Assessment of Pipeline Installation Using the Eliminator: a New Guided Boring Machine

by

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Abstract

The Eliminator is a new guided boring machine developed to address the market need for Pilot Tube Microtunneling (PTMT) installations in non-displaceable soils. This study is part of a multi-phase research project sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the City of Edmonton. The main objectives of this research is to investigate the productivity of the Eliminator, risks associated with this machine, and methods to predict the required jacking force for installation of pipes. To achieve these goals, firstly a broad literature review was conducted on PTMT and the Eliminator as well as similar technologies such as microtunneling and pipe jacking. The study then introduces the first pipeline installation project performed with the Eliminator and assesses the technology's economic performance using the project's productivity and risk measures. The jacking force of the project was also monitored for analysis using hydraulic pressure transducers. Five existing jacking force prediction models used for technologies similar to the Eliminator were analyzed and compared with each force measured in the field. Based on the comparison, appropriate methods for estimating the jacking force of Eliminator projects are suggested.

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1. Chapter 1: Introduction

1.1. Background

A majority of underground utilities in North America were installed during the 1950s and 1960s postwar construction boom. These systems, constructed in green fields and the sparsely developed environments, presented few impediments to large-scale open trenching, which was the standard practice at that time (Mckim, 1997). However, due to increased growth and development, performing open-cup installations in today's municipalities requires additional arrangements for road detours, ground water management, storage of excavated materials onsite, backfilling and compaction of the ground, and restoration of the ground surface following installation. In addition to the installation process itself, these factors are associated with significant social and financial costs, which has led to the development of several methods for minimizing trench work referred to as trenchless technology (Gottipati, 2011). Trenchless technology is defined as, "Techniques for utility line installation, replacement, rehabilitation, renovation, repair, inspection, location and leak detection, with minimum excavation from the ground surface" (NASTT, 2014). Environmental concerns, social costs, new safety regulations, difficult underground conditions, and new developments in equipment have caused an increasing demand for trenchless technology (Najafi et al., 2001). An growing number of metropolitan public works departments are understanding that both tangible and intangible costs of trenchless construction can be decreased when compared to open trench construction (Bruce, 2002).

Different trenchless technologies have emerged for different applications such as pipe jacking, microtunneling, and Pilot Tube Microtunneling (PTMT). Pipe jacking is a technique used for the installation of underground pipelines where powerful hydraulic jacks push the project pipe through the ground. This method provides a flexible, structural, and watertight pipeline (Pipe Jacking Association, 2005). The Inner Diameter (ID) of the jacking pipes is usually greater than 800 mm (Stein, 2005), which limits the applicability of the method for pipes with a smaller diameter. Meanwhile, microtunneling is a remotely-controlled, guided pipe-jacking method that does not require personnel entry into the tunnel (Bennett, 1998). Although Microtunneling has variety of capabilities, its associated costs are a deterrent for many contractors.

PTMT has been gaining popularity since it was introduced in the United States in 1995 (Haslinger et al., 2007). The primary reason for this popularity is that PTMT installations can be as accurate as conventional microtunneling but with significantly lower equipment costs (Haslinger et al., 2007). The PTMT installation process generally consists of three stages: pilot tubes installation, reaming and auger casings installation, and product pipe installation. PTMT can be used in most displaceable soils with standard penetration test (SPT) N-values of less than 50 blows per foot (Gill, 2010). This limitation arises from the pilot tube's inability to advance through non-displaceable soils.

