Report	Description
Project Summary by Licensee	Allows the user to display project data relating to all the projects a particular Licensee reports for an entered year.
Project Summary by State/Province or City	Complies a report with the State/Prov, City, Project Name, Owner/Client, Host OD, New OD and Length by Licensee and year that the project was reported.
Lengths Burst/Installed by Host, Product Pipe or Equipment	Summarizes the lengths of pipe burst or installed by pipe material, grouped by size of host pipe and by type of pipe, for all Licensees by year.
Royalty Reports: Licensee Summary	Compiles a report containing total length of pipe burst by pipe size, calculating the royalty to collect using the total length by pipe size and the royalty fee. The report also totals the length and royalty to collect by quarter and the query year. From the total burst in the year, a balance can be calculated by comparing the total burst to performance lengths negotiated in the Licensee's License.
Royalty Reports: Year Summary	Prepares a report with the total royalties for a user supplied year for each Licensee, grouped by replacement pipe size and quarter.
Licensee Summary	Provides information relating to the Licensee's vital information including addresses, phone numbers, contact name, start and end data of Licensee's License agreement, as well as equipment and performance clauses by year.
Project Estimator	Designed to assist in the selection of equipment and to help determine if a project can be burst. After the user enters the original pipe material and its diameter, the report compiles a list of average tonnage and pressures historically encountered on jobs with that host material and diameter grouped by soil conditions, length and upsize diameter. All upsizing values equal to or greater than the original host diameter are displayed in the report.

One application of the database that has great potential is in project estimation and planning. Pipe bursting is still very much in its infancy in North America and subsequently, not many people understand the capabilities of the equipment and the bursting process as a whole. It was deemed important that suitable measures be developed to provide potential clients with information on the feasibility of utilizing pipe bursting according to their specific requirements. With the database in place, it is possible to determine the likelihood of successful bursts based on project data from the historical records. Using these records, a query was created to assess the capabilities for bursting a pipe given a set of criteria including length of installation, diameter of host and product lines, soil characteristics and original pipe material.

When the query is initiated, the user need only enter information on the original pipe material and diameter. The database subsequently searches for all prior projects completed with these criteria and sorts these records by product diameter with information on the average length of installation, average tonnage or pull force required, soil type, bedding, and moisture characteristics as shown in Figure 4-3. The user can use this to determine the expected successful length of pull based on upsize and soil conditions. Future modifications to the report will include facts on the average and longest lengths accomplished for a set of conditions.

Project Estimator by Host Material and OD

Original Pipe Material: Clay

Original Pipe Diameter: 12

New Product Pipe Diameter	Length (ft)	Soil	Bedding	Conditions	AveTon	AvePres (psi)	MaxTon	MaxPres (psi)
12								
	320	Gravel	Native	Moist	103.5	2,300	157.5	3,500
	745	Clay	Gravel	Moist	157.5	3,500	202.5	4,500
14								
	400	Gravel	Native	Moist	103.5	2,300	157.5	3,500
	900	Clay	Gravel	Moist	157.5	3,500	202.5	4,500
16								
	140	Gravel	Native	Moist	103.5	2,300	157.5	3,500
	1,120	Clay	Gravel	Moist	157.5	3,500	202.5	4,500

Page: 1

Figure 4-3 Project Planning Report
(Data for illustrative purposes only)

From Figure 4-3, it can be seen that if a 300 mm (12 inch) diameter clay pipe were to be burst and upsized to 350 mm (14 inches) in diameter, that a 122 m (400 ft) length of pipe could be installed in a gravel soil using approximately 140 tonnes (157 tons) of pulling force. Alternatively, 275 m (900 ft) could be installed in a clay soil using 180 tonnes (202 tons) of pulling force. For conditions not in the database, the user could extrapolate and use this data to provide an educated estimate. This provides the user with information in determining lengths for installation, as well as the selection of suitable equipment for a particular project.

4.3.2 Implementation Results

The implementation and incorporation of the database into he daily operations of TRS has been slow. One of the biggest hindrances to obtaining useful data for the database is the amount of data required by the contractors to be entered into the new royalty reports. Additionally, for royalty reporting periods after the introduction of the new royalty report forms, contractors have been slow in the adoption of the new forms. Many of the contractors were still submitting reports using the older forms. This situation may be rectified in the future through communication with the contractors as to the purpose of the new reporting system and data required.

At this stage in the implementation of the database there is very little project data recorded. In order for the database and its queries to operate as intended, it is essential that a substantial amount of data be incorporated to create meaningful reports. Subsequently, the amount of project information contained in the database will determine its usefulness in the planning of pipe bursting projects.

4.4 DECISION SUPPORT SOFTWARE

4.4.1 Decision Support Software an Introduction

The creation of a project database is the first step in the ultimate goal of developing software capable of selecting equipment based on project characteristics. As an extension to the project tracking database, the Equipment Selection Program (ESP) was developed. Using a specially created data set from the larger project database, the ESP can help planners effectively evaluate the proper choice of equipment for specific project conditions. Such software could be distributed to contractors, consultants, and owners to assist in marketing the pipe bursting technology. Factors including soil type, upsizing diameter, pipe material, and pressure are considered in determining equipment selection and predicting productivity. Information collected from various projects and through an industry survey of pipe bursting contractors is used in the development this tool, in conjunction with the database information.

The Equipment Selection Program was developed in Microsoft Visual Basic 5.0 using the Microsoft Access database engine. In addition to helping select equipment for projects, the program contains valuable information about the various static pipe bursting equipment available through the manufacturer and contact information. It is anticipated that the program will be of great benefit to municipal planners and consultants alike.

When the program is executed, the main user interface, shown in Figure 4-4, appears on the screen. From this window, the user simply inputs the project particulars and determines the type of equipment best suited for the task according to historic data from previous pipe bursting projects. The expected hydraulic pressures are calculated and presented for each of the different static equipment lines. Pressures highlighted in red indicate those that exceed the capabilities of a particular line of equipment. From this, the user can determine the equipment best suited to perform the pull and subsequently, select additional information on that piece of equipment from the equipment menu. By using this program, the user has the benefit of prior historical records to assist in the selection of the most suitable equipment for a particular application.

In general, once the program is initiated, the user may enter data pertaining to the original pipe material and diameter, new pipe diameter, predominate soil in the area, type of bedding material, and moisture condition of the soil. Using these parameters, the program searches through the database to find all the projects that fit those characteristics and then calculates the expected pressure for each of the equipment lines. Future enhancements will be made to include the replacement length as one of the factors contributing in the pressures expected for the equipment.

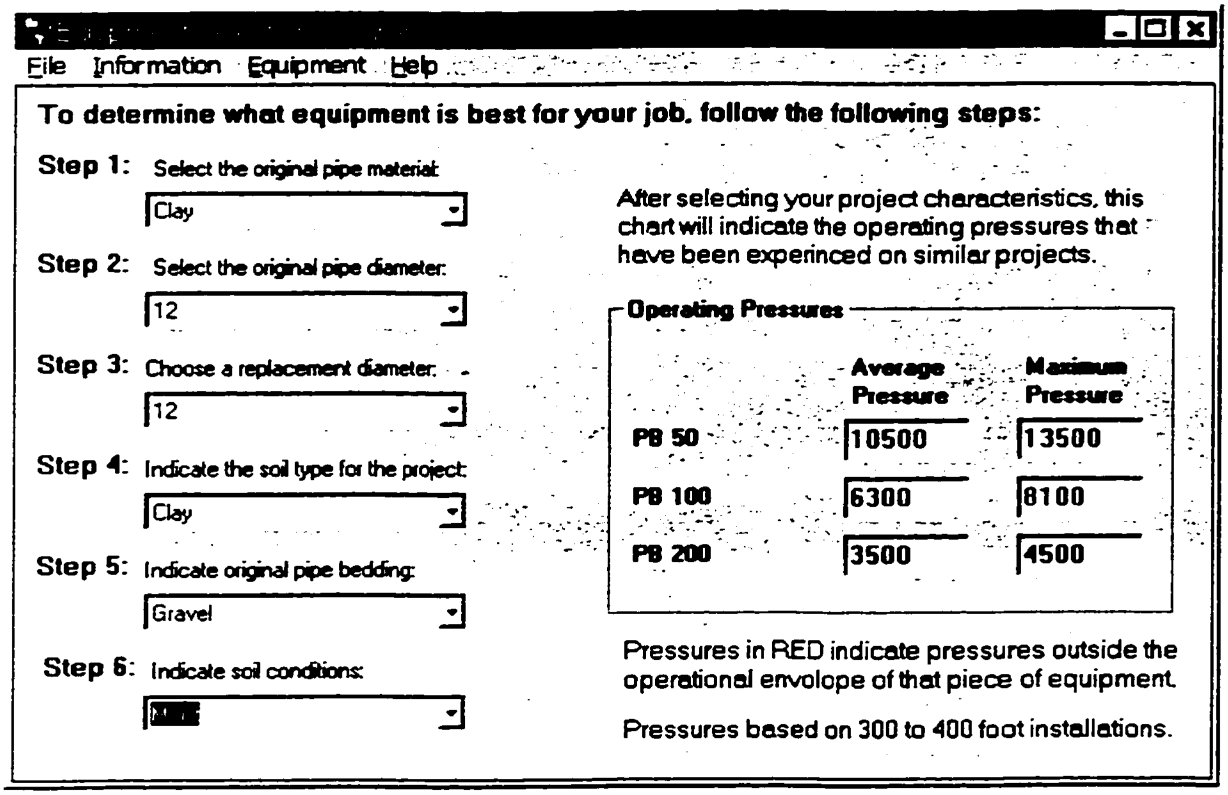

Figure 4-4 Equipment Selection Program

4.4.2 Future Enhancements

To improve the effectiveness of the Equipment Selection Program the addition of a productivity estimation module, as well as algorithms to calculate effective installation lengths and upsize capabilities will be implemented. The addition of these elements should provide a more complete picture of the capabilities of the static pipe bursting process.

Collection of productivity data is the first step in developing this module. This information can be obtained through surveys and interviews of static pipe bursting contractors. Information on productivity values for various soil conditions and host pipe material will be solicited. Initial productivity data is summarized in Table 3-8. This data only represents bursting rates by original and upsize diameter. As additional data is collected, productivity rates for different host materials will be developed.

Additionally, the incorporation of upsize capabilities with length of installation will determine how the upsize factor affects the effective installation length. As the upsize factor increases, so does the amount of material that is displaced and compacted by the bursting head. This compaction limits the degree to which the diameter of the host pipe can be enlarged, as well as increases the pulling force required for the installation. By incorporating an algorithm in the Equipment Selection Program to account for this effect, the application would more realistically reflect the capabilities of each equipment line.

To develop this algorithm, additional data is required to determine the effects of installation length, host and product diameter, as well as host composition on the overall bursting process. Terraco Excavating Ltd. and Midsouth Trenchless Inc. submitted project data to help develop the initial model. Performance data for each of the manufacturer's equipment lines are necessary to provide factors that relate the magnitude of the pulling force to the length of the installation. This preliminary data is presented in Figure 2-13.

To simplify the presentation no distinction was made between the equipment lines in this graph, though in the program, once more data is collected, each equipment line would have a curve similar to that in Figure 2-13. Data collected from 85 installations performed using the static pipe bursting method demonstrates the correlation between upsize factor and length of installation. This information, correlated to the soil conditions, original pipe diameter and material, would allow the ESP to more realistically provide upsize diameters along with the effective installation length. This in turn should assist in providing more accurate productivity assessment.

4.5 SIMULATION

The following presents an application of a general purpose simulation platform developed at the University of Alberta called Simphony, used to create a special purpose simulation application of the pipe bursting process. Information gained from the simulation output can assist in the designing and planning of a pipe bursting project.

4.5.1 Special Purpose Simulation in Construction Applications

Special purpose simulation (SPS) is defined as "*a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications and reporting are completed in a format native to the domain itself*" (AbouRizk and Hajjar, 1998). Building a SPS tool requires knowledge in three main areas, namely: the tool's intended application domain, simulation theory, and object oriented programming. The process is iterative, requiring good design and implementation strategy based on a balance between flexibility of the modeling environment and ease of use. SPS has been shown to be a promising approach for integrating simulation into the construction management process (AbouRizk and Hajjar, 1998). Its application; however, has been hindered by the effort and resources required to build a individual SPS tools.

4.5.2 Background of Simphony

Simphony is a simulation platform for building SPS and other simulation tools referred to as Simphony templates. Simphony is based on an "object oriented application framework" approach, which provides a structured approach for building a new template. The services provided under the framework include simulation (a discrete event simulation engine), trace manager (to trace required simulation events, errors encountered, etc), statistics collection, graphical (enabling a structured and cost effective approach for creating visual/iconic interfaces for a given template), random number generation, report generation, and planning. At the heart of Simphony is the concept of a modeling element, which is a class that encapsulates functionality common across most SPS tools. This modeling element provides a structured way for extending the functionality of the system for the intended domain.

4.5.3 Special Purpose Simulation for Pipe Bursting Operations

To model the pipe bursting process, essentially only two classes of elements are constructed. These element classes consist of pipes and pits. Pits represent the physical manifestation of the excavations used to access the pipe. The pipe element is used to connect the pit elements and transport the entity through the model. Pits are grouped by function into categories: machine pits that house the pipe bursting machine and insertion pits where the product pipe is inserted into the original pipe to be pulled to the machine pit. Depending on the layout and orientation of the host pipe and the manholes, the sequence and number of machine and insertion pits may vary.

In general, for each section of pipe that is to be replaced in the ground, one machine pit and one insertion pit are required. Alternatively, if two sequential sections of pipe are to be replaced, there need only be one machine pit at the junction of the pipe segments and two insertion pits at each end a pipe segment. Subsequently, the setup may be performed using two machine pits and one insertion pit at the junction of the pipe segments. Sequencing of pits is constrained by the amount of space available on site. Insertion pits typically require more space than machine pits since the entire length of the new line must be strung out of the pit prior to pipe bursting commencing.

In the simulation model, six types of pits are identified and constructed to model actual project conditions. These are distinguished by the direction in which the product line is inserted into the pit, as well as the direction that the pipe bursting machine pulls the product line into the ground. Therefore there is a machine and insertion pit for pulls and installations that occur from the left side of the screen to the right, right to left, and from both directions. In actuality, there is no difference between how machine pits operate amongst the different directions of operation, but is available to more closely represent the orientation and setup of the project. Additionally, pits can be linked together to represent conditions where essentially a new pit is required to complete the installation.

To complete the model two other elements were added, the Job Start and Job Finish elements. The Job Start element created one entity that is sent in a linear fashion through the model. This entity transports information to the Job Finish node, where productivity values are calculated and stored. In the Job Finish element the user may also view the productivity data for the project. Project elements used in the simulation model are illustrated in Figure 4-5.

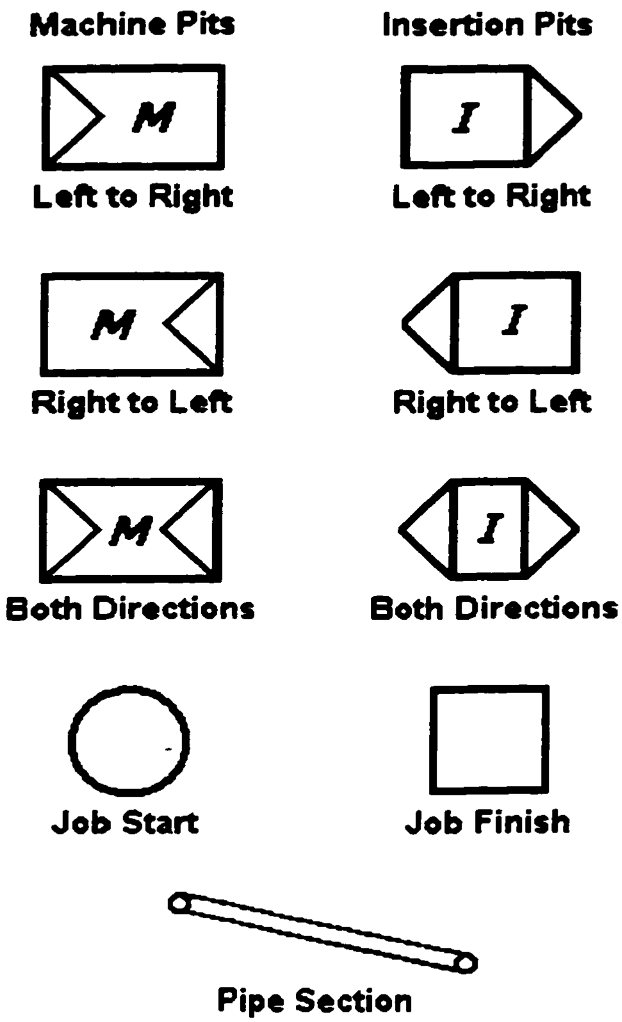

Figure 4-5 Simphony Pipe Bursting Modeling Elements

To construct a model based on a given project, the user need only click and drop the project elements into the project model. An illustration of the user interface is shown in Figure 4-6. In this figure, a typical bursting project is composed, consisting of two insertion pits with two machine pits. Between the pits are three pipe sections to transport the project entity through the network. On the left hand side of the network is the Job Start node, as well as the Job End node at the other end of the network.

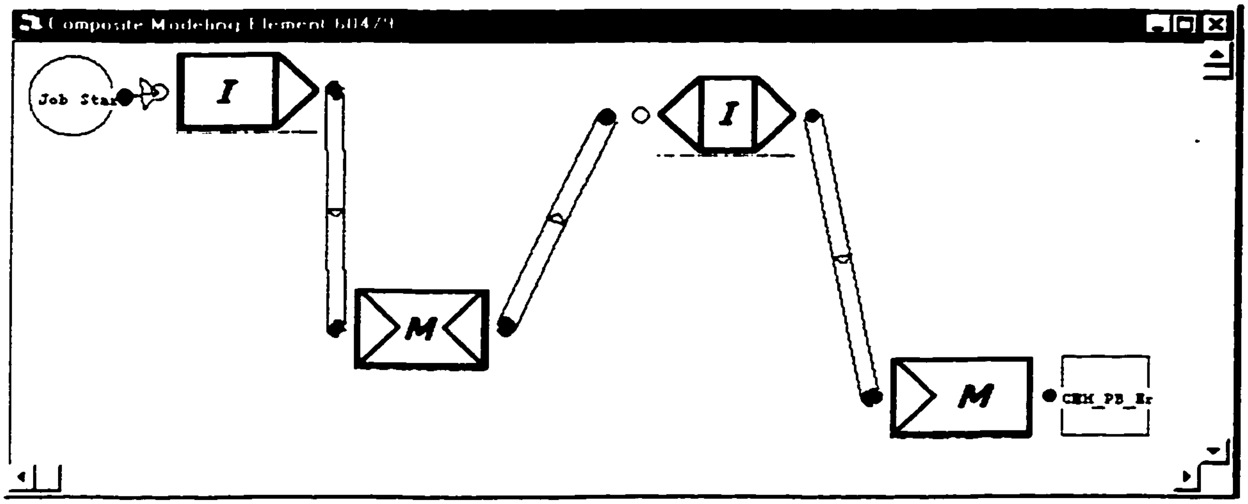

Figure 4-6 Pipe Bursting Project Model in Simphony

Each element in the simulation model has both a series of properties and attributes that are assigned by the user at the start of the simulation and those that change as the simulation progresses. These properties can be classified as micro properties, which are assigned for each model element, or as macro properties that are assigned at the project level. Simphony utilizes a micro and macro hierarchy structure which allows the user to assign properties to the level from which they were used and directly affected the process. Project and element user defined attributes are shown in Table 4-2. The attributes related to the pipe segment are used to determine the time as well as the amount of force required to burst the line. This in turn will calculate whether the selected equipment specifications, as outlined in the project, are sufficient to complete the pull. Currently, modeling the relationship between soil and pipe type, as well as the degree of upsizing as related to the force required to burst the pipe is still under development.