Consequently, the Eliminator is a new guided boring machine developed to address the market need for PTMT in non-displaceable soils. It works as a cutter head installed at the front of the auger casings. As the Eliminator has steering capability, it eliminates the need for pilot tube installation to develop the desired line and grade; this is the reason why the machine has been called "Eliminator". The installation process using the Eliminator includes two stages: auger casings installation and pipe installation. The Eliminator was developed by Akkerman Inc. in 2012, and only a few projects have been performed with this machine to date. The Eliminator was first used in a sewer line installation project in Edmonton, Alberta, Canada. Although the installation process with the Eliminator is similar to the conventional PTMT, there are substantial differences between the two technologies, which necessitate further research on the Eliminator. As a new technology, the Eliminator's productivity is of interest to the industry, and the factors and risks affecting productivity require evaluation (Tang et al., 2013). Jacking force prediction is another significant step in planning Eliminator projects since the maximum jacking force required affects several design factors. This study is aimed to investigate productivity and risks associated with the Eliminator, and the maximum required jacking force during installations with the technology.

1.2. Objectives

The main objectives of the current study can be summarized as follows:

- To perform a comprehensive literature review on trenchless technologies; specifically on PTMT and the Eliminator regarding productivity, risk, and jacking force analysis;
- To investigate the productivity of each stage of installation with the Eliminator through a sewer line installation project in Edmonton, which can be used for future project scheduling;
- To identify the potential risks of each stage of installation and their influence on the duration of the project; and
- To instrument and measure the required jacking force for sewer line installation and to compare existing jacking force prediction models for the determination of the most applicable method in predicting the maximum applied jacking force; an element critical to project design.

1.3. Methodology

The first recorded application of the Eliminator in sewer line installation was monitored for field assessment. Appropriate instrumentation was chosen and installed on the power pack, which provides hydraulic support for the Eliminator, to record real data. In addition to automated data logging, physical observations were recorded onsite to confirm the reliability of the recorded data. The raw data was then analyzed and processed manually to determine the installation and preparation duration for each auger casing and pipe section. Additionally, the required jacking force for each pipe section was also measured. @RISK add-in was used to execute curve fitting on recorded durations for the analysis of each installation step in greater detail. In addition, a statistical analysis was performed on the duration of activities during the project.

By investigating the recorded data and field notes, a total of 13 risk items were identified for the project. The stoppage duration for each of these items was then calculated, as was the effect of each risk event with respect to the project's duration in terms of percentage. Furthermore, causes of each risk item were investigated to determine whether the item is preventable and controllable in future projects.

The project's geotechnical characteristics were extracted from its geotechnical report. To perform jacking force analysis on the Eliminator, different jacking force prediction models for microtunneling and pipe jacking are studied. By applying the project's characteristics, the models were compared and their applicability to Eliminator projects was examined.

1.4. Thesis Structure

This thesis is presented with the following organization:

- Chapter 1 – Introduction: In this chapter, a brief background on trenchless technologies is provided and PTMT's background is discussed. Next, the Eliminator is introduced and the need to perform a productivity, risk, and jacking force analysis for this new technology is discussed. The objectives, methodology, and organization of the thesis were also described.

- Chapter 2 – Literature Review: In this chapter, general information related to the trenchless technology, PTMT, and the Eliminator are introduced. A literature review on productivity and risk analysis is also performed.

Lastly, different methods of jacking force prediction for microtunneling and pipe jacking are detailed.

- Chapter 3 – Field Assessment of Pipeline Installation Using the Eliminator: A New Guided Boring Machine: In this chapter the Eliminator's construction process is presented through a sewer line installation project in Edmonton. A productivity and risk analysis were conducted on the Eliminator's performance in two sections of this project, and the results are discussed.
- Chapter 4 – Jacking Force Analysis of Pipeline Installation Using the Eliminator: Instrumentation and data collection for the sewer line project in Edmonton are discussed. In addition, different jacking force prediction models for technologies similar to the Eliminator are discussed and used to predict the required jacking force for the sewer line installation project. The results are then compared to the force measured in the field. Based on the comparison, the most applicable methods for jacking force estimation of Eliminator projects are suggested.
- Chapter 5 – Conclusions: In this chapter, the research approach and the findings of the study are summarized, and future research topics are proposed.