Table 4-2 Project and Element User Defined Attributes

Element Attributes		Project Attributes
Pipe Segment	**Pits**	
Length	Length	Rod Length
Original Diameter	Width	Cylinder Stroke Length
New Diameter	Depth	Cylinder Diameter
Soil Type	Excavation Productivity	Number of Cylinders
Pipe Type	Machine Placement Time	Pump Flow Rate
	Product Placement Time	Coupling Time
	Time to Disconnect Lines	Rod Load and Unload Time
	Time to Reconnect Lines	Bursting Head Attach Time

Attributes related to the machine and insertion pits determine the time required to excavate the pits, place the machine (for machine pits) or product line (for insertion pits), as well as the time to disconnect and reconnect the line after the burst is complete. In the bursting operation, the existing line must be taken out of service until the new line is installed. Pit attributes are unique for each pit and depend on the accessibility and available space to set up either the machine or insertion pit. Additional element and entity attributes are used though out the model but are kept hidden from the user. These attributes are used to store data for the simulation as well as to pass information from one element to the next via the entity.

In general, the contractor would use the same pipe bursting machine though out the entire project, therefore attributes relating to the machine and activities not dependant on the layout of the site may be stored in the macro or project level. There are a number of attributes relating to the pipe bursting machine that can be changed to determine the effect on bursting productivity. This was one of the main objectives of the simulation model, not only to assist in project planning but also to assist in equipment design and selection for a given set of project characteristics. In the model, pre-determined equipment specifications with assigned attributes will be available, from which the user can modify to suit various project requirements.

4.5.4 Model Layout

In the creation of the special purpose pipe bursting simulation, key activities or events were identified to be scheduled in the model. The essential steps in the bursting process as were modeled are shown in Figure 4-7. Each event as listed in the flow chart represents an event that Simphony scheduled during simulation. There are two loops that occur in the process, one where rods are pushed through the existing line to the insertion pit, and the other where these rods are then pulled back through the line with the bursting head and product line attached to actually burst the pipe. The continuation of these loops is dependent on the length of the line being replaced as well as the length of the bursting rods, as specified by the user. Schedule times relating the push loop and the bursting loop are calculated according to machine specifications. In this manner the user could determine the effects that modifications to the basic bursting machine would has on the overall productivity of the operation.

The model utilizes three resources through out the simulation; these include the pipe bursting machine, a surface crew, and an underground crew. For each activity, various combinations of these crews are required to complete the task. Due to the linear nature of the process, events in the model will rarely wait for these resources to be released from prior activities, these resources are used to determine resource utilization from a project management perspective.

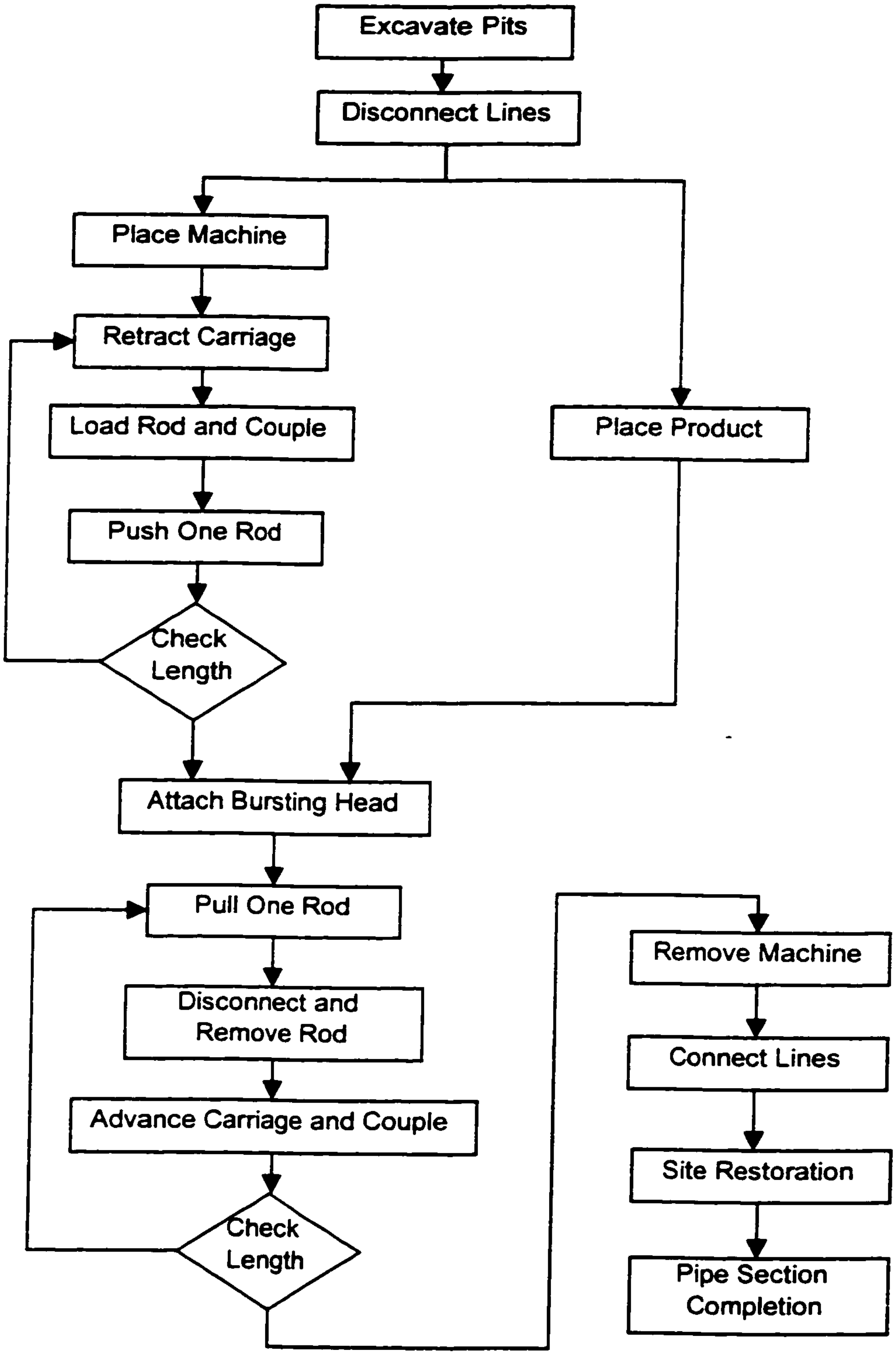

Figure 4-7 Pipe Bursting Process Flowchart

4.5.5 Results

The initial validation of the pipe bursting simulation template was performed on field data collected from an actual pipe bursting project conducted in Naniamo, British Columbia in May of 1999. Three installations of varying lengths and soil conditions were measured. The project itself was the replacement of a 325 mm O.D. concrete sewer pipe with a new 675 mm O.D. high-density polyethylene line. Information pertaining to the project statistics is listed in Table 4-3. Soil and bearing capacity qualifications are based on subjective field observations. Additionally, the number of hydraulic cylinders used to pull the rods and pipe are indicated in the table. The number of cylinders directly affects the travel speed of the carriage for both the push and pull back operations.

To validate the model project data was entered into a project network consisting of one insertion pit, one machine, and a pipe section. A Job Start and Job Finish node were added to complete the model. Each installation length was simulated as an independent event to correlate actual productivity. The simulated and actual burst completion times and productivity are compared in Table 4-3. The table reveals that the productivity simulated for installation 2 and 3, are very similar to the actual burst productivity, while the productivity for installation 1 was calculated to be much lower than the actual productivity. This difference may be attributed to the lower bearing capacity of the soil that was the predominate condition throughout the first installation. Additionally, the surface conditions on the first installation were such that the bearing pressure provided by the overburden was uneven. In the location of installation 1, the pipe was in the vicinity of a drainage ditch where there was less soil on top of the pipe, thus allowing the burst to progress in a more timely manner. To improve the simulation accuracy, validation will continue with additional simulation factors added to account for varying project characteristics, and in particular, soil conditions.

Table 4-3 Simulated and Actual Project Productivity Results

	Installation #1	Installation #2	Installation #3
Length (ft)	561	541	229
Soil Description	Clay	Clay/Gravel	Clay
Bearing Capacity	Low	Medium	Medium
Water Table	N/A	N/A	High
Number of Cylinders	4	4	2
Actual			
Total Time (hrs)	2.60	3.85	2.13
Productivity (ft/hr)	215.8	140.6	107.7
Simulated			
Total Time (hrs)	3.86	3.75	1.87
Productivity (ft/hr)	145.4	143.9	122.1

The main advantage of using simulation in the field of trenchless pipe replacement is in the modeling of larger projects. It should be noted that in the previous simulated pipe segments only one run was performed on each segment. This method of productivity estimation could be accomplished using a simple spreadsheet or even by hand calculations. The advantage that simulation of this nature has on larger projects is that pit properties and locations can be planned over the sequencing of many pipe segments. Subsequently allowing the user to optimize the installation process and setup procedure by observing the effect pit sequencing has on the overall productivity by literally moving, adding or modifying pits and locations within the project screen. When modifications are made to equipment, their effect on the overall productivity is better demonstrated on the replacement of multiple pipe segments. Additionally, a simulation model, such as the one presented, is intended it be run over multiple runs where the same project is simulated several times. This allows for productivity and time estimates to be calculated based on the variability of the activities and events in the model. It is these aspects that make simulation a more useful and effective tool in estimating productivity on large-scale projects.

4.5.6 Future Enhancements

There are many factors that contribute to the pipe bursting process as well as to the success of a project. Presently, the simulation model accurately depicts the progression of events based on the mechanics of the pipe bursting operation. To make this model more valuable as a planning tool, various situations pertaining to events that affect the operation must be incorporated. These events would add elements of uncertainty that can be simulated to gain a more accurate perspective on the proper utilization of equipment, as well as the success of the project.

Currently, there are four variables in the process of being incorporated into the simulation template to improve the modeling of bursting projects. These variables include factors for soil conditions, crew experience, environmental conditions, as well as the geometry of the original pipe installation. It is proposed that these variables be based on a numeric scale to incorporate the judgement of the user into the mechanics of the bursting simulation.

Soil factors would account for soil bearing capacity, water table location, and the available information from geotechnical investigations. This factor affects the amount of force required to displace soil in upsizing operations, as well as combine with equipment specifications to determine the chance of overpowering the equipment during the burst. Crew experience directly affects the productivity of the operation, and is accounted for in the time to complete activities. Issues relating to the amount of space available to move equipment and excavate are considered in the environmental factor. The original pipe installation geometry determines the force required and success of the burst based on the equipment and soil factor. To depict actual project conditions, soil, environmental and geometry factors would be applied for each pipe section. With the addition of these factors and issuing multiple runs, productivity rates and project success rates with various project and equipment specifications can be achieved.

To enhance the project management and planning aspect of the model, it is essential that a cost estimation module be added. Costs could be calculated from the variables entered in the modeling elements with the addition of a database to provide crew compositions and rates. This may assist planners to simulate costs and productivity over multiple runs to determine the best cost and productivity for the level of risk that the planner wishes to undertake.

4.6 CONCLUSIONS

This chapter presented the development of special purpose software and applications of existing software for the pipe bursting industry. The main contribution of this research was in the application of these pipe bursting specific applications to the trenchless pipe replacement industry. Research had revealed that there was no commercially available software packages for the pipe bursting industry, and that these applications would be the first generation of applications specifically designed for the industry.

Utilization of project planning and tracking software, and decision support software is expected to increase as more people involved in the pipe bursting industry become aware of the advantages of these programs. An important factor in the development of this software is the access to data from pipe bursting contractors. With more data pertaining to the various methods of pipe bursting utilized in North America, these basic models can be expanded to be used for all bursting techniques.

The simulation modeling of trenchless renewal of underground urban infrastructure using Simphony, a simulation platform developed at the University of Alberta, was also presented. Simphony was designed to act as a platform to enable the creation of special purpose simulation models for real-world applications.

The developed model was compared to actual field results obtained from a trenchless pipe replacement project in Nanaimo, British Columbia in May of 1999. Productivity simulated for two of the three installation sections modeled similarly to actual productivity. As additional factors are added to the model to account for project uncertainty and differing soil conditions, the accuracy of the simulation should increase thus providing benefits to owners, engineers, contractors, and equipment manufacturers in the designing and planning of trenchless pipe replacement projects. With information provided by decision support software and simulation tools, planners and contractors could better provide solutions to their clients' rehabilitation requirements. It is hoped that, through the sharing of knowledge, pipe bursting becomes more recognized as an effective rehabilitation tool in the municipal arena. As more and more municipalities are faced with the daunting task of repairing or replacing their aging buried infrastructure, there should be greater emphasis placed on tools to assist in designing and planning.

CHAPTER 5 SUBSURFACE GROUND MOVEMENTS

5.1 INTRODUCTION

One of the primary concerns associated with pipe bursting is the interaction of the displaced soil with surrounding utilities and the surface. As the product line is installed in the original pipe cavity, the soil around the cavity is compacted and displaced to provide the additional space required to accommodate the new pipe diameter. Even if the host pipe is replaced size for size, ground movements still occur due to the over burst as well as the displacement of the original pipe wall material. These soil movements have the potential of damaging existing buried lines and structures around the line being burst. All methods of pipe bursting displace soil in the bursting process even if the replacement pipe is the same size as the existing pipe. In general, the soil and pipe properties, in addition to the installation characteristics of the original pipe determine the magnitude and effect of ground movements.

This chapter outlines previous work conducted in the area of ground movements associated with pipe bursting, as well as a feasibility study and analysis conducted by the author, in conjunction with StrykerForge Consulting Inc. and Terraco Excavating Ltd., of a new technique to measure these ground movements. In general, field measurements of pipe bursting operations have mainly consisted of monitoring surface heave during bursting, as well as using subsurface survey points along the axis of the pipe to measure displacements at different depths directly above the pipe. The main problems in accurately developing a model to predict ground movements is the lack of subsurface displacement data and the inability of conventional methods to accurately and effectively determine soil displacements that do not occur directly above the pipe being burst.

The risks associated with subsurface ground movement limit the application of trenchless pipe replacement to situations where bursting operations are planned in areas of high underground utility congestion, or when bursting in close vicinity to existing utilities such as gas distribution lines. It is believed, that if this movement mechanism could be better understood, that the application of pipe bursting would increase in the municipal arena due in part to risk reduction.

5.2 PREVIOUS GROUND MOVEMENT ANALYSIS RESEARCH

There has been some research conducted on the ground movements associated with trenchless pipe replacement processes. Most of the previous work has been based on theoretical equations, laboratory work and field measurements. Some of the most notable research conducted in this area is summarized in the following text.

The Trenchless Technology Center at Louisiana Tech University conducted a study that focused on the ground vibrations associated with pipe bursting to obtain a safe distance for utilities from the replacement pipe. Using peak particle velocities as an indicator of the potential to cause structural damage, a series of 11 field measurements were conducted using various bursting methods, pipe materials, upsize configurations, depths and pipe sizes. Through this analysis, peak particle velocity vs. distance relationships were developed and compared to criterion used in the blasting industry and other sources of construction vibration. It was found that ground vibrations that occur in close proximity to the bursting operation quickly dissipate to levels that would not cause even cosmetic damage to buildings, and would have negligible effects on buried structures and utilities (Atalah et al. 1997). This method of analysis was only able to determine that the vibrations do not cause damage, but did not address the issue of damage caused by ground displacements associated with the bursting process.

Additionally, ground movements resulting from trenchless and open cut installation procedures were compared in work conducted at Loughborough University of Technology by Rogers (1990). The research describes patterns of ground movements that can be expected from underground construction activities. This analysis indicated the effects of ground composition based on the magnitude of the ground movements expected from various methods of installation. From field and laboratory observations, it was determined that the displacements caused by trenchless pipe replacement are typically smaller that those caused by trenching operations. Laboratory studies in which bursting heads were pushed through observation containers filled with sand allowed the determination of displacement vectors from which magnitudes of ground movements could be extrapolated. It was found that most displacement movements diminish at distances greater than 300 mm from the pipe being replaced in dense sand, and over a smaller distance in loose sand.

To determine the effects of pipe bursting on utilities in close proximity to the pipe being burst, Leach and Reed (1989) conducted a series of field bursting trials at the Water Research Center. They installed cast iron and clay pipes of various diameters at varying depths, then burst these pipes and replaced them with high-density polyethylene pipe of varied upsize factors. To determine the effects of the soil interaction on adjacent utilities, instrumented ductile iron pipes were buried both perpendicular and parallel to the pipe being burst. Additionally, British Gas conducted monitoring programs on contract work in a similar manner to that undertaken in the controlled field trials. The data collected was used to develop proximity charts to determine safe distances for buried utilities and to predict the effects of surface heave. Additional work in the development of these charts needs to be conducted to account for varying depths and soil conditions.

Swee and Milligan (1990) conducted laboratory tests on the effect of soil characteristics on the amount of soil movement observed with pipe bursting. Laboratory tests simulating field replacements of scaled down bursting operations were conducted using sand, clay, and a combination of sandy-clay backfill in tanks that had transparent walls to observe the ground movements associated with the displacement process. Using positional markers in the cut away sections, time lapse photography was used to determine the vector displacement of the soil particles during bursting. The different soils enabled the measurement of displacements varying with drained and undrained soil conditions as well as air void content and density. These tests provided information related to ground movements for bursts conducted in cohesiveless and cohesive soils, and determine a predicted zone of influence. The analysis concluded that the main factors influencing the magnitude of ground movements associated with pipe bursting include soil properties, geometry of the installation and drainage characteristics. Of note was that less ground movements were observed in soils that had higher void ratios, such as loose sands and clays.

Heinz et al. (1992) conducted research based on instrumented projects in Edmonton, Alberta. An empirical format is outlined for the evaluation of surface displacements above pipe bursting projects. Additionally, an analytical model based on cavity expansion theory was proposed for estimating subsurface displacements. This model can be used to estimate displacements based on geometric characteristics of the bursting project. The model presented in this research is compared to field results attained from a study conducted by the author, the results of which are presented later in this chapter.

Though several studies have been conducted pertaining to the nature of subsurface ground movements associated with pipe bursting, it has been difficult to determine how the ground surrounding the pipe actually behaves. Much of the current theories on soil movements associated with pipe bursting are based on foundation equations and were developed in controlled laboratory or field environments. Cavity expansion theory, in reverse to subsidence associated with tunneling, may also be an avenue to explore. To develop a better understanding of the subsurface ground movement mechanism of pipe bursting, it was deemed necessary to take a different approach to traditional methods of ground movement monitoring.