2. Chapter 2: Literature Review

2.1. Trenchless Technology

Over the past 40 years, rapid change has taken place in regards to the techniques available to install, maintain, repair, and renew underground utility systems (Sterling, 2010). Trenchless technologies have been increasing in popularity as they greatly reduce direct and in-direct costs associated with traditional open-cut methods. Minimizing disturbance to the environment, reducing steering and control problems associated with new routing, and minimizing possible interference with existing utilities are typical advantages of trenchless technology application (Najafi et al., 2001). To summarize their capabilities, Stein (2003) categorized trenchless methods on the possibility of access to the working face (unmanned or manned techniques) and the constant positional determination and directional control of the boring head (non-steerable or steerable), as shown in

Figure 2.1.

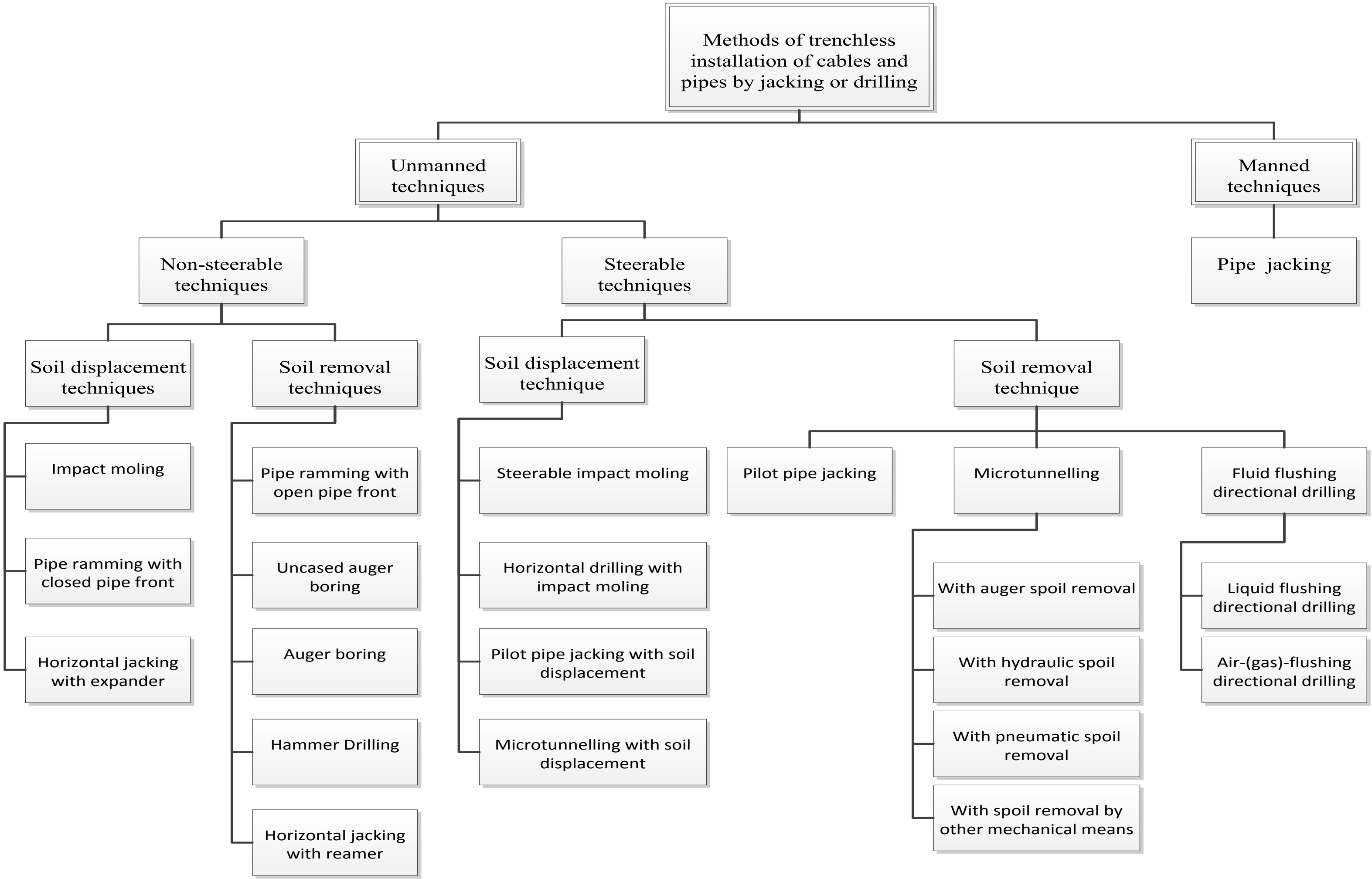


Figure 2.1 Methods of trenchless installation of cables and pipes by jacking or drilling (Stein, 2003)

As shown in Figure 2.1, a variety of trenchless technologies has been developed for different applications. Pipe jacking, one of the most common and cost-effective trenchless construction methods, uses hydraulic jacks to push pipe sections through the ground while excavation is being performed at the face (Rahjoo et al., 2012). Pipes in the range of 800 mm to 5000 mm can be installed with an accuracy of ±1-1/4 in. through this method (Clarkson and Division, 1983). Methods of excavation can range from hand digging within a simple shield to highly sophisticated machinery (Marshall, 1998). Theoretically, the length of drive for the pipe jacking method using intermediate jacking stations is unlimited, although economic and practical factors can influence its application. With this method, pipe's with a length over 3280 ft (1000 m) have been successfully installed (Clarkson and Division, 1983). Since pipe jacking is a manned technique, a portion of the crew works inside the pipeline, resulting in limitations to the minimum pipe diameter for projects installed with this method.

Until the beginning of the 1980's, unmanned methods of trenchless installation were known as non-steering soil displacement or soil removal methods; consequently, these methods were not applicable for installation of gravity pipelines (Stein, 2003). However, the development of PTMT in the past 35 years has altered the situation (Stein, 2003). Microtunneling can be defined as a steerable, remote controlled pipe jacking technique used to install pipes with an internal diameter less than that permissible for man-entry (usually determined as less than 900 mm in the UK and less than 800 mm in Japan) (Chapman and Ichioka, 1999). The most obvious