5.3 SUBSURFACE GROUND DISPLACEMENT MONITORING FEASIBILITY STUDY

One technique found by the author that showed potential in the measuring of subsurface movements associated with the bursting process is tilt meter technology. Initially created for the express purpose of introducing an advanced geophysical technique to the environmental remediation industry, the technology also has potential for site investigation. Using technology that has been proven in the oil field industry, tilt meters have the capability of providing detailed and accurate three-dimensional strain measurements that vary with time. Thus, it would be possible to know the magnitude and direction of soil displacements around the pipe being burst, and have a record of displacement changes with time. Using the displacement or strain from the results, one could calculate the changes in the stress field of the soil around the pipe. From this, the effect of the bursting operation on buried utilities and structures could be determined.

Data from the tilt meters provides information on strain measurements around the pipe in three dimensions. This technique can provide definitive measures of the ground movement mechanics associated with the bursting operations. From this data, a simulation model may be developed to predict soil movements around the pipe in question. With a tool to assist in the prediction of ground movements, planners can more effectively design bursting projects in situations where the burst is conducted in close proximity to buried utilities. We constructed a feasibility study that was conducted with industry support to determine if tilt meters could be used to measure the ground movements caused by pipe bursting, with the ultimate goal of using data collected from the tilt meters to develop a soil displacement model.

The main advantage of using tilt meters over other methods of subsurface ground measurements is that tilt meters provide a non-destructive means of investigation. Data can be collected from the bursting process without excavation or installation of subsurface probes. If this measurement method were feasible, it would allow for the collection of data under actual project conditions and scale, as well as provide information on soil conditions from the vicinity around the pipe, including the possibility of lateral displacements. In comparison to other non-destructive means of ground monitoring, including ground penetrating radar and seismic measurements, tilt meters were the only technology that allowed for the quantification of displacements directly above and around the pipe that could be monitored in relation to time.

5.4 OBJECTIVES OF FEASIBILITY ANALYSIS

The main scope of the work conducted on this project was to determine the feasibility of using tilt meters to measure the subsurface ground movements associated with the pipe bursting technique in the gathering of soil displacement data. The collection of data for this analysis was conducted on the Millstone Sanitary Trunk Sewer pipe bursting project in Naniamo, British Columbia, under difficult site and project characteristics. The goals of this feasibility study were as follows:

1. Evaluate the accuracy of the determination of the soil displacements measured by the tilt meters.
2. Compare results obtained from the tilt meters to those obtained with more conventional linear potentiometer measurement instruments.
3. Observe the soil displacement characteristics resulting from the bursting process.
4. Develop procedures for the use of tilt meters to measure the ground movements associated with the bursting process.
5. Determine if the data gathered from the tilt meters were of the quality that could be used to develop computer simulation models to predict ground movements resulting from the bursting process.

5.5 TILT METER TECHNOLOGY

To collect more direct and detailed measurements on the ground movements associated with the bursting process, the research team utilized tilt meters. This trenchless technology, more reserved for the oil and gas industry, was applied to the rehabilitation of utility infrastructure. Generally used to map and locate subsurface ground movements caused by the fracturing of oil and gas bearing structures, tilt meters are a tool that shows promise in measuring the ground movements caused by the bursting process. The ground movements gathered by the tilt meters can be used to interpret and extrapolate subsurface strains and stresses based on surface movements.

The measurement of the subsurface ground movements utilizing tilt meters is accomplished using an array of meters installed on the surface and, in this case, over the pipe to be replaced. A photograph of the tilt meters used on this project is shown in Figure 5-1. Tilt meters measure the change in the tilt of the ground surface over time, with an accuracy of 0.5 microradians. This accuracy is equivalent to the angle that would result from a surface uplift of 5 microns over a 10 m baseline. Using an array consisting of 8 to 24 tilt meters, the area of interest can be mapped. After the raw surface data is collected, a profile or curve of the surface deformation is integrated to determine the area or volume change beneath the surface. This process can map the change in strain, which a soil structure exhibits, varying with time as the burst progresses. A graphical representation of the soil strain field could be developed that would provide a three dimensional interpretation of the soil movements completely surrounding the pipe being burst.

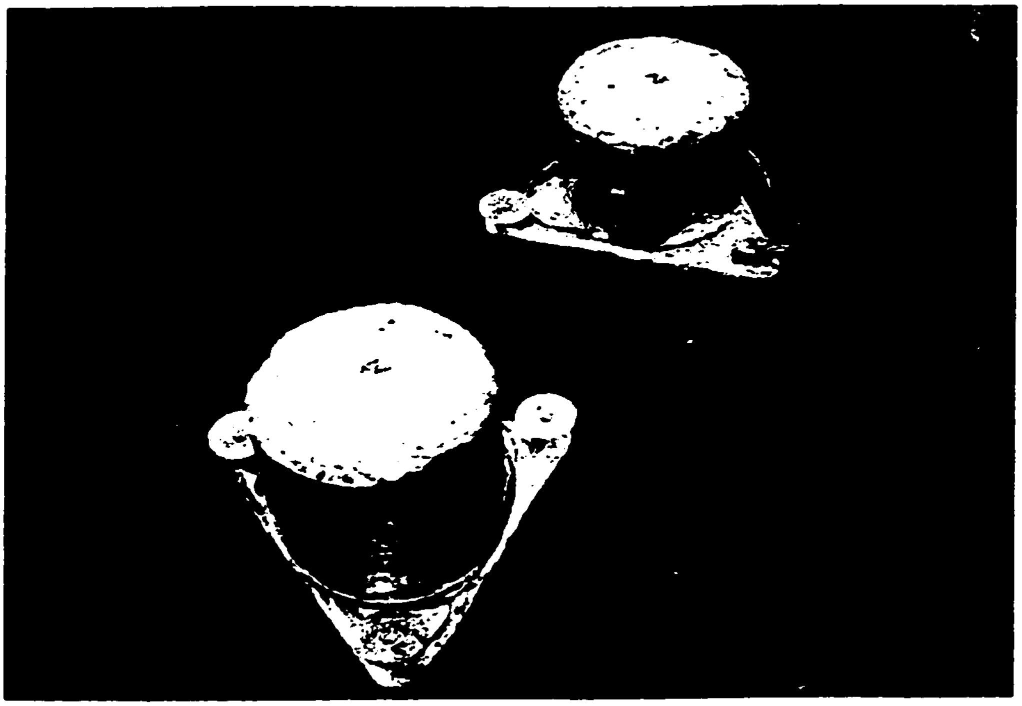

Figure 5-1 Typical Tilt Meters

Installation of the tilt meters is accomplished by mounting the meters on a specially prepared surface location of approximately 300 by 300 mm in dimension. On soft ground, the meter is placed on a base plate on a layer of sand to ensure even contact with the ground surface. On harder surfaces such as asphalt or concrete, the tilt meters can be placed directly on the surface without the need for base plates. The meters are then leveled and connected to data loggers prior to the commencement of the measuring sequence. Array configuration is typically in a rectangular grid like configuration though the instruments need not be placed in precise locations, therefore allowing for their placement to be clear of obstacles. To facilitate the analysis of the data collected, the meters need only be surveyed to determine their Cartesian coordinates, as well as their initial and final elevations.

5.6 LINEAR POTENTIOMETERS

Linear potentiometers were used on this project to establish the accuracy of the tilt meter measurements as well to establish a base line to which data from the tilt meters could be calibrated. Potentiometers are established measuring instruments that have been extensively utilized in geotechnical practice. One of the linear potentiometers used on this project is illustrated in Figure 5-2. The potentiometers used on this project resemble a piston and cylinder setup, where the piston moves within the cylinder and is measured in voltage. This voltage is calibrated with a measured travel of the piston to determine the movement that occurs. Data from the potentiometers is collected using data loggers and can be analyzed after the voltages are calibrated to the actual movements that occur.

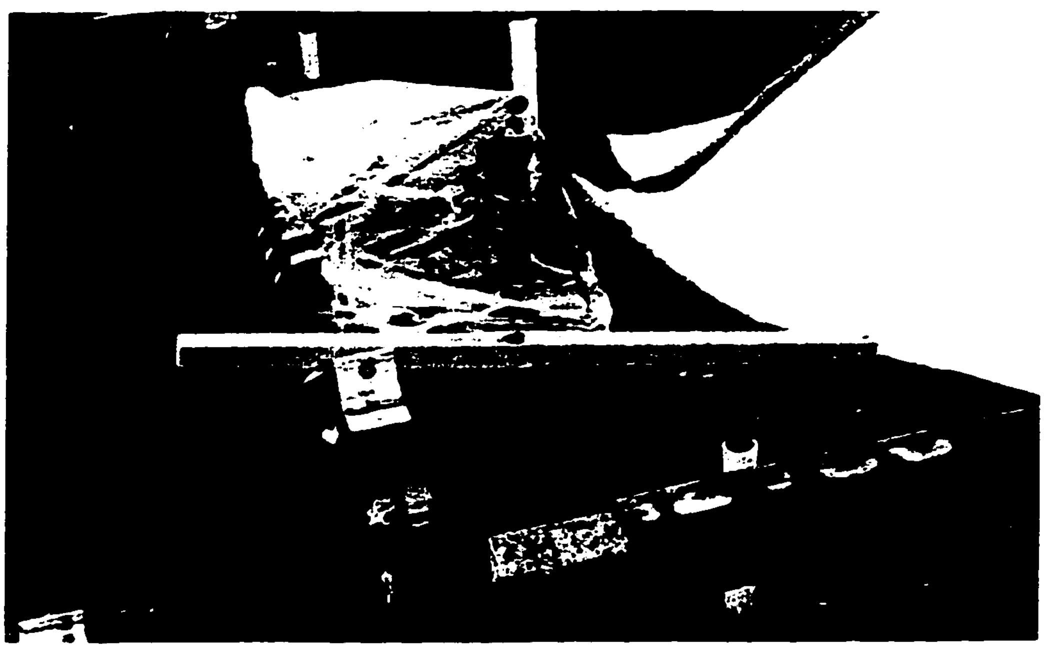

Figure 5-2 Linear Potentiometer in Protective Rain Bag

5.7 EXPERIMENTAL PROCEDURE

5.7.1 Project Site Information

To determine the effectiveness of the tilt meter technology on the measurement of ground movements associated with the pipe bursting process, a feasibility study was conducted on a bursting project in Naniamo, British Columbia, Canada. The Millstone Sanitary Trunk Sewer project consisted of the replacement of an existing 325 mm asbestos cement sewer line with a high-density polyethylene line of 675 mm outside diameter. This project was selected due to the large upsize, limited depth of cover, and soil conditions, all of which are considered conditions that are far from ideal. If the tilt meters performed well under these conditions, it would demonstrate this measurement technique as being both feasible and effective in the field environment.

The section of pipe selected for subsurface monitoring was the second section of pipe of the project sequencing. This section was approximately 171.8 meters in length and had a grade of 0.33%. It maintained a depth of cover above the existing line ranging between 1.8 and 2.0 meters. Bore-hole samples collected in the vicinity of the pipe indicated several soil strata, one from the surface to a depth of 2.1 meters consisting of sand with some gravel and trace silts that ranged from being in a loose to compacted state. The nature of the top layer compaction may be a result of the sample being taken at the edge of the road that runs parallel to the pipe. Beneath this layer is a firm silt strata from 2.1 to 3.6 meters. It is described as containing fine sand and some moisture. From 3.6 to 4.6 meters, a sand and gravel layer was indicated, followed by a silt layer to 5.2 meters which was the depth of the bore hole. The water table over the pipe section ran parallel to the axis of the pipe at a depth of approximately 2.1 meters.

Of interest is the location of the pipe in relation to the soil strata composition. In this situation, the crown of the original pipe is located in close proximity to the boundary between the sand and silt layers revealed in the bore logs. With the lower silt layer being of firmer composition to the looser sand, the majority of the movement of the soil would occur on the sand layer, or the top 2.1 meters. This creates a boundary situation where the top may be considered a free surface, and may influence the behavior of the ground movements that occur during the burst.

5.7.2 Test Sites

The main goal of this project was to determine the feasibility of using tilt meters to measure the ground movements associated with the pipe bursting process. Of a secondary note was the development of procedures for using tilt meters on future bursting projects. This would include determining an optimal number of tilt meters to use as well as an appropriate distribution pattern for placing the meters. In general, the tilt meters can be placed in any location as their locations are surveyed to determine their relative placement to one another during analysis. Additionally, it was felt that there would be a minimal number of tilt meters required to compose an effective measurement array. To accomplish these goals, two test sites were devised along the test pipe section.

The test pipe section was located between two manholes, Test Site 1 was located approximately 60 meters south of the northern manhole, and Test Site 2 approximately 120 meters south of the northern manhole. Site 1 was instrumented with 11 tilt meters and 5 linear potentiometers, while Site 2 only had 6 tilt meters and 5 subsurface survey points. Test Site 2 had fewer tilt meters to give an indication of the minimum number of meters necessary to effectively measure the subsurface ground movements. Later when the tilt data is analyzed, an optimal number of tilt meters could be determined for future data collection procedures.

5.7.3 Test Site 1

A testing frame was erected over the centerline of the pipe being replaced. The test frame consisted of round hollow structural sections approximately 75 mm in diameter and 3048 mm in length. Five metal pipe sections were configured in the shape of an "H" using connecting pipe tees that slipped inside the pipe sections. Once assembled, the test frame provided a plane of reference from which to survey locations as well as an anchor to which the linear potentiometers could be attached. The configuration of the test frame as well as the linear potentiometers is shown in Figure 5-3. The test frame was supported and isolated from the ground under review by placing the frame on sand bags on the pavement, and on large concrete blocks in the ditch to the east of the pipe alignment as illustrated in Figure 5-4. Being suspended over the ground and supported a distance from the centerline of the pipe ensured that the potentiometers could measure ground movements from a fixed reference point. Tilt meters were installed on the surface in various locations based on the space available. More tilt meters were located west of the buried pipe than on the east side due to the limited right-of-way on the eastern side. To gain additional information on the nature of the surface deformation, surface points were added from which elevation changes could be monitored.

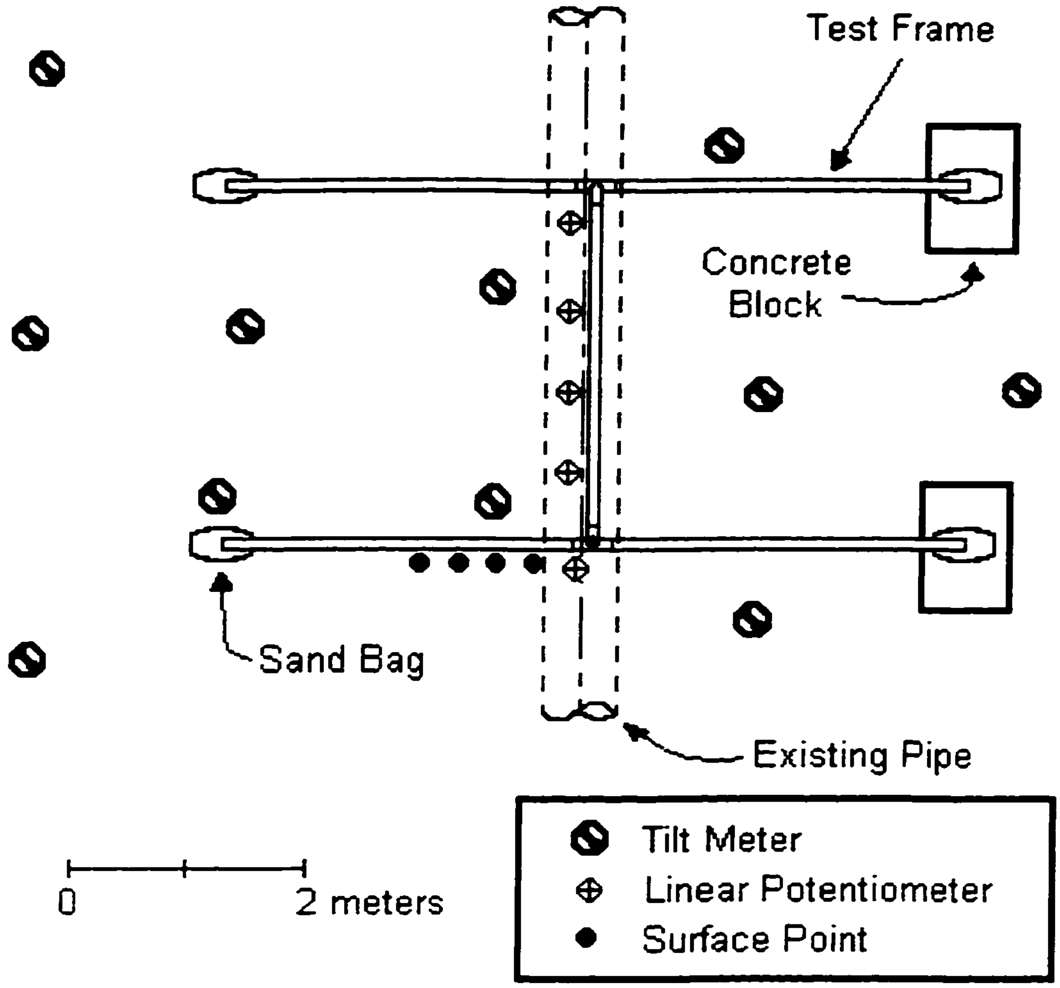

Figure 5-3 Site #1 Setup with Frame and Tilt Meters

As previously mentioned, linear potentiometers were used to assist in calibration and confirmation of the data supplied from the tilt meters. The potentiometers were installed along the approximate centerline of the pipe being burst at varying depths. Figure 5-5 illustrates the configuration of a typical potentiometer installation. To install a potentiometer, a hole was initially excavated to the appropriate depth, a base plate and connection rod inserted into the hole, and soil replaced in the excavation. As the ground moved during the burst, the base plate would be pushed upwards and this movement measured by displacement of the lever arm. The lever arm was used to limit the measurement range required by the potentiometer.

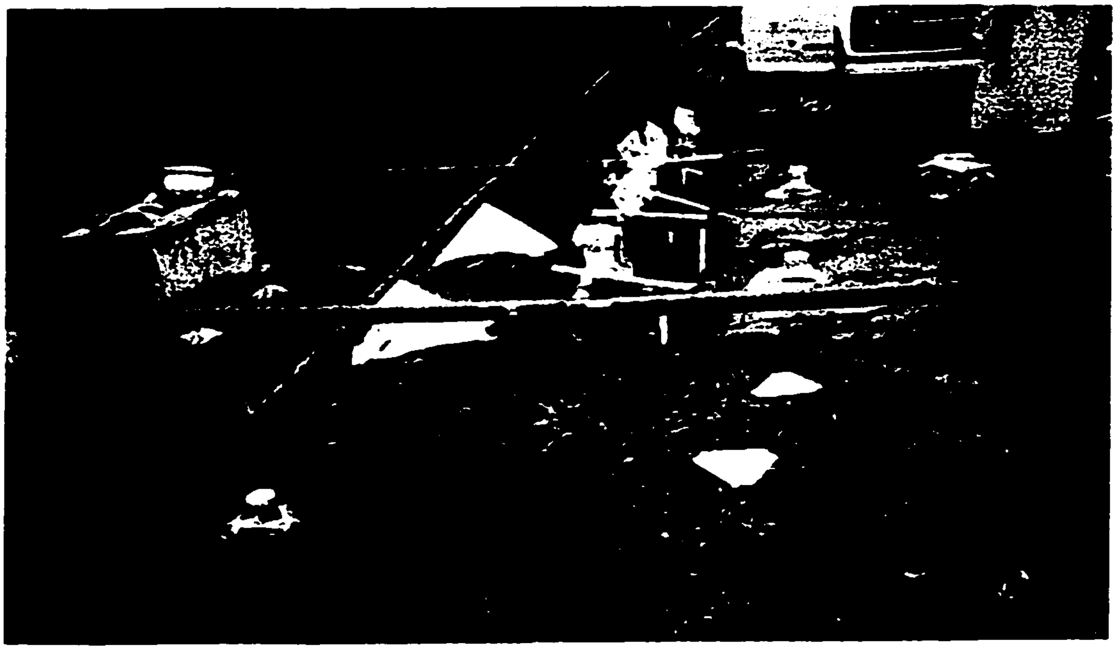

Figure 5-4 Test Frame with Potentiometers and Tilt Meters

At Test Site 1, five linear potentiometers were installed in this alignment at various depths. From the as-built drawings, it was estimated that the crown of the new pipe would be at a depth of approximately 1800 mm. Therefore, to collect data on the nature of the ground disturbance directly above the pipe, potentiometers were installed at depths of approximately 300 to 1500 mm, at intervals of approximately 300 mm.

Additionally, at Test Site 1 Surface Points were established to determine the amount of surface heave that would be experienced during the burst. These consisted of nails driven into the ground and pavement at various distances from the original pipe.

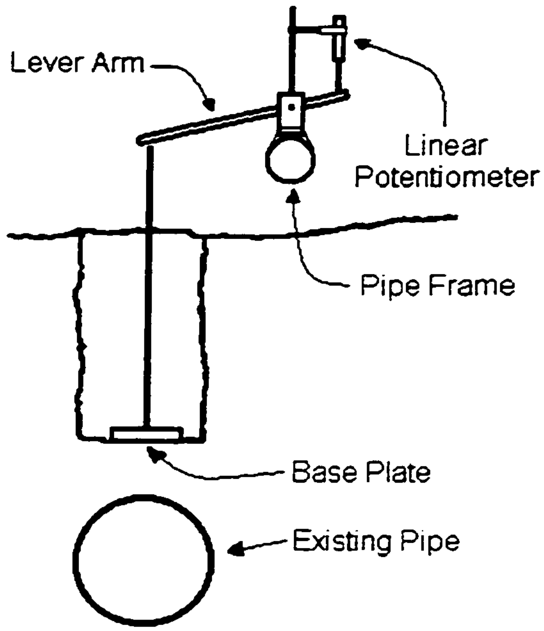

Figure 5-5 Linear Potentiometer Configuration

5.7.4 Test Site 2

Test Site 2 was selected approximately 60 meters from the first test section, so that the tilt meters from the first test section could be moved and utilized. An approximate grid consisting of 6 tilt meters was established, installed directly on the surface of the pavement with no base plates. The configuration of the site is illustrated in Figures 5-6 and 5-7. One of the advantages of using tilt meters over other means of ground monitoring equipment is that access to the area above the location in question is not required. This allowed us to install the meters on the pavement, away from the pipe, and still collect data on the ground movements that were occurring above the pipe. The more meters installed on the surface, the more accurate the profile of the ground movement measurement.

On the second test site, linear potentiometers were not used to collect data from the subsurface points as was done on Site 1. This was due to the time constraint that existed during the burst; therefore the subsurface points were only surveyed before and after the bursting head had passed the location. The configuration of the subsurface points is shown in Figure 5-5 and Figure 5-8, with the exception that, for the second test section, the testing frame and potentiometers were not utilized.

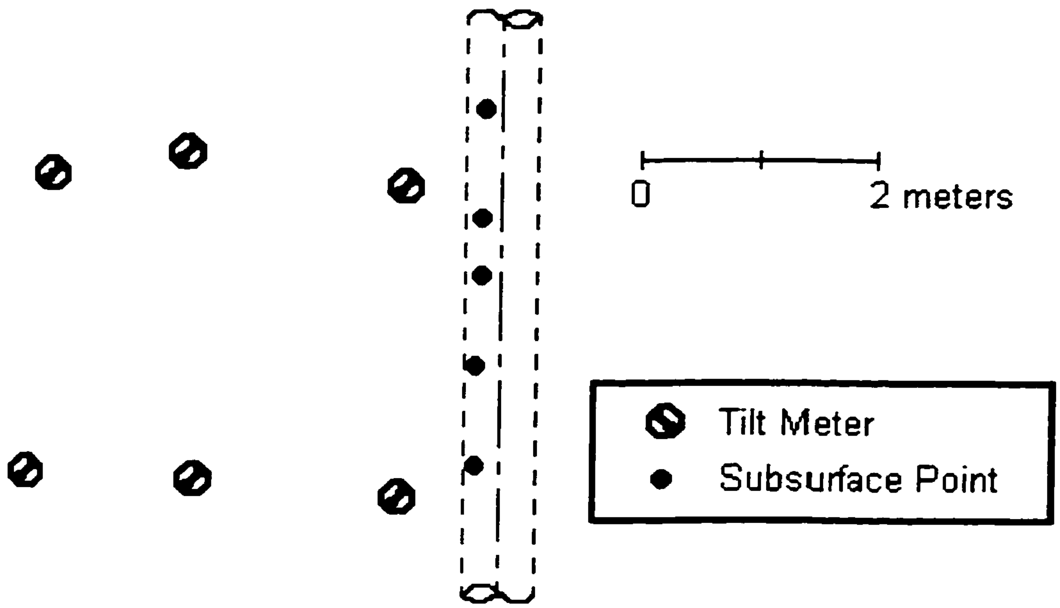

Figure 5-6 Site #2 Tilt Meter Configuration

Data collection for both test sites was accomplished primarily with automated electronic data collectors. Manual surveys were conducted to determine the location of the tilt meters as well as the vertical differential of the subsurface points on test section 2.

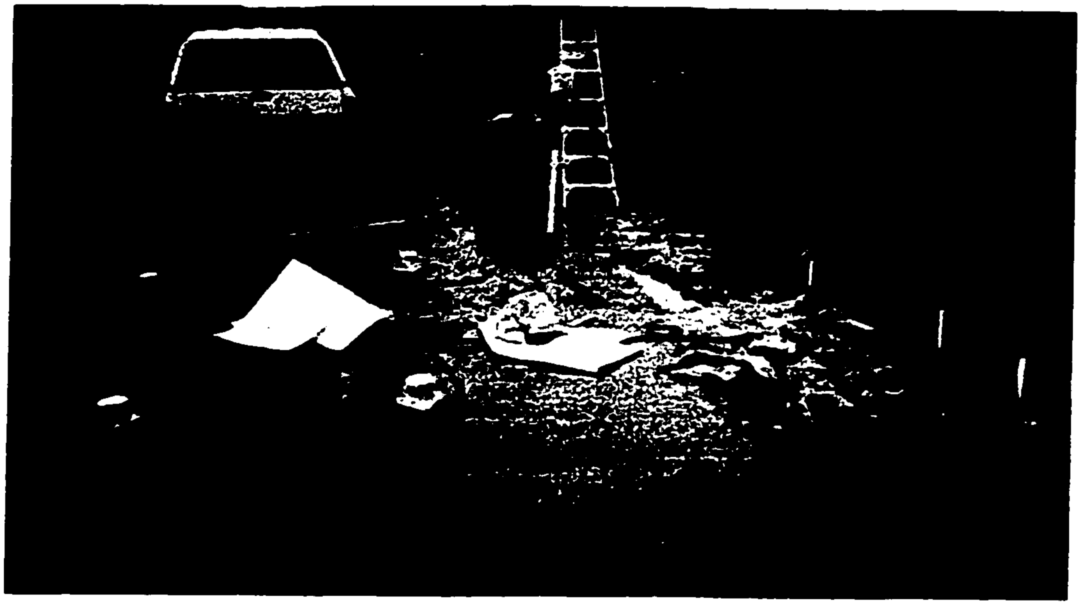

Figure 5-7 Tilt Meter Configuration for Test Site #2

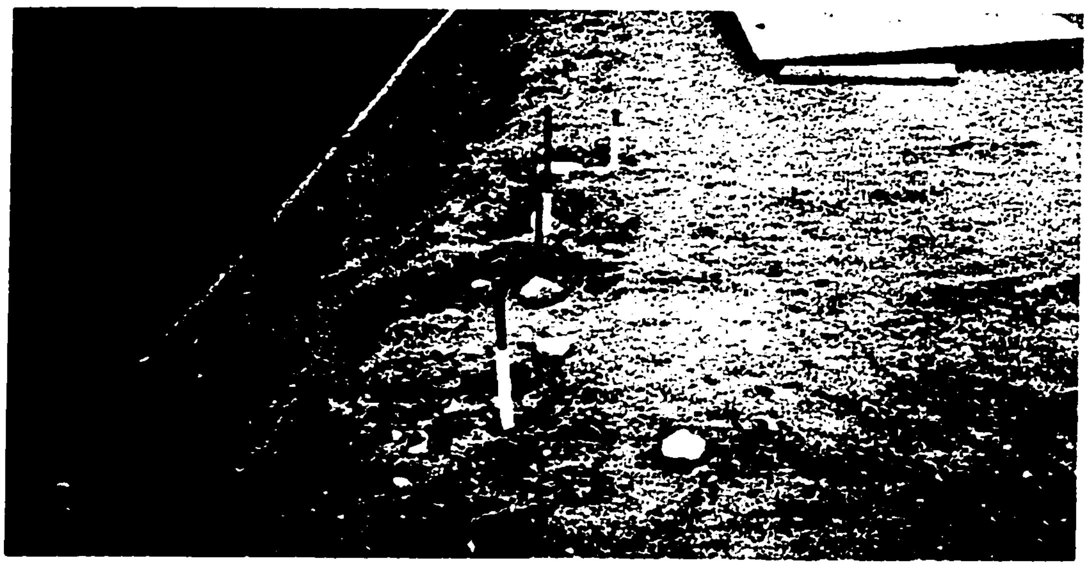

Figure 5-8 Subsurface Data Collection Points at Test Site #2

5.8 RESULTS

The gathering of the data from the test site was accomplished using automated data collection devices. Each tilt meter provided two channels of data, one for movements on a north-south axis, and one on the east-west axis. In the analysis, these channels were combined to produce a resultant vector that indicated the magnitude and direction of the surface tilt at the location of the tilt meter. A tilt vector diagram for one time frame is shown in Figure 5-9. At the time increment captured in this illustration, the bursting head is located to the west of tilt meter 2. The vectors illustrate that the surface is sloping in a radial manner away from the location of the bursting head. For selected increments in time, there is a corresponding tilt vector diagram showing the surface profile.

Through interpolation of the data, it is possible to determine tilt vector diagrams for cross-sections parallel to the surface, from the surface to the crown of the pipe. Boundary conditions resulting from the shallow cover and large upsize, on this project, eliminated the possibility of determining tilts below the crown of the original pipe. With this information, and a complex patented algorithm embedded in a computer application, it is possible to conceptually integrate between the tilt surfaces to determine the change in volume between the surfaces as the burst progresses. This can then be transformed into a three-dimensional relative displacement image, showing the movement of the soil above the midsection of the pipe with respect to time. As a result, it is possible to observe surface profiles at various depths and times as the burst progresses. Three-dimensional surface profiles for one time sequence are shown in Figure 5-10.

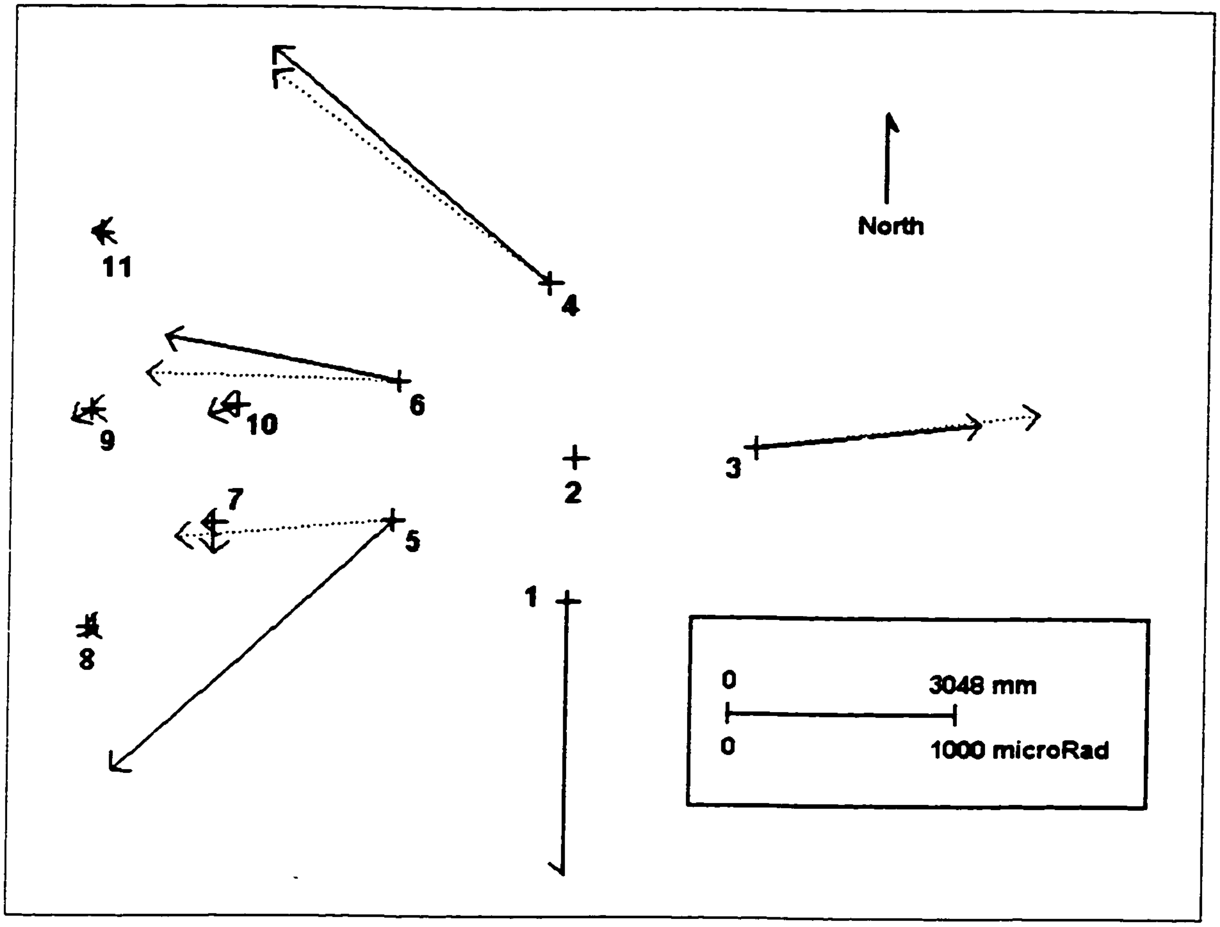

Figure 5-9 Surface Tilt Vector Diagram

Figure 5-10 illustrate the surface profile from test site #1, and layers parallel to the surface at depths of 600 and 1200 mm. The profiles are of an area that is approximately 12 m by 12 m in dimension centered on the test frame, with a grid pattern of 600 mm (2 feet). In the diagram, the bursting head is approaching the viewpoint and is directly beneath the large distortion near the center of the surface. Surface settlements can be observed directly behind the bursting head and surface heave directly in front and in a lateral direction to the bursting head.

Data to create the plots include coordinates for the x, y, and z positions as well as the change in the z-axis resulting from the vertical movement caused by the passing of the bursting head. It is also possible to determine the change in the x and y directions, through additional data analysis. In the future, it may be necessary to include at least the movement perpendicular to the pipe cavity to resolve a vector to show radial displacements away from the centerline of the pipe.

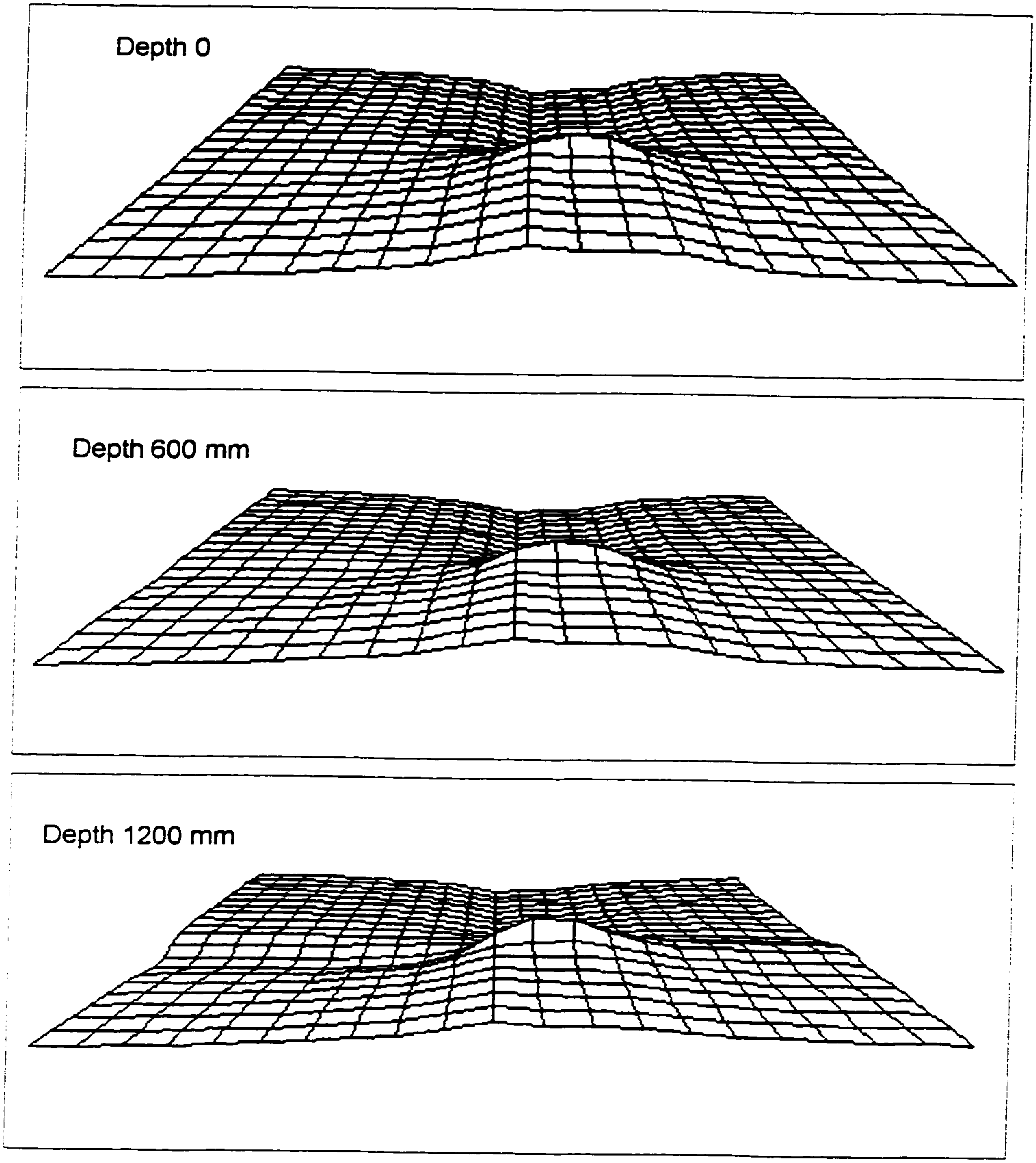

Figure 5-10 Surface Profiles at Various Depths

Once the relative displacement of the soil is determined, data from the linear potentiometers can be used to quantify the displacements and strains observed. Figure 5-11 presents the displacements observed from the first test section. As shown previously in Figure 5-3, the potentiometers were placed with a slight offset from the centerline of the existing pipe at depths between 300 mm and 1500 mm below the surface. The depth and location of the potentiometer relative to the southern intersection of the two east-west pipes of the test frame with the one north orientated pipe are presented in Table 5-1. The observed displacements illustrate that as the bursting head progressed through the pipe, the potentiometers all observed an upward displacement, followed by settlement after the bursting head passed. This is a result of the bursting head being approximately 100 mm in diameter larger than the new pipe being installed and the soil repositioning itself after the initial expansion. Additionally, this movement confirms the surface profiles determined by the tilt meter data analysis. The soil response is indicative of the pipe bursting process, although the magnitude is slightly exaggerated due to the relative shallow depth of the installation and upsize.