distinction between microtunneling and pipe jacking is that microtunneling is controlled remotely from an operator's console located at the surface, while pipe jacking is typically controlled by an operator at the face inside the pipe (Bennett, 1998). Another important distinction between these two methods is microtunneling's provision of greater control of face stability by means of mechanical and fluid pressures, resulting in increased capability under challenging ground conditions, (Bennett, 1998). Microtunneling is used for pipe with a diameter ranging from 500 to 1500 mm which can go up to

2000 mm (FSTT, 2006). Accuracy in microtunneling projects is typically less than 2 cm over 100 m (Ueki et al., 1999). Microtunneling can be divided into two main categories: slurry types and earth pressure balance (EPB) types. In slurry machines, the excavated material is transported from the face suspended in a slurry (Pipe Jacking Association, 2005). In EPB machines, the excavated material is transported from the face by a balanced screw auger or screw conveyor. Meanwhile, the face is supported by excavated material held under pressure behind the cutter head, and the pressure is controlled by the rate of transportation of excavated material through the balanced screw auger or valves on the screw conveyor (Pipe Jacking Association, 2005). The characteristics of each type is summarized in Table 2.1.

Table 2.1 Basic characteristics of slurry and EPB microtunneling methods (Ueki et al., 1999)

Characteristics	Slurry type	EPB type
System	The most popular microtunneling method. Slurry containing bentonite is pumped to the face of the tunnel, transports excavated material to driving pit, and is then discharged above ground surface. The slurry also acts to support face.	Excavated material is transported by auger in casing and directly discharged to buckets located in driving pits. Cranes are used to lift buckets when dumping.
Advantages	▪Available for a wider range of soils and diameters; universal system. ▪Can be chosen from various types. ▪Tunneling more than 3 m below ground-water table can be achieved. ▪Some types are available for soft rocks. ▪Longer drives can be achieved ▪Driving pits can be cleaner as material is automatically sent to slurry plants.	▪Whole system is simpler and less expensive than slurry systems; fewer issues may occur. ▪Effective for smaller diameters and shallower installations. ▪More effective for cohesive soils and low water level sites.
Disadvantages	▪System is more complicated and costly than EPB types. ▪There may be problems driving through cohesive soils when installation depth is shallow.	▪Tunneling below water table is limited. ▪Limited diameter variations. Usually available for less than 120 cm pipes. ▪Drive length is limited to around 90m due to cutter torque.

2.2. Pilot Tube Microtunneling (PTMT)

PTMT originated in Europe nearly three decades ago for the installation of four- and six-inch house connections (Bruce, 2004; Haslinger et al., 2007). The method is a hybrid of three trenchless boring methods: it has a slant faced steering head similar to directional drilling; it utilizes the guided accuracy of conventional microtunneling; and it relies on a auger-type spoil removal system similar to an auger boring machine (Boschert, 2007). PTMT has been gaining popularity since it was introduced in the United States in 1995 (Haslinger et al., 2007). The primary reason for the increased popularity is that PTMT installations can be as accurate as conventional microtunneling at less than 0.25 inch per 300 ft (Gottipati, 2011), but with significantly lower equipment costs (Haslinger et al., 2007). A relatively limited footprint, increased worker safety, deep installation potential, and minimal environmental impacts also contribute to the popularity of this method (Sewing et al., 2009). In the categorization shown in Figure 2.1, PTMT is equivalent to pilot pipe jacking with soil removal.

The PTMT installation process consists of three stages: 1) pilot tubes installation, 2) reaming and auger casings installation, and 3) product pipe installation. In the first stage (Figure 2.2), the desired line and grade is developed by installation of pilot tubes from the launch shaft to the reception shaft by using a slanted face steering head at the front of the pilot tubes. There is an illuminated LED target inside the steering head, which can be seen through the string of pilot tubes to locate the position of the steering head. A video camera mounted on a theodolite is connected to the operator’s screen to enable tracking of the LED target. The pilot tubes’ length, similar to auger casings and pipe sections, are typically 3.3 ft or 6.6 ft with an outer diameter of 4.25 in; pilot tubes may be either single or dual walled (Gottipati, 2011). The desired line and grade is provided by rotation of the slant-faced steering head at the tip of pilot tubes during the advancement of the pilot tubes. Only the inner tube on the dual walled pilot tube will rotate with the steering head, and bentonite lubricant may be pumped to the steering head to reduce the friction between the tubes and surrounding soil (Haslinger et al., 2007). The position of the LED target inside the steering head, as well as the lubrication system for the steering head and the first dual walled pilot tube is shown in Figure 2.3.