Table 5-1 Location and Depth of Potentiometers at Site #1

Linear Potentiometer	Approximate Depth below Surface (mm)	Distance North of Base Line (mm)
1	900	1778
2	1200	1168
3	300	406
4	600	2946
5	1500	-279

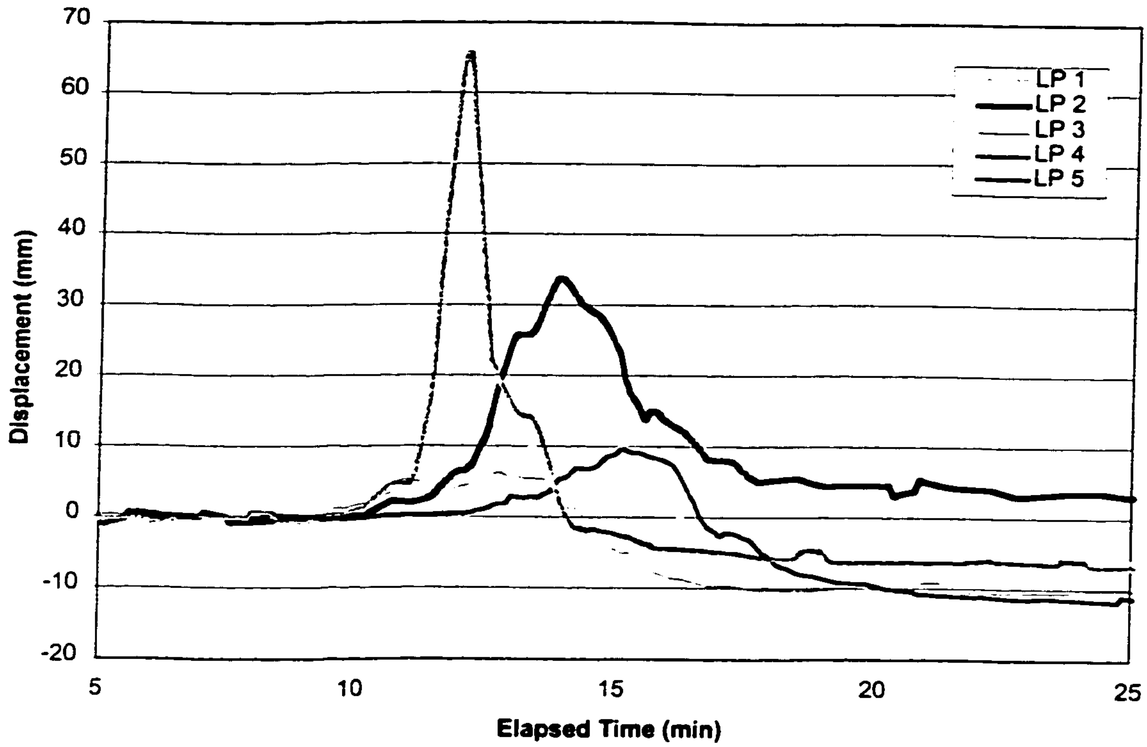

Figure 5-11 Displacement Measurements from Linear Potentiometers

Figure 5-11 illustrates the progression of the burst. The first potentiometer to peak is LP#5, which is also the southern most potentiometer. As the burst progressed, the potentiometers peaked in order from south to north.

Data collected from the surface points is presented in Table 5-2. It can be seen that there was approximately 21 mm of surface heave at the surface point closest to the crown of the pipe (surface point #1). The surface displacement decreases with distance away from the centerline of the pipe. General observation of the surface above the pipe revealed tension cracks propagating and opening above the crown of the pipe. Cracks varied in width and, in general, did not exceed 12 mm in width.

Table 5-2 Surface Point Displacements from Site #1

Surface Point	Distance West of Southern Pipe Intersection (mm)	Vertical Displacement (mm)
1	584	21
2	889	12
3	1244	5
4	1559	2

Tilt meter data from test site #2, has yet to be analyzed. From the analysis of the tilt meter data from site #1, it appears as if more tilt meter measuring points may be required to accurately measure the ground surface. On test site #2, only six tilt meters were used, and this may not be sufficient to provide an accurate subsurface profile. Data from the subsurface points provided only the maximum displacement that occurred as the bursting head progressed past the test site. This did not provide data as valuable as that in the first test section.

5.9 SUBSURFACE DISPLACEMENT MODELS

In general, there are two approaches to the modeling of subsurface ground movements that are commonly utilized. One method is through the use of finite element models, and the other is based on theoretical or empirical formulas. Finite element models for the prediction of geotechnical problems are becoming more powerful and more accurate through the use of improved computers and constitutive soil models (Rogers and Chapman 1998). Unfortunately, this method requires considerable time to setup a reasonable mesh or net, and requires a large number of soil parameters that are sometimes difficult to attain. Additionally, finite element analysis is very sensitive to input parameters, subsequently a small change in a parameter may cause a large effect on the output. Because of these reasons, finite element analysis tends to be difficult in the generalization or prediction of situations that differ from that initially used in the development of the model.

Based on the limitations and parameters required of the finite element analysis, there is need for a simplified approach to the prediction and modeling of subsurface displacements. This simplified approach is provided through closed form solutions, developed from theory and practice. These analytical solutions provide methods that are simple to employ, yet are still accurate enough to provide a good prediction of the ground movements that may be expected under a given set of soil and project parameters.

For pipe bursting, there has been four model solutions developed or modified to predict the subsurface ground movement mechanism. These include the a) modified Sagaseta analysis, b) Vafaeian's analysis, c) cavity expansion theory, and d) analysis based on geometric parameters. To study the feasibility of the tilt meter method, the linear potentiometers were used as a comparison. Since the potentiometers were installed along the centerline of the pipe, it will only be in this location where direct comparisons between the tilt meters and potentiometers are made. In this situation, Vafaeian's analysis becomes the same as the Sagaseta analysis, as the lateral distance away from the axis of the pipe is zero (Rogers and Chapman, 1998). Additionally, the cavity expansion theory determines the distance of the border between the plastic and elastic zone of the soil from the axis of the burst pipe (Atalah et al., 1997). Subsequently, cavity expansion theory would not be able to predict movements at specific distances above the centerline of the pipe that would be required to compare these methods to the data collected. A detailed description of the modified Sagaseta and Vafaeian's analyses can be found in Rogers and Chapman (1998), cavity expansion in applications of pipe bursting in Atalah et al. (1997), and the geometric analysis in Heinz et al. (1992). Analysis prepared using the Sagaseta and geometric analysis are presented in this chapter, and compared to field data collected by the linear potentiometers and tilt meters.

5.9.1 Sagaseta Analysis

The modified Sagaseta analysis was developed as a general method for modeling ground movements. Originally developed as a means to predict ground movements around tunneling operations where localized subsidence occurs, the method can also be used to predict ground movements due to expansion. The method is based on the assumption that the soil behaves as a fluid and flows radially towards a point of volume loss, or away from a point of volume addition. The general formula for the radial displacement around a cavity as shown in Rogers and Chapman (1998) is as follows:

$$W_r = k\left(\frac{a}{2}\right)\left(\frac{a}{r}\right)^a \qquad \text{Eq 5-1}$$

W_r = Radial displacement (m)

α = Radius of void (m)

r = radial distance from the origin of the point source (m)

k = Constant

In order to take into account the effect of dilation in the soil, relationships that alter the rate at which the displacements vary when moving away for the source in dense or loose soil were developed.

For a source in loose soil:

$$a = \frac{1}{a_a} \qquad \text{Eq 5-2}$$

For a source in dense soil:

$$a = a_a \qquad \text{Eq 5-3}$$

Where

$$a_a = \frac{(1 - \sin\psi)}{(1 + \sin\psi)} \qquad \text{Eq 5-4}$$

In this methodology, ψ is the angle of dilatancy of the soil measured in degrees, and α is the radius of the void. This value is best approximated using the following equation:

$$0.8\psi = \phi - \phi_{crit} \qquad \text{Eq 5-5}$$

Where ϕ = angle of maximum shearing resistance (degrees)

ϕ_{crit} = angle of shearing resistance at critical state (degrees)

General equations for horizontal and vertical component displacements can now be derived. Only the equation for vertical displacements will be outlined below, as the data collected in the fieldwork were restricted to vertical displacements.

$$W_y = \left(Q\frac{x}{a}\right)\left(\frac{1}{r_1^a} + \frac{(2z-y)}{r_2^a}\right) \qquad \text{Eq 5-6}$$

where

$$Q = k\left[(2R\delta R)^{0.5}\right]^a \qquad \text{Eq 5-7}$$

$$r_1 = (x^2 + y^2)^{0.5} \qquad \text{Eq 5-8}$$

$$r_2 = \left[x^2 + (2z-y)^2\right]^{0.5} \qquad \text{Eq 5-9}$$

where

W_y = Vertical component of radial displacement (m)

R = Radius of installed pipe (m)

δR = Difference in radius between the new and old pipe (m)

x = Lateral distance from pipe centerline (m)

y = Vertical distance above pipe axis (m)

z = vertical depth of pipe axis below ground surface (m)

Rogers and Chapman (1998) state that the Sagaseta analysis produced results that gave relatively good correlation to those observed in the field. This method of analysis relies on the geometry of the pipe configuration along with soil shearing parameters to predict ground movements.

5.9.2 Geometric Analysis

To simplify the analysis of the ground movements, an approach that considers the geometry of the original and new pipe can be utilized. The geometric analysis, based on concepts introduced by Wroth and Windle (1975), and presented by Heinz et al. (1992), may be used to estimate displacements around the pipe being burst based on the displacement of the wall of the cavity. Therefore, if the original and replacement external pipe diameters are known, an estimation of the ground movements can be determined. The assumptions required for this solution are as follows:

1. The soil surrounding the cavity is assumed to deform under plane strain conditions,
2. The soil mass is considered to be homogeneous and isotropic,
3. Conditions of axial symmetry prevail, and
4. Small strains are assumed.

The conditions of plane strain and axial symmetry create restrictions on the behavior of the displacements, and limit the prediction of the displacements to a radial direction away from the axis of the pipe.

In the application of this prediction model, a distinction is made between the drained and undrained soil conditions. The distinction between these two states is associated with the advancement rate of the bursting head as well as the rate of dissipation of pore pressures. Pore pressure dissipation is dependent of the type of soil in which the burst is conducted. It can be assumed that bursts conducted in clay type soils are performed under undrained conditions, while those in more loose sandy soils are done under drained conditions.

For undrained conditions:

$$u = u_a \left(\frac{a_O}{r_O} \right) \qquad \text{Eq 5-10}$$

For drained conditions:

$$u = u_a \left(\frac{a_O}{r_O} \right)^{1-l} \qquad \text{Eq 5-11}$$

Where u is equal to the displacement that a point situated r_O from the axis of the burst pipe undergoes, as the cavity is expanded from and initial external radius of a_O by a distance u_a, which is the displacement of the wall of the cavity (Figure 5-12). To account for soil dilation, the factor l is applied that ranges from 0 to 0.5 as a maximum in dense sand. In the case of no dilation l is equal to zero, which corresponds to undrained soil conditions. In general, a value for l can be assessed from knowledge of the volumetric strains that take place during a shear strength test.

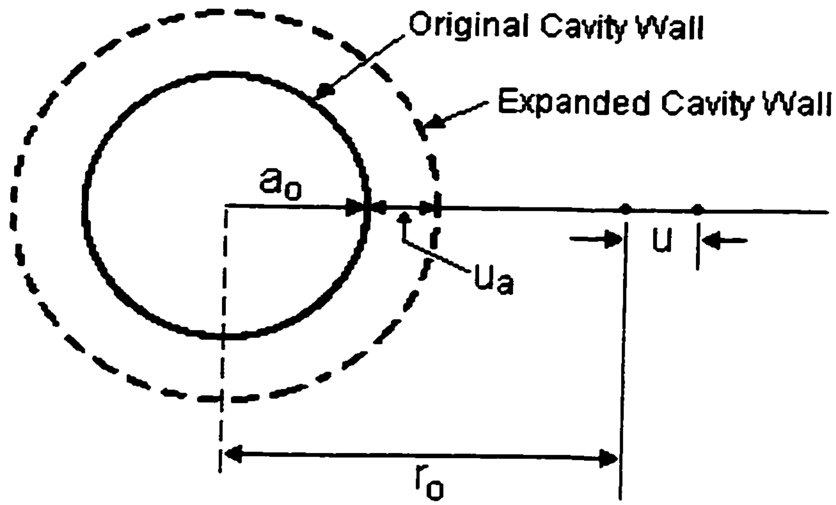

Figure 5-12 Configuration of Parameters for Geometry Method

5.10 GROUND MOVEMENT ANALYSIS

From the fieldwork conducted in Naniamo, two sets of data were collected: 1) data from the tilt meters, and 2) data from the linear potentiometers. As per the objectives of the study, the values from these methods were compared to determine the accuracy of the tilt meter method of ground movement measurement. Additionally, these results were compared to the Sagaseta and geometric analysis methods to evaluate the solutions of these models in the prediction of ground displacements.

Data collected from the linear potentiometers provided a direct measurement method of the ground displacement at the depth at which the base plate was installed. In this analysis, data provided by the linear potentiometers is considered to be the most accurate and will be the base line to which the tilt meter data and the two models will be compared. Since the models predict the greatest displacement attained under the parameters used in the analysis, the largest displacements from the linear potentiometers and the tilt meters will be presented. The following table summarizes the results of this comparison.

Table 5-3 Subsurface Displacement Measurements and Predictions (mm)

Depth Below Surface (mm)	Linear Potentiometer	Sagaseta Analysis	Geometric Analysis	Scaled Tilt Meter Data
300	6	13	24	
600	9	14	28	100
900	15	18	33	
1200	34	26	41	190
1500	65	44	56	

From table 5-3, it can be seen that there are differences between the predictive models and the data collected. In the analysis of the tilt meter data, the tilt meter contractor only provided data for the surface, and distances 600 mm and 1200 mm from the surface. This accounts for there only being values at those depths in the table.

In the calculation of the values for the Sagaseta analysis, the original pipe outside diameter was 350 mm, the new outside diameter at 675 mm, and a k value of 1 assumed. The angle of dilatency was approximated from work presented by Swee and Milligan (1990) as being 30 degrees. This approximation was made by determining the angle from the vertical that an imaginary line makes between the invert of the pipe and the outer extent of the surface heave caused by the pipe bursting process from the centerline of the pipe. According to the surface heave data, the distance between the centerline of the pipe and the outermost extent of the surface heave is approximated as 1500 mm, with the invert of the pipe estimated at 2400 mm. This analysis predicted displacements that were similar to those measured by the linear potentiometers.

To account for the behavior of the replacement process, it was assumed that the new pipe axis would not coincide with the axis of the original pipe. Instead, the two pipes would share inverts rather than their axis, as in the actual pipe replacement situation. Subsequently, in the calculation of the displacement above the pipe, the difference in diameters of the pipes was used rather than radiuses. Calculations based on the difference in diameters produced results more in line with those measured by the potentiometers.

The geometric analysis produced values for displacements higher than those measured or predicted using the linear potentiometers and the Sagaseta analysis. In this prediction, the initial cavity radius was 175 mm and the expanded cavity radius set at 337.5 mm. In the analysis, the axis of the new and replacement pipe are assumed to be the same after the replacement. Additionally, it was assumed that the soil would behave in a slightly drained condition, based on soil observations on site. Therefore, the drained solution was used with a value for l of 0.2, in Equation 5-11. This value of l was assumed as the angle of dilatency of the soil was not measured in the field, though the composition of the soil being a mixture of clay and gravel would indicate that the soil would exhibit some characteristics of the drained solution. Additionally, this value predicted movements that more closely represented those measured in the field, and predicted by the Sagaseta analysis.

To interpret the data provided by the tilt meters, the results had to be scaled and then used as a guideline to estimate the displacement experienced between the pipe and the surface. Since this was the first attempt at using tilt meters to measure a line source of displacement, the tilt meter contractor had to make some assumptions and approximations. As a result, the values attained may not be an accurate representation. The scaling of the results was approximated by taking the maximum surface heave value and the maximum upwards displacement of the pipe, in this case 25 mm and 325 mm. The difference between these values was scaled to reflect the relative displacements measured by the tilt meters at 600 mm and 1200 mm below the surface. These results are presented in Table 5-3. Currently, the tilt meter contractor is in the process of refining the model that determines these values to obtain quantitative results more representative of the actual measured values for vertical displacement.

5.11 CONCLUSIONS AND RECOMMENDATIONS

The tilt meters functioned well and collected data, despite the unfavorable conditions on this project. With the large upsize between the host and product line, and limited depth of cover, the effectiveness of this measurement technique was demonstrated. Though further calibration of the model used to interpret the tilt meter data is required so the tilt meters can be utilized as a direct measurement technique.

Tilt meters provided a convenient method to measure the ground movements caused by the pipe bursting process. Additionally, data collected from the tilt meters provided an indication of the soil displacements induced by the passing of the bursting head. Soil displacements observed by the tilt meters, linear potentiometers and the surface survey points recorded movements that were anticipated, and appear from initial data analysis to confirm the actual movements of the soil.

Additional data is required to construct a more detailed model of the ground movements incurred during the bursting process. This could include collecting data at specific time intervals such that a sequence of ground profiles can be attained. Sequential data sets are required to determine the time effects of the bursting head and soil interaction as the head progresses through the original pipe.

For optimal measuring of the subsurface ground profiles, ten or more tilt meters should be used. Additionally, the tilt meters should be placed as close as possible to a grid pattern to increase the efficiency of the data analysis. Additional pre-burst site surveys should be conducted to assist in the data analysis and improve the accuracy of the analysis.

The ground displacement models based on the Sagaseta and geometric analysis's produced results that were very similar to those measured by the linear potentiometers. This indicates that these models could be used to provide an initial assessment of the expected ground movements. With additional data collection, these models could be better calibrated to more accurately predict subsurface ground movements.

Through better understanding of the ground movements associated with pipe bursting, it is possible to reduce the risk of damaging existing utilities in close proximity to bursting operations. Increased utilization of pipe bursting methods may be achieved with the development of computerized tools to assist in project planning and risk reduction.

CHAPTER 6 CONCLUSIONS

6.1 CONCLUSIONS

Increased demand on existing underground networks as a result of urbanization has contributed to the deterioration of existing lines and increased flow requirements that have, in some cases, exceeded predicted design life utilization. The repair and rehabilitation of existing lines is a continual task facing municipalities as they strive to provide the most cost effective and efficient service possible to their customers. Increased underground utility congestion in growing municipalities has made the installation of new pipes difficult is some areas as there is limited space for additional lines. Conventional methods of utility installation using trenching techniques can be difficult, risky, and costly from a social perspective. These concerns have initiated a new perspective on underground construction that eliminates or minimizes many of the risks and social costs commonly associated with conventional open cut installation procedures.