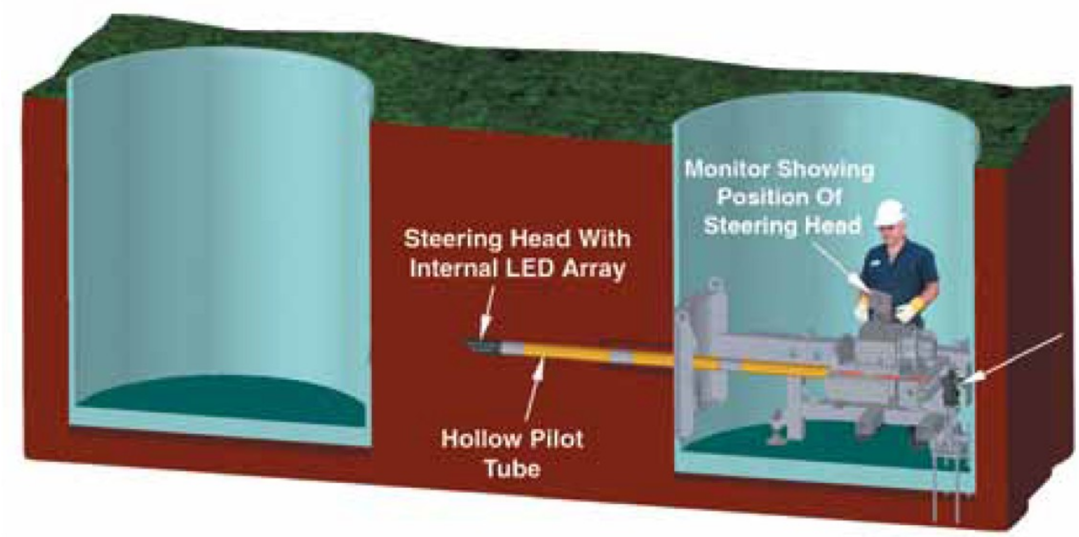


Figure 2.2 Pilot tube installation (Akkerman, 2013)

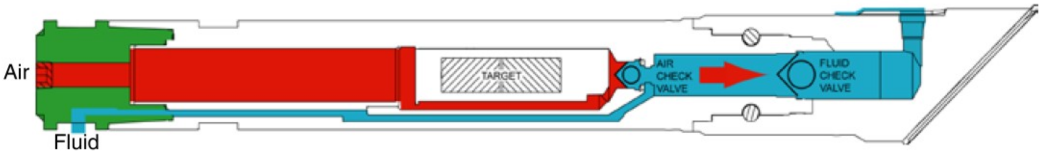


Figure 2.3. The steering head and the first dual walled pilot tube attached to the steering head (Akkerman, 2013)

In the second stage, the borehole diameter increases by means of a reaming head from the pilot tubes' diameter to the casings' diameter, usually from 30.5 to 40.6 cm (12 to 16 inches). During this stage, auger casings are pushed through the soil and replaced with the installed pilot tubes. A reaming head is attached to the last installed pilot tube to increase the borehole diameter to a diameter slightly larger than that of the auger casing. The augers inside the casings remove the excavated soil to the launch shaft, and by using a dirt bucket and a crane, removed the soil from the shaft. At the end of this stage, all installed pilot tubes and the reaming head are removed from the reception shaft, and a stem of augers is installed between the reception and launch shaft, as shown in Figure 2.4.

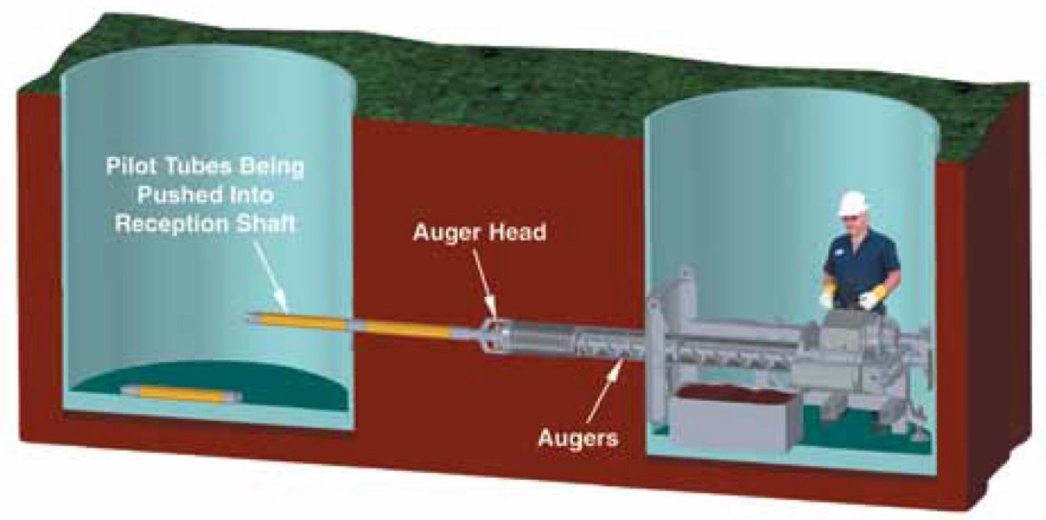


Figure 2.4. Auger casings installation (Akkerman, 2013)