Trenchless pipe replacement, or pipe bursting, represents and emerging field of new construction that provides a practical alternative to conventional open cut construction. It is recognized as the only method of trenchless construction where an existing line can be replaced size for size, or upsized in some cases by 320% the original diameter. Additionally, pipe bursting allows for the total replacement of the existing line with a complete structural replacement that functions independently of the original line. Trenchless pipe replacement is relatively new in North America, and as a result most of the knowledge in the industry is possessed by the practitioners of the technology.

Contributions to the field of trenchless pipe replacement have been made in the following areas:

1. The documentation of issues related to the practice of this technology obtained from site investigations and the author's involvement in the planning and implementation of pipe bursting projects.
2. Creation, distribution and analysis of a survey to obtain a profile of the trenchless pipe replacement industry.
3. Development, programming and implementation of pipe bursting specific software applications in the areas of project and licensee tracking, equipment selection, and simulation.
4. The development and implementation of a feasibility study to evaluate the effectiveness of tilt meters in the gathering of subsurface ground movement data. Additionally, this data was analyzed and compared to existing analytical models designed to predict ground movements caused by the pipe bursting process.

To provide a background on trenchless pipe replacement, Chapter 2 provides an introduction to trenchless technology, the history of pipe bursting, methods, and procedures used in the industry. This background describes how the bursting process works and methods to install both continuous and sectional pipe, as well as service laterals. Additionally, a comparison of trenchless pipe replacement to other trenchless rehabilitation and trenching methods is provided. The later half of the chapter discusses issues related to the practice of this technology to provide insight to increase productivity and reduce risk. Various considerations in the planning of projects from the sequencing of bursts, pipe considerations, soil movements, risks specific to pipe bursting and considerations related to upsizing of pipes were presented in this chapter. To illustrate project specific examples, three case studies were presented and discussed to provide insight into planing and design considerations for specific applications.

Chapter 3 provided a profile of the pipe bursting industry that was attained through the distribution of a survey. The survey was designed to gather data to obtain a profile of the typical pipe bursting contractor; project information; bidding and cost estimation practices; and project planning and control of operations. It was revealed that the majority of projects undertaken by pipe bursting contractors were for municipal clients, with the contractor acting as the general for the project. Additionally, most projects were obtained through competitive bidding processes, with unit price contracts being the most widely utilized.

The most common pipe replaced using trenchless pipe replacement in the 1996-97 construction season was clay tile, accounting for 49% of the total pipe replaced. Additionally, 85% of the total pipe replaced was under 300 mm in diameter. These values indicate that most replacements involved sanitary or storm lines, which are typically collector pipes in the network. Product installation costs typically increase with increased diameter for both the original and product lines. In general, the costs for the replacement of pipe in size for size applications is $0.75/mm diameter/linear meter (approximately $6.00/inch diameter/linear foot). Additionally, productivity decreased as both the product and replacement pipe diameters increased. The survey also indicated that the majority of pipe bursting contractors had plans to expand their services through the hiring of additional staff, purchasing of new equipment, and the expansion of their area of business.

Computer applications in the trenchless pipe replacement industry are presented in Chapter 4. Summarized is a collection of research conducted in the development of a project and royalty tracking data base, a decision support system designed to assist in the selection of equipment based on project characteristics, and a simulation template to assist in the planning of pipe bursting projects. Results from the simulation predicted productivity with in reason to that experienced on actual projects. With modifications to the simulation model including the addition of factors to account for soil variability, geometric considerations, and the influence of upsizing on productivity, the model may more closely predict project productivity. Additionally, the implementation of the project tracking database is discussed.

Lastly, in Chapter 5, the analysis of subsurface ground movements associated with trenchless pipe replacement is presented. Contained in the analysis is the summary of field work conducted in Naniamo, British Columbia, where a project was instrumented with linear potentiometers and tilt meters to measure the ground movements during the bursting process. This study was conducted as a feasibility analysis to determine the effectiveness of using tilt meters to measure ground displacements. The tilt meters were determined to be an effective measuring technique, though additional calibration of the analysis procedure is required to obtain a more detailed and accurate displacement measurement.

Additionally, the data from the tilt meters and linear potentiometers were compared to two predictive models of soil displacement. The models predicted ground displacements that were very similar to those measured by the linear potentiometers. A discussion and outline of the models is contained in the chapter.

It is hoped that through the sharing of the knowledge and experience presented in this thesis, an increased awareness of the trenchless pipe replacement industry may be achieved. The industry is very much in its infancy in North America, with endless opportunities for research and development. As the knowledge base related to this technique grows, increased utilization will result.

6.2 AREAS FOR FUTURE RESEARCH

6.2.1 Practice of Trenchless Pipe Replacement Projects

In further research into the planning of trenchless pipe replacement projects, the development of project specifications should be explored. Currently, there are no comprehensive pipe bursting specifications in use by municipalities or contractors that employ this technique. With specifications for planning and design, more municipalities may become involved in the utilization of pipe bursting for their rehabilitation requirements. Included in the specifications could be procedures and guidelines for the design and utilization of bursting heads for differing soil conditions and pipe materials. Additionally, procedures and guidelines for product pipe installation may be included to assist in the planning of pull lengths and pipe upsize based on project and soil conditions. With additional research in ground movements, guidelines could also be added to provide safe distances from existing buried utilities and structures.

6.2.2 Computer Applications

There are several enhancements that can be performed to the computer applications presented in this research that would prove invaluable in the preparation of effective planning and estimation tools. Firstly, the further implementation of the project and royalty tracking database with the static pipe bursting equipment manufacture should be explored. Once implemented, the database can be used as a method to collect additional data that can be used in other computer applications. The information collected could be used to assist in the preparation of productivity, cost, and installation models.

Data collected from the project and royalty tracking database would be essential in the addition of a productivity estimation module for the Equipment Selection Program. Additionally, the incorporation of effective installation lengths and upsize capabilities would increase the effectiveness of the ESP in the planning and design of pipe bursting projects. With these enhancements the ESP could be developed into an educational tool that would increase the awareness of the pipe bursting alternative in pipe rehabilitation with owners, consultants and contractors.

To further enhance the simulation template presented in this research, additional factors to account for soil conditions, crew experience, environmental conditions and constraints, as well as the geometry of the original pipe installation can be incorporated. With the addition of these factors the simulation model may be better calibrated to predict the variability in productivity due to particular project characteristics. Additionally, a cost estimation module should be incorporated into the simulation model. This would allow the user to test different site setups and equipment configurations to determine the most cost effective replacement strategy.

6.2.3 Ground Movements

Presented in the research is the measurement and analysis of the ground movements associated with the replacement of a line conducted on a project in Naniamo, British Columbia. Unfortunately, as a result of project constraints, only one set of data could be collected with the tilt meters and linear potentiometers. The ultimate goal of continuing research in ground movements using the tilt meters, is to develop a predictive model based on the three dimensional imagery provided by this measurement technique. To accomplish this goal three objectives need to be met.

First, the tilt meter analysis process has to be calibrated to account for the ground movements that occur with the pipe bursting process. Originally, the tilt meter contractor used the meters to measure fractures caused by the injection of slurry into oil bearing structures several hundred meters in depth. The displacements caused by this fracturing can be characterized as being planar in nature, while those caused by pipe bursting can be considered as a line source. Subsequently, the procedure has to be modified to account for the different nature of the source of ground displacements. This calibration would involve working with the tilt meter contractor to better depict the source. The calibration of the tilt model could be incorporated with the next goal of further data collection.

The next area in any future research work in the area of ground movements would be to conduct additional measurements with both the tilt meters and linear potentiometers. With additional data, the tilt meter model could be calibrated and the trends developed based on differing soil conditions, depths, pipe materials, and upsize requirements. This additional data would be required to develop an effective predictive model of the ground movements associated with the pipe bursting process.

Finally, the incorporation of horizontal displacements in the tilt meter analysis is necessary to further enhance the predictive nature of the ground movement model. This would be accomplished through the collection of horizontal displacement data using inclinometers in conjunction with tilt meters in the measurement of the ground displacements. With this additional data the tilt meter data analysis could be modified to provide the horizontal displacements using this data for calibration.

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APPENDIX A

UNIVERSITY OF ALBERTA
CONSTRUCTION ENGINEERING AND MANAGEMENT

SURVEY OF THE
NORTH AMERICAN
PIPE BURSTING INDUSTRY

CONFIDENTIAL

If you have any questions concerning this survey, please do not hesitate to contact Dr. Samuel T. Ariaratnam at (403) 492-5110 or Mr. Jason Lueke at (403) 492-8966.

Company Identifier Number: ______________________________

Title or Position of Respondent: ______________________________

Date of Response: ______________________________

Would you like your company name listed as a participant in this survey in the report to be released to all participating companies? Under no circumstances will your company be identified with any of the data you have provided.

______Yes ______No

Part 1: Company Profile

1. Regions of operation (Please check all that apply):

   Canadian Regions:

   Western Canada (Alberta, BC, Yukon, NWT) .... ☐

   Prairies (Manitoba, Saskatchewan) .... ☐

   Central Canada (Quebec, Ontario) .... ☐

   Maritimes (NB, Nova Scotia, PEI, Nfld. and Labrador) .... ☐

   United States Regions:

   US Region I (ME, VT, MA, NH, RI, CT) .... ☐

   US Region II (NY, NJ) .... ☐

   US Region III (PA, VA, WV, MD, DE) .... ☐

   US Region IV (KY, TN, NC, SC, GA, AL, MS, FL) .... ☐

   US Region V (OH, IN, IL, MI, WI, MN) .... ☐

   US Region VI (OK, AR, LA, TX, NM) .... ☐

   US Region VII (IA, NE, KS, MO) .... ☐

   US Region VIII (ND, SD, MT, WY, CO, UT) .... ☐

   US Region IX (CA, NV, AZ, HI) .... ☐

   US Region X (WA, ID, OR, AK) .... ☐

   Mexico .... ☐

   Other - please specify .... ________________ ☐

2. How many projects has you company completed **installing** the following new product pipe materials over the last five years?:

	Year				
Material	1994	1995	1996	1997	1998
HDPE					
Clay Tile					
Steel					
Ductile Iron					
Concrete					
PVC					

3. Typical clients (what % falls under each category):

City or Municipal Government .... ________%
State or Provincial Government .... ________%
Federal Government .... ________%
Private .... ________%

4. Percent of jobs undertaken as a general contractor .... ________%
Percent of jobs undertaken as a subcontractor .... ________%

5. What type of pipe bursting/splitting machines do you own?:

Method	Manufacturer	Number of Units	Capacity
☐ Percussive ☐ Chain ☐ Solid Rod ☐ Cable	☐ TRS ☐ TT ☐ TTS ☐ Vermeer ☐ Other		☐ < 50 ton ☐ 50 – 175 ton ☐ >175 ton
☐ Percussive ☐ Chain ☐ Solid Rod ☐ Cable	☐ TRS ☐ TT ☐ TTS ☐ Vermeer ☐ Other		☐ < 50 ton ☐ 50 – 175 ton ☐ >175 ton
☐ Percussive ☐ Chain ☐ Solid Rod ☐ Cable	☐ TRS ☐ TT ☐ TTS ☐ Vermeer ☐ Other		☐ < 50 ton ☐ 50 – 175 ton ☐ >175 ton
☐ Percussive ☐ Chain ☐ Solid Rod ☐ Cable	☐ TRS ☐ TT ☐ TTS ☐ Vermeer ☐ Other		☐ < 50 ton ☐ 50 – 175 ton ☐ >175 ton

Part 2: Project Information

1. What percentage of your work is obtained through:

	Bidding	Negotiation	Contract Extension
None	☐	☐	☐
Less than 25 %	☐	☐	☐
25 - 49 %	☐	☐	☐
50 - 74 %	☐	☐	☐
75 - 100 %	☐	☐	☐

2. What length (in feet) of pipe did you burst last year, 1996-97?:

Original Pipe Material

Original Diameter	Asbestos Cement	Steel	RCP	NRCP
2 – 4"	________	________	________	________
6 – 8"	________	________	________	________
10 – 12"	________	________	________	________
12 – 24"	________	________	________	________
26 – 36"	________	________	________	________
> 36"	________	________	________	________

Original Pipe Material

Original Diameter	Cast Iron	Ductile Iron	Clay	Corrugated Metal Pipe
2 – 4"	________	________	________	________
6 – 8"	________	________	________	________
10 – 12"	________	________	________	________
12 – 24"	________	________	________	________
26 – 36"	________	________	________	________
> 36"	________	________	________	________

Part 3: Bidding and Cost Estimating Stage

1. Cost ranges for **just** pipe bursting ($/linear foot) only consider the cost to pipe burst, **do not** include cost of new pipe, mobilization, demobilization or pit and service excavation and restoration (Please pick the appropriate cost code).

Original Diameter	Replace in Kind	Doubled Diameter
2"	______	______
4"	______	______
6"	______	______
8"	______	______
10"	______	______
12"	______	______
24"	______	
36"	______	

Cost Codes:
1 = $10-$44/ft
2 = $45-$74/ft
3 = $75-$149/ft
4 = $150-$224/ft
5 = $225-$300/ft
6 = over $300/ft

2. Types of contracts undertaken (Please check all that apply):

Unit price (rate per meter) .... ☐

Per Diem (daily rate) .... ☐

Hourly .... ☐

Lump sum .... ☐

Lump sum with schedule of unit prices .... ☐

Cost plus percentage fee .... ☐

Cost plus fixed fee .... ☐

Other - please specify ____________________ ☐

3. Do you see a place for development of Pipe Bursting dedicated software in:

	Yes	Somewhat	No
Cost estimating	☐	☐	☐
Cost control	☐	☐	☐
Project planning/budgeting	☐	☐	☐
Project scheduling	☐	☐	☐
Asset management	☐	☐	☐

Part 4: Project Planning and Control of Operations

1. Which one of the following soil formations do you encounter **most** in your area?:

☐ Clay ☐ Silt ☐ Sand ☐ Gravel

☐ Pit Run ☐ Hard Pan ☐ Rock

2. What is the most common original pipe material encountered in your area when conducting **waterline** rehabilitation:

☐ Asbestos Cement ☐ Steel ☐ RCP ☐ NRCP

☐ Cast Iron ☐ Clay ☐ Ductile Iron ☐ CMP/SMP

3. For the most common soil encountered (Question 1) and for the most common host pipe material you encounter during **waterline** rehabilitation (Question 2), what is your productivity (feet/day*): (*Note: based on an 8 hr. day) Fill in the appropriate grid values.

Replacement Pipe Diameter

Original Pipe Diameter	2-4"	6-8"	10-12"	14-24"	26-36"	>36"
2-4"						
6-8"						
10-12"						
14-24"						
26-36"						
>36"						

4. Which one of the following host pipe materials do you encounter most when conducting **sewer** rehabilitation?:

☐ Asbestos Cement ☐ Steel ☐ RCP ☐ NRCP

☐ Cast Iron ☐ Clay ☐ Ductile Iron ☐ CMP/SMP

5. For the most common soil encountered (Question 1) and for the most common host pipe material you work with on **sewer** rehabilitation projects (Question 4), what is your productivity (feet/day*): (*Note: based on an 8 hr. day) Fill in the appropriate grid values.

Replacement Pipe Diameter

Original Pipe Diameter	2-4"	6-8"	10-12"	14-24"	26-36"	>36"
2-4"						
6-8"						
10-12"						
14-24"						
26-36"						
>36"						

6. Comment on how and where you see the most potential growth with respect to the pipe bursting industry:

   Equipment ______________________________

   ____

   New Applications ______________________________

   ____

7. Are you considering increasing your company in any of the following?:

   Region of business .... ☐ Yes ☐ No

   Personnel .... ☐ Yes ☐ No

   Equipment .... ☐ Yes ☐ No

   Other - please specify .... ☐ Yes ☐ No

General Comments:

____

____

APPENDIX B

PROJECT REPORT

Licensee: ______________________________

Address: ______________________________

____

Owner/Client: ______________________________

Project Address: ______________________________

____

Project Name: ______________________________

Quarter Reporting:	1 2 3 4
Year:	

Date: ______________

State/Prov: ______________

Contract No.: ______________

Project Start Date: ______________ Project End Date: ______________

Equipment: □ H45 □ H125 □ H225 □ TLR45 □ Percussive □ Other

Pressures: Maximum: ______________ Average: ______________

Original Pipe: □ Cast Iron □ Steel □ RCP □ Asbestos Cement

Age: ______ yrs □ Clay □ Ductile Iron □ NRCP □ Other ______

Replacement Pipe:

□ HDPE □ Clay Tile □ Steel □ Ductile Iron □ Concrete □ PVC

Ground Information:

Bedding: □ Sand □ Gravel □ Concrete □ Native □ Unknown

Soil: □ Clay □ Silt □ Sand □ Gravel □ Pit Run □ Hard Pan □ Rock □ Other

Conditions: □ Wet □ Moist □ Dry

Replacement Pipe Length	Original Pipe O.D.	Depth	Replacement Pipe O.D.	Number of Services	Duration in Days	Size of Bursting Head

APPENDIX C

Project and Royalty Tracking Database Manual

Introduction

The TRS Project Database was created to record data from pipe bursting projects to calculate royalty fees and project productivity. Designed entirely in Microsoft Access, the database has a user-friendly "point and click" type interface to avoid the confusion of using the Database Window that typical database applications use with Access. This "point and click" interface gives the user access to each of the database's forms and reports, and also allows the user to enter data into the database.

This manual outlines the construction and organization of the database to assist future users to modify or update the features included in this initial version. Included in this manual will be procedures to input data, print reports, and create the database that is used in the TRS Project and Marketing Software. For more information on how to use Microsoft Access please refer to the online manuals under help or the Access Manuals that came with the Access program.

Instructions

When the database is opened the user is greeted with the introduction screen that presents two options to the user, to **Enter/Modify Data** or **Reports** as seen in Figure 1.

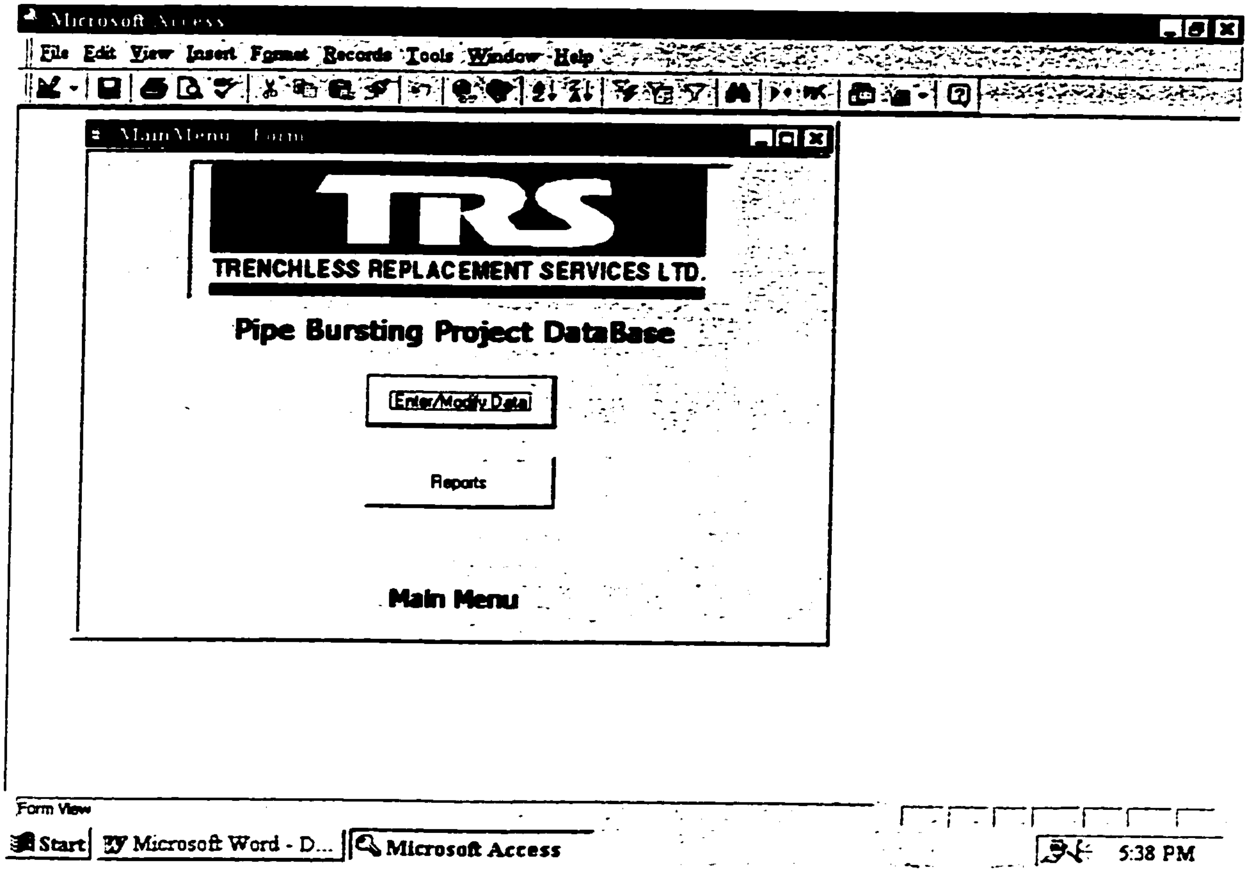


Figure 1: Database Start-up Screen

The **Enter/Modify Data** option would be chosen to enter Royalty Reports, Licensee information, pipe royalty fees or equipment data. The **Reports** option takes the user to the Report Manager that allows the reporting of data on various aspects of the project and licensee data contained in the database.

Before the database can be used to record project data the database must be initialized.

Database Initialization

Before using the database for reporting purposes it must be setup correctly. To initialize the database the following steps must be followed when the database is first opened:

1. **Preparation of Licensee Data**

a) Licensee Data includes all information pertaining to the Licensees including their names, addresses and phone numbers. This data is vital to the performance of the database and must be entered first. The database refers to this data when one enters projects as well as equipment. All Licensees should be entered into the database using the **Enter/Modify Licensee Data** option that can be found under the **Enter/Modify Data** option from the start-up screen. The **Enter/Modify Data** form is shown in Figure 2; the **Enter Modify Licensee Data** is located on the upper right side of the form.

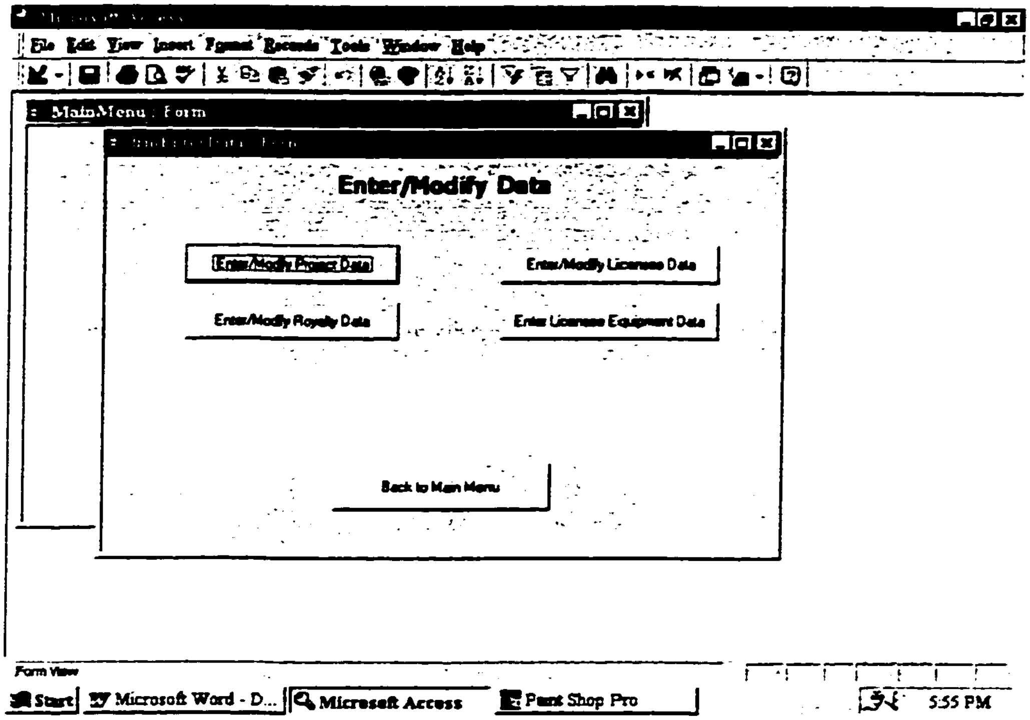


Figure 2: Enter/Modify Data Screen

Figure 3 displays the form into which Licensee data is entered. When entering the data it is important to be as complete as possible. To enter a new Licensee select the enter new record button (an arrow pointing to the right with an asterisk), all boxes in the form should become empty and is now ready to input new data.

Any information relating to the Licensees can be modified at anytime after the Licensee's initial entry into the database. This may be necessary if the Licensee address changes. This can be done by selecting the **Enter/Modify Licensee Data** form then scrolling through the Licensees using the Left and Right arrows, then modifying the data. All changes will be automatically saved after exiting the screen.

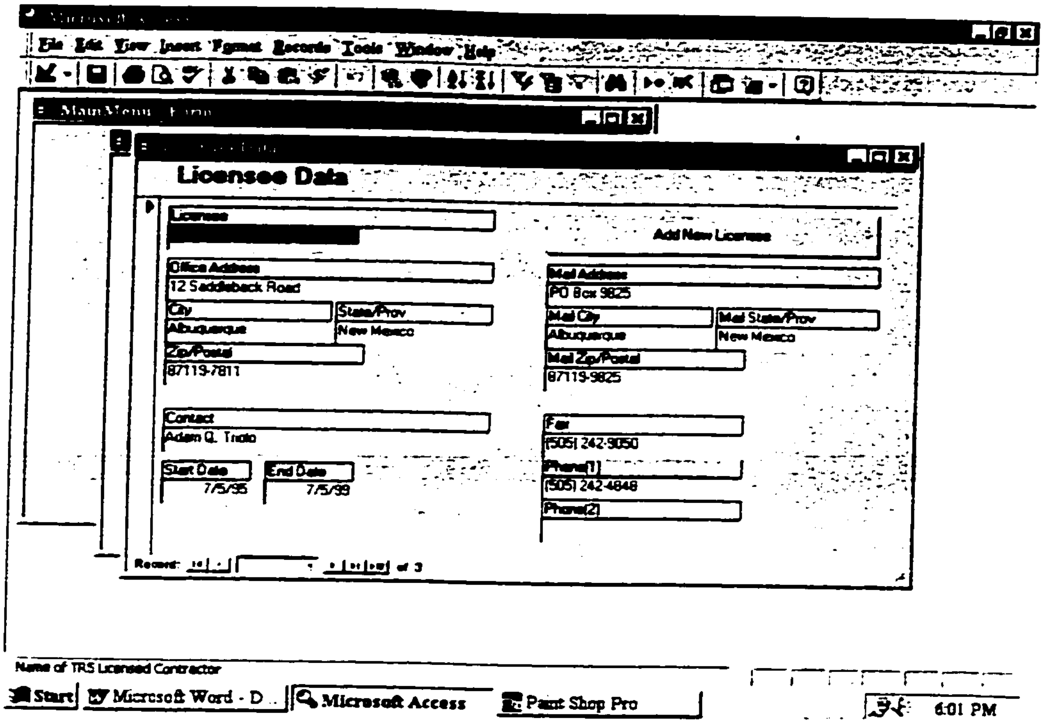


Figure 3: Enter/Modify Licensee Data Form

b) After the Licensees are entered, input the additional Licensee information by selecting the **Enter/Modify Equipment Data** option from the Enter/Modify Data main option screen. This is where the number of pieces of equipment each Licensee owns are entered, and performance clauses if any. Data in this table can be entered as required on a yearly basis, but it is essential that the current year data be entered for the database to function properly. Thus this information must be updated each year. The Licensee Information form is shown in Figure 4.

Once the list of Licensees are entered into the database the drop down menu for Licensee name will display all Licensees entered into the database. To activate the drop down menu click on the down arrow on the combo box relating to Licensee name.

Note: This table must be updated on a year to year basis for the reports to function correctly.

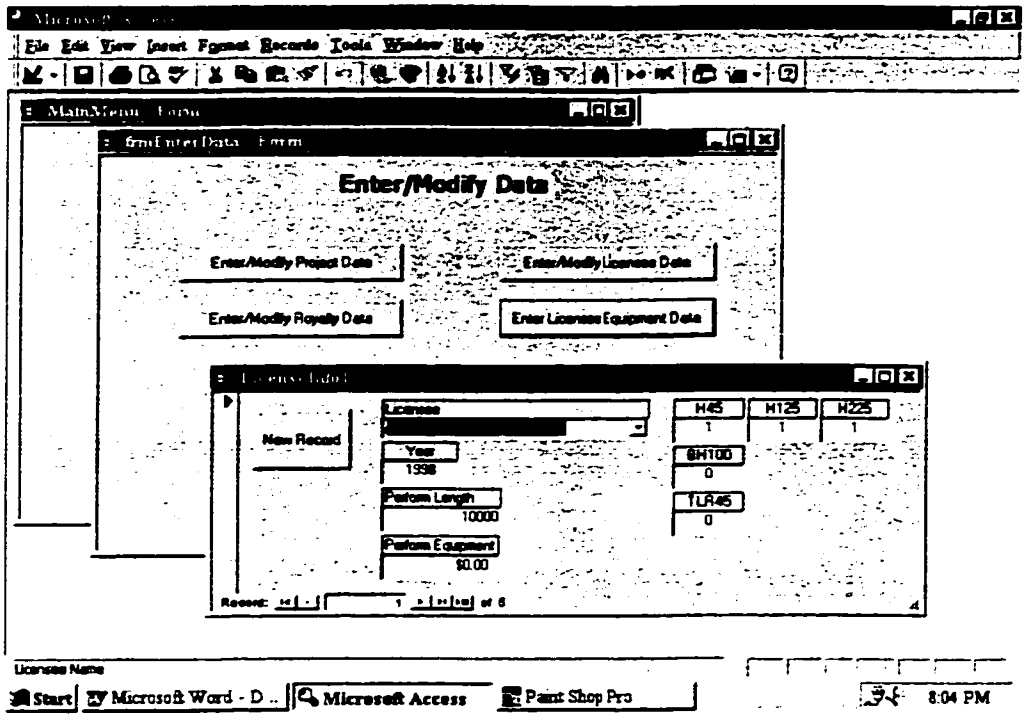


Figure 4: Additional Information for each Licensee

c) New Licensees can be entered at any time after the database is initially setup. It is important that all data pertaining to the Licensee is entered into the database. For each new Licensee entered into the database there must be a Licensee Information form filled out for each relevant year for the Licensee.

2. Entry of Equipment Data

Data in the Equipment Table will be pre-entered in the database. There is no button to change or modify this data since the frequency of this occurring is small. Generally the only time data in this table will be modified is if new equipment is developed or the equipment specifications change. If this occurs the data can be entered or modified in the Equipment table directly. To modify equipment data select the Database Window button from the Form View toolbar. Select the tables tab from the tab bar, then open the Equipment table. Modify the required data then close the table. The new data will automatically be updated.

3. Setup of Royalty Data

The Royalty Table can be setup by using the **Enter/Modify Royalty Data** button on the Enter/Modify Data form. This data must be entered on a yearly basis in order for the reports to be generated correctly. It is important to note that EVERY diameter of pipe that is installed and is entered in the database MUST have that size in the Royalty Table. If the Royalty Table does not have data for a particular size of pipe, it WILL SKIP that pipe size in reports when calculating royalties without notifying the user. This will provide inaccurate results in the total royalty calculation – usually totaling to a value less than the actual total royalties.

VERY IMPORTANT:

The Royalty Table will not accept ranges for royalty fees as they are outlined on the Licensee Agreements. Thus one must convert the range to specific values. For example if the royalty fee for pipes sized 12 to 24 inches in diameter is $4.00/foot. The entire range, or at least all values for replacement or product pipe in the database, must be entered with values for 12, 14, 16, 18, 20, 22 and 24 inches of $4.00/foot. If not done in this manner the reports will not calculate the royalties properly.

The royalty entry screen is shown in figure 5.

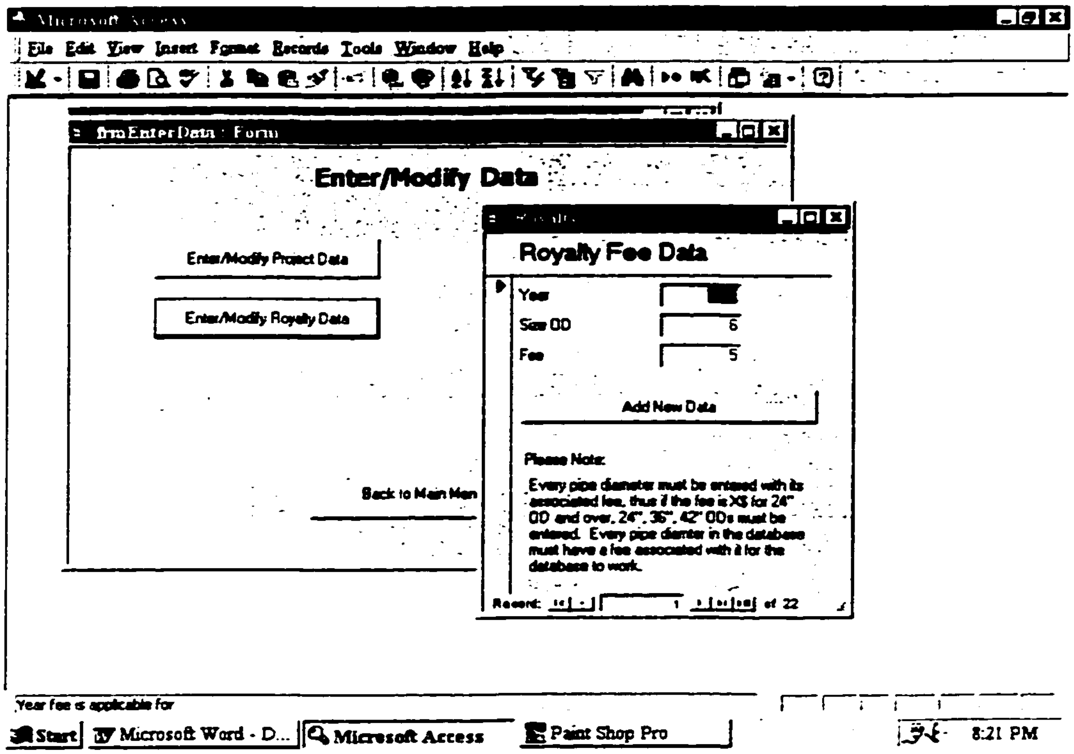


Figure 5: Royalty Data Screen

After these steps are complete the database is ready to accept project and pipe data as well as prepare reports. If reports do not function properly it is a good assumption that data in the initial setup of the database was not entered properly. Microsoft Access will catch many data entry errors, but to assist in the entry of this data refer to the Database Data Charts that describe each table and what each field value mean.

Entering Royalty Reports

To enter Royalty Reports into the database use the **Enter/Modify Project Data** on the Enter/Modify Data screen from the Main Screen. Data from the Royalty Reports can be directly entered into the Database through this form. To enter a new set of data from a Royalty Report click on the **Enter New Project Data** button, to fill out a clean form. Refer to Figure 6 for the project entry screen and the Enter New Project Data button.

The database is auto saving, if data is entered and the form closed it automatically saves. This protects the user in the sense that no data will be lost, but if data in the Project form is accidentally changed and the form closed the data will be changed and there is no undo function. IT IS IMPORTANT THAT THE USER BE VERY CAREFUL NOT TO MODIFY THE DATA ALREADY IN THE DATABASE BY ACCIDENTALLY CHANGING DATA.

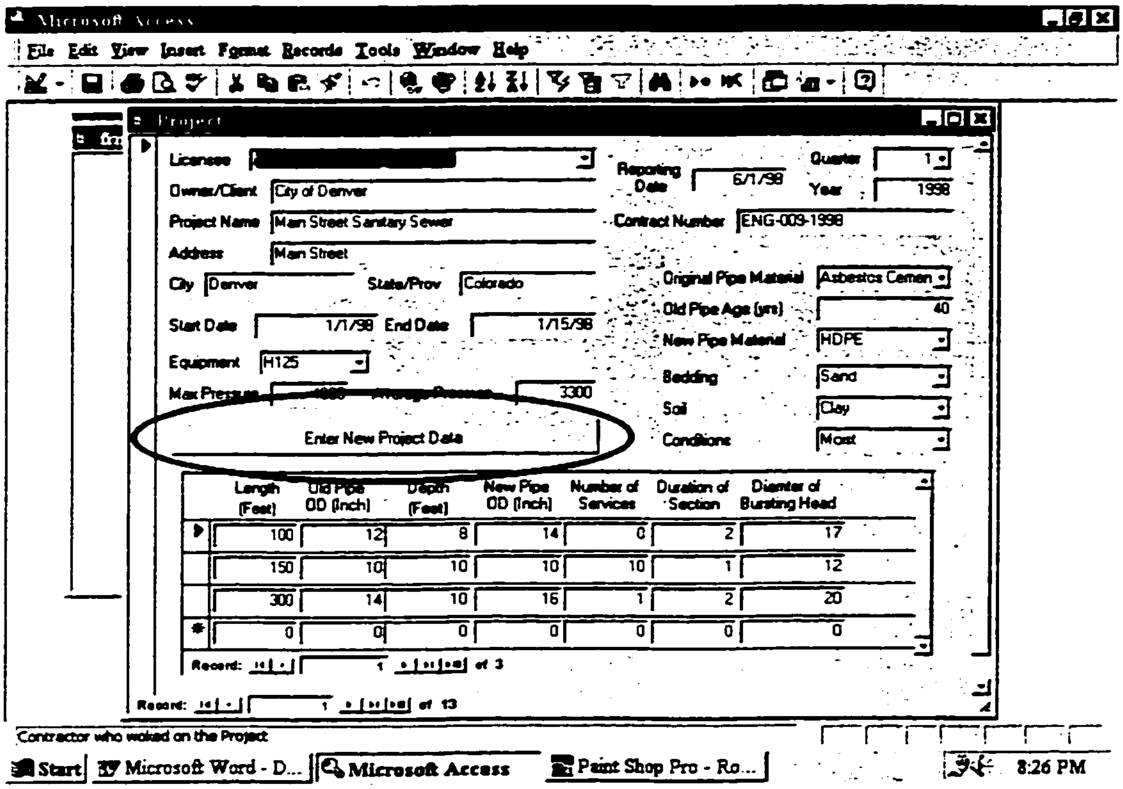


Figure 6: Project Form

Notice that there are many drop-down menus to help limit the amount of typing. The Licensee can be chosen from the drop down box as long as the Licensee was entered into the Licensee Table on setup of the database. There are also drop-down menus for pipe materials and soil information. To navigate through the form while entering data one can use the mouse or the TAB key. The TAB key is set to move from box to box in a similar manner to how one would read the Royalty Report that would be submitted by the Licensees.