Figure 2.5. Auger casings placement on site (Boschert, 2007)

In the third stage (Figure 2.6), the installed auger casings are replaced with final product pipes. The last installed auger casing is attached to the first pipe section using an adapter. In case the diameter of the product pipe is larger than the installed casing, a Powered Reaming Head (PRH) or a Powered Cutter Head (PCH) is used to increase the borehole's diameter (Figure 2.7). The PRH's rear end is attached to the lead end of the first pipe, while the PRH's front end is attached to the last installed auger casing. Typically, PRH is used for pipe diameters ranging 40.6 to 50.8 cm (16 to 20 inches) and PCH is used for pipe diameters ranging 50.8 to 111.8 cm (20 to 44 inches). When PRH or PCH are used, the spoils are removed to the reception shaft. Both PRH and PCH have jetting lines at the face to facilitate spoil removal and to separate lubrication lines on the rear section for the reduction of friction between the pipe section and the soil.

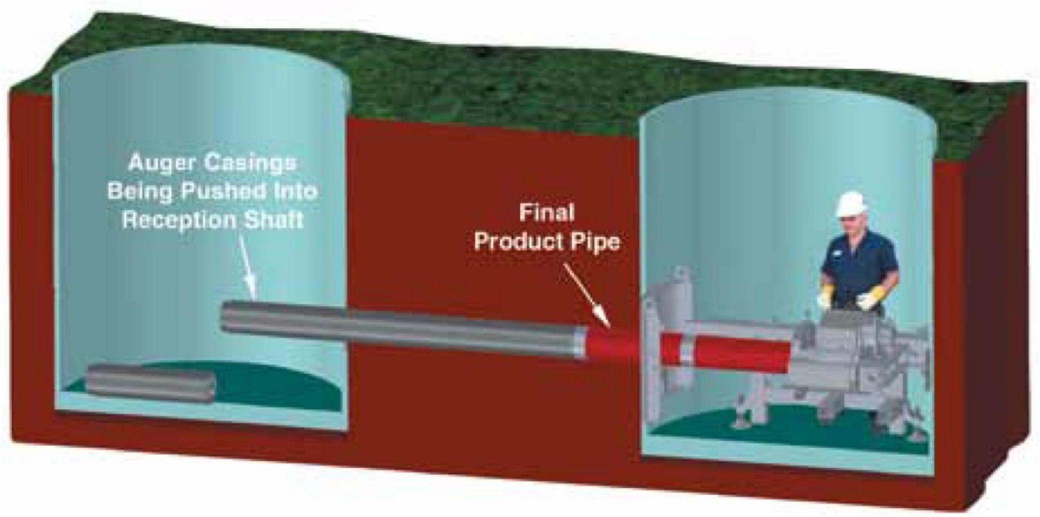
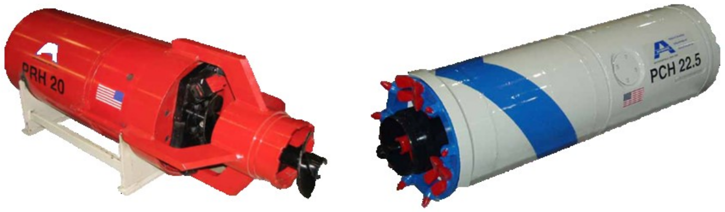


Figure 2.6. Final product pipe installation (Akkerman, 2013)



Powered Reaming Head (PRH)

Powered Cutter Head (PCH)

Figure 2.7. Powered reaming head and powered cutter head (Akkerman, 2013)

PTMT was originally only applicable to pipes with a diameter between 10.2 to 30.5 cm (4 to 12 inch) and maximum drive lengths up to 75 m (250 ft) (Boschert, 2007). Nowadays, installation of pipes with a diameter between 10.2 and 121.9 cm (4 and 48 inches) is possible, and projects as long as 175 m (575 ft) in a single drive have been performed using PTMT (Lueke et al., 2012). PTMT is a successful tool for installations in weak soil where other methods, such as open-cut and auger boring, have failed (Boschert, 2007). However, this technology is applicable only for displaceable soils with Standard Penetration Test (SPT) values lower than 50 (Gill, 2010).