To enter pipe data click or tab to the first empty Pipe Length box and input the pipe length. Use the TAB key to navigate to enter pipe diameter data, depth, number of services, duration, and bursting head diameter. After the diameter of the bursting head is entered click press the TAB key to enter another pipe section or use the mouse to click on the next available data entry line. Use the scroll bar to scroll through all the pipe sections associated with a particular project.

From the Project Form the user can navigate through all the projects entered in the database by using the record navigator on the bottom of the form. It operates very similarly to a Compact Disc player, the arrows can skip forward or back.

Summary of Data Entry Options

Option	Description
Enter/Modify Project Data	This allows the user to enter data pertaining to a project directly off the quarterly royalty reports. Links to the Project and Pipe Tables through the Project Form using a Pipe Sub-Form embedded in the main Project form.
Enter/Modify Royalty Data	This option allows the entry of royalty fees for pipe installed based on the diameter of the pipe and the year that the fee applies to. This option allows the entry of royalty data into the Royalty Table using the Royalty Form.
Enter/Modify Licensee Data	In this form data can be entered or modified that relates to addresses, phone and fax numbers as well as contact names.
Enter Licensee Equipment Data	Allows the entry of data relating to the number of pieces of equipment the Licensee owns as well as any performance clauses contained in the Licensee agreement for that Licensee.

Preparing Reports

To create or prepare a report from the main menu select the **Reports** button to take you to the Report Manager screen, Figure 7. From here reports can be prepared on many aspects of the database. The reports are divided into several groups: Project Summary, Lengths Burst/Installed, Royalty Reports and Lists, in addition there are the Project Estimator, Create Program Table and Licensee Summary buttons. There is a sample of each report included in the Appendix of this manual, refer to these to get the report best suited for your needs.

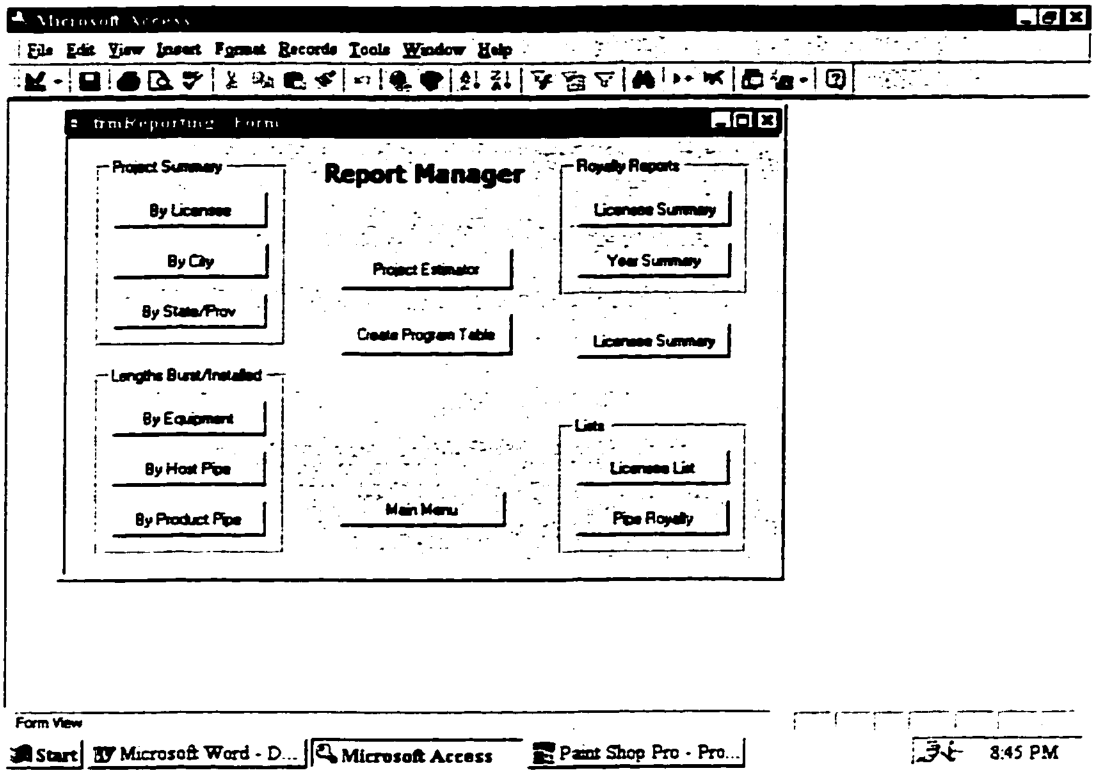


Figure 7: Report Manager

Project Summary:
Under this heading data from pipe bursting projects can be organized by Licensee, City or State/Prov. Each report displays different data so refer to the samples for the data can be displayed or reported on each report.

Lengths Burst/Installed:
This group of reports compiles data about lengths and diameters of pipe installed by Equipment, Host Pipe and Product Pipe.

Royalty Reports:
These two reports can summarize Royalty data by Licensee or by Year. These reports can be used to account for the royalties collected over the year from each Licensee.

These reports also include data pertaining to the performance clause associated with each Licensee.

Lists:
These two options provide simple lists of Licensees and Pipe Royalties. The list of Licensees can be used to help spell Licensee names when entering them for the preparation of reports as well as list all the Licensees in the database. The Pipe Royalty list can be used to ensure that the proper diameters of pipes are entered in the database as well as the proper fees associated with each diameter.

Licensee Summary Button:
This report summarizes all the vital data for the Licensee that is entered in the database. This would include addresses, phone numbers and equipment inventories.

Project Estimator:
This button produces a report based on the input of an Original Pipe Material and an Original or Host Pipe diameter. The report contains data grouped by soil type and upsize diameter indicating tonnage and pressures encountered while installing pipes over the indicated distances. This report is designed to help plan and determine if a pipe can be burst or help determine what equipment is best to use for a particular project.

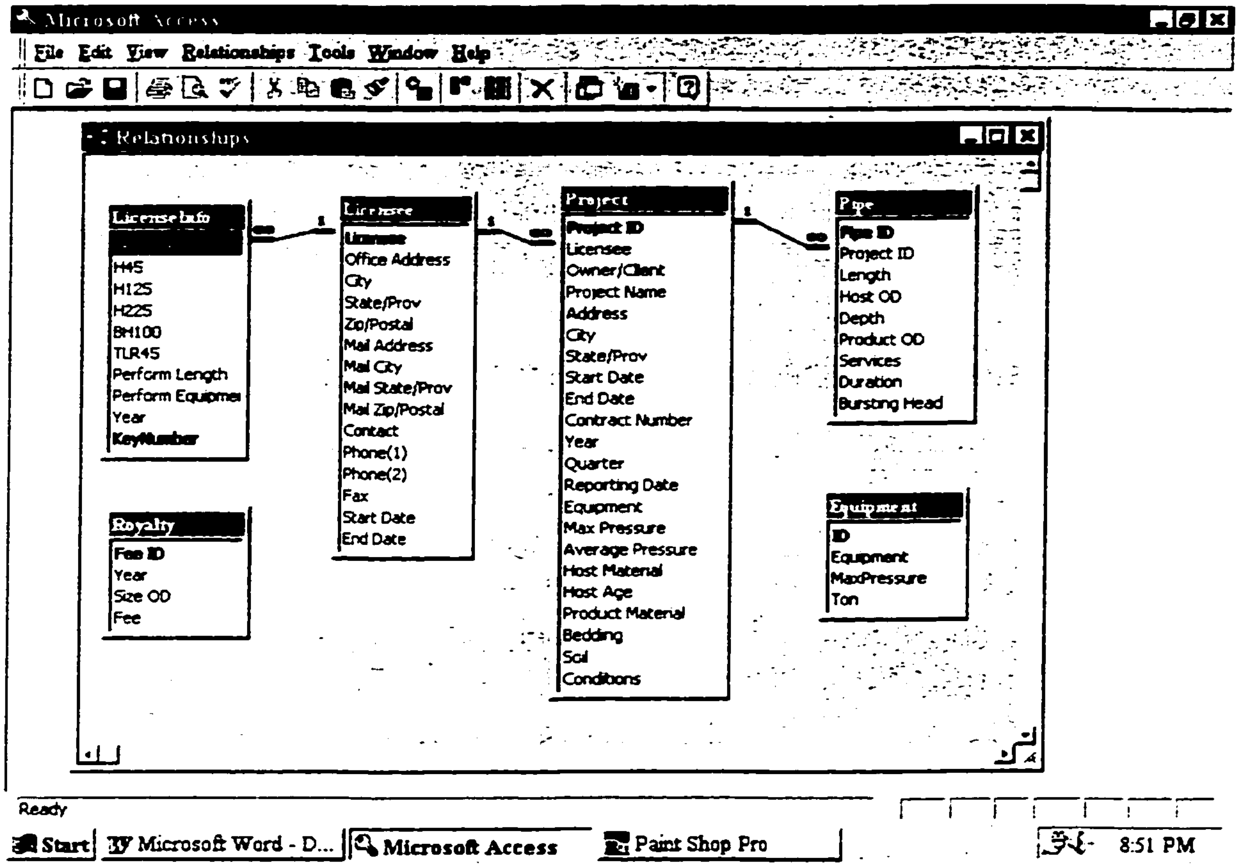
Create Program Table:
By selecting this option, Access will generate a small project database for use with the TRS Project and Marketing Program. The new Database contains only data relating to pressures, tonnage and pipe and soil data; there is no indication of which Licensee or Project the data came from. This will be discussed in more detail later in the manual.

Summary of Report Options

Option	Description
Project Summary by Licensee	Allows the user to display project data relating to all the projects a particular Licensee reports for an entered year.
Project Summary by City	Prepares a report displaying the State/Prov, City, Licensee, Quarter, Host OD, Product OD, Length and the Owner or Client base on the year that the project was reported in.
Project Summary by State/Prov	Complies a report with the State/Prov, City, Project Name, Owner/Client, Host OD, New OD and Length by Licensee and year that the project was reported.
Lengths Burst/Installed by Equipment	Summarizes the lengths pulled or installed by equipment type grouped by Quarter and Licensee for a particular year.
Lengths Burst/Installed by Host Pipe	Summarizes the lengths of pipe burst by host pipe material, grouped by size of host pipe and by type of pipe, for all Licensees by year.
Lengths Burst/Installed by Product Pipe	Summarizes the lengths of pipe installed by product pipe material, grouped by the size of the product pipe, and material composition of the product pipe, for all Licensees by year.
Royalty Reports: Licensee Summary	Compiles a report containing total length of pipe burst by pipe size, calculating the royalty to collect using the total length by pipe size and the royalty fee. The report also totals the length and royalty to collect by quarter and the query year. From the total burst in the year, a balance can be calculated by comparing the total burst to performance lengths negotiated in the Licensee's License.
Royalty Reports: Year Summary	Prepares a report with the total royalties for a user supplied year for each Licensee, grouped by replacement pipe size and quarter.
Licensee Summary	Provides information relating to the Licensee's vital information including addresses, phone numbers, contact name, start and end data of Licensee's License agreement, as well as equipment and performance clauses by year.
Licensee List	Prepares a simple list of Licensees in the database to ease the entry of Licensee names when selecting reports or queries.
Pipe Royalty	Lists the royalty fee associated with a diameter of pipe by the year entered by the user.
Project Estimator	Designed to assist in the selection of equipment and to help determine if a project can be burst. After the user enters the original pipe material and its diameter, the report compiles a list of average tonnage and pressures historically encountered on jobs with that host material and diameter grouped by soil conditions, length and upsize diameter. All upsizing values equal to or greater than the original host diameter are displayed in the report.
Create Program Table	Creates another database containing one table for use with the TRS Project and Marketing Visual Basic Program. Use this button only when a new database for the Visual Basic Program is required. Recommend updating the database for the program every second reporting quarter.

Database Organization

The main database is composed of six tables, four of which are linked with the other two serving as information tables for queries and calculations. The following relationship diagram explains how the database is constructed.



Relationships

The database consists of six tables, of which two operate as independent data sources. The other tables are linked as follows:

Parent Table	Linked Through	Child Table
Licensee	Licensee	LicenseInfo
Licensee	Licensee	Project
Project	Project ID	Pipe

Each of the parent tables has a "one to many" relationship with their child table. Therefore a child table could have many records relating to one record in the parent table.

Table Construction

The following describes the construction of each table as well as indicates the data type required for each entry into the table.

Licensee Table

Designed to contain data pertaining to the licensee that is seldom changed. It is essential that all Licensees contained in this table are kept intact. This data should be kept up to date. It is also important to not delete Licensees, as this will create linkage problems in the database. If a Licensee in the table is no longer a Licensee do not remove it from the database for at least a year after the year that the Licensee ceases to be a Licensee. New Licensees can be added as required. For a Licensee to show up on the drop down menus in the various forms, they must first be entered in this table.

Heading	Data Type	Description
Licensee	**Text (KEY)**	**Name of the Licensee**
Office Address	Text	Address of the shipping or office
City	Text	City where Office Address is located
State/Prov	Text	State of Province where Office Address is located
Zip/Postal	Text	Zip or Postal code of Office Address
Mail Address	Text	Mailing Address of the Licensee (if different from above)
Mail City	Text	City for Mail Address
Mail State/Prov	Text	State or Province of Mail Address
Mail Zip/Postal	Text	Zip or Postal code of Mail Address
Contact	Text	Contact name for primary correspondence
Phone(1)	Number	Primary phone number of Licensee
Phone(2)	Number	Secondary phone number of Licensee (if available)
Fax	Number	Facsimile number of Licensee
Start Date	Date	Start Date of the license agreement
End Date	Date	End Date of the license agreement

Project Table

Table contains data relating to the project as entered directly off the royalty reports. This table is linked with the Pipe table and the Licensee table. There can be many pipe lengths per project. If a licensee has different soil conditions on the project they will have to put the project in for as many projects as soil conditions, thus filling out more than one royalty report.

Heading	Data Type	Description
Project ID	**Number (KEY)**	**Unique number assigned automatically to project**
Licensee	Text	Licensee as entered in the Licensee Table
Owner/Client	Text	Owner or Client project was initiated by
Project Name	Text	Name of the project as per the contract documents
Address	Text	Address of the project
City	Text	City where project is located
State/Prov	Text	State or Province where project is located
Start Date	Date	Start Date of the project
End Date	Date	End Date of the project
Contract Number	Text	Contract Number on project contract documents
Year	Number	Year project is undertaken
Quarter	Number	Quarter of the year in which the project is undertaken
Reporting Date	Date	Date report was filled out of sent in to TRS
Equipment	Text	Equipment used on the project
Max Pressure	Number	Maximum Pressure equipment operated at on the project
Average Pressure	Number	Average Pressure equipment operated at on the project
Host Material	Text	Composition of the original pipe
Host Age	Number	Age of the original pipe
Product Material	Text	Composition of the replacement pipe
Bedding	Text	Composition of the bedding around the pipe
Soil	Text	Predominant soil in projects vicinity
Conditions	Text	Moisture Conditions of the soil around the pipe

Pipe Table

This table contains data relating to sections of pipe installed on a project. There can be many sections of pipe associated with each project. Each pipe section length is identified by a unique Pipe identification number, and is associated with a unique Project identification number.

Heading	Data Type	Description
Pipe ID	**Number (KEY)**	**Unique number assigned automatically to pipe section**
Project ID	Number	Links pipe section to a particular project
Length	Number	Length of pipe section in feet
Host OD	Number	Diameter of the host or original pipe in inches
Depth	Number	Average depth of the pipe section
Product OD	Number	Diameter of the product or replacement pipe in inches
Services	Number	Number of services along this section of pipe
Duration	Number	Duration in days for the installation/replacement of pipe
Bursting Head	Number	Diameter in inches of the bursting head used on section

Equipment Table

The data in this table is used by the queries in the database to calculate the tonnage by the pressures used on the project. In this manner the database can relate the soil conditions to the pressures required for the equipment on a project. This table is independent of all tables in the database.

Heading	Data Type	Description
ID	**Number (KEY)**	**Unique number assigned automatically to equipment**
Equipment	Text	Name of equipment (H45, H125, H225, TLR45, BH100)
MaxPressure	Number	Maximum pressure capable by machine type
Ton	Number	Maximum tonnage capable by machine

Royalty Table

The Royalty table contains the royalty fees associated with the diameter of the new or replacement pipe. This table will need new data entered into it once a year to update the royalty fees. Do not delete the old royalty fees – as the fee for diameter of pipe is distinguished by the year. Thus if a year is erased no royalty reports can be generated for that year. As new years are entered, the old ones can be used to project trends or calculate previous year data. This table is independent of all tables in the database.

Heading	Data Type	Description
Fee ID	**Number (KEY)**	**Unique number assigned automatically a Royalty fee**
Year	Number	Year in which that royalty applies
Size OD	Number	Diameter of the replacement pipe
Fee	Number	Royalty for that year and diameter of pipe

Very Important:

When entering data directly into this table or by using the input form, it is necessary to enter data for every size pipe. Due to the limitations of my visual basic programming skills I could not determine how to enter a range for the fees. The royalty fees usually are described such that for pipes between 12 to 24 inches in diameter an $X amount per foot is collected. For the database to operate correctly in this situation all diameter of pipe between 12 and 24 inches must be entered. Thus one must enter 12, 14, 16, 18, 20, 22 and 24 inches at $X per foot. **Or more basically any diameter of pipe you wish to calculate royalties for must be entered into this database. If it is not entered than the database will not calculate that royalty fee – and worst of all *will not tell you that it is skipping a diameter of pipe in the calculations.* Thus it is essential to insure that every diameter of pipe installed in that year has an associated fee for that diameter in the Royalty table.**

LicenseInfo Table

The LicenseInfo Table contains data relating to performance requirements by the licensee as well as the number of pieces of equipment each Licensee owns. This data is sorted by year and is linked to the Licensee Table.

Heading	Data Type	Description
KeyNumber	**Number (KEY)**	**Unique number assigned automatically**
Licensee	Text	Name of Licensee from the Licensee Table
H45	Number	Number of H45's owned by the Licensee
H125	Number	Number of H125's owned by the Licensee
H225	Number	Number of H225's owned by the Licensee
BH100	Number	Number of BH100 owned by the Licensee
TLR45	Number	Number of TLR45 owned by the Licensee
Perform Length	Number	Minimum length to be pulled that year by Licensee
Perform Equipment	Currency	Minimum amount of equipment Licensee must purchase in that year, by Licensee agreement
Year	Number	Year for which the data applies

Note:

This data must be entered once a year or can even be input in advance. All this data must be entered in for each year the Licensee is under License. Also note that no data in this table form previous years can be deleted or modified.