2.3. The Eliminator

The Eliminator (Figure 2.8) is a new guided boring machine developed by Akkerman Inc. in 2012, to address the market need for PTMT in non-displaceable soils. It works as a steerable cutter head installed at the front of the auger casings, eliminating the need for pilot tube installation to develop the desired line and grade and providing the basis for its name, the "Eliminator". In the categorization shown in Figure 2.1, the Eliminator is equivalent to pilot pipe jacking.

Figure 2.8. The Eliminator (Akkerman, 2014)

The installation process using the Eliminator includes two stages: auger casings installation and pipe installation. In the first stage (Figure 2.9), the Eliminator is attached to the front of an auger casing as a lead tool (Figure 2.10 and Figure 2.11) to create a 40.6-cm (16-inch) diameter borehole on the desired line and grade. The Eliminator advances by a combination of rotation and thrust provided by the jacking frame and transferred via auger casings. Since the soil can be cut and removed (not displaced), the Eliminator is applicable only in non-displaceable soils. Spoils are moved by auger casings to the launch shaft and removed from the shaft by means of a dirt bucket. Once the Eliminator is removed from the reception shaft and the auger casings are installed on the desired alignment, the first stage of installation is complete.

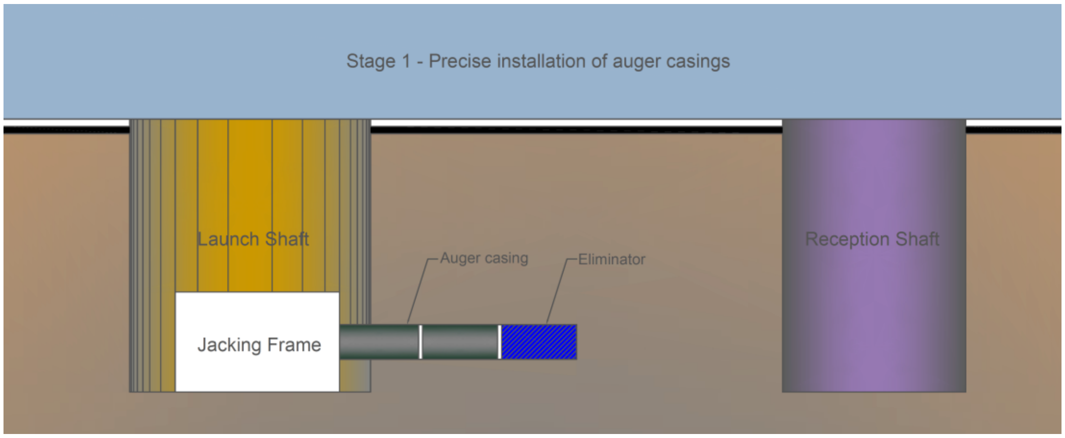


Figure 2.9. Auger casings installation with the Eliminator

Figure 2.10. The Eliminator preparation for installation

Figure 2.11. The Eliminator configuration (Akkerman, 2014)

The Eliminator's guidance system is similar to that of the conventional PTMT; there is a battery-powered illuminated target inside the cutter head which can be seen through the string of hollow stem augers on the operator's screen by a video camera mounted on a theodolite (Figure 2.12) in the launch shaft. For steering, the Eliminator uses three independent controllers (steering shoes) located on the top and bottom portions of the Eliminator. When each steering shoe (Figure 2.13) is opened and the Eliminator is pushed into the ground, the Eliminator will move in the opposite direction. The Eliminator is also equipped with a jetting nozzle (Figure 2.14) at the face to ease the excavation process and facilitate soil removal.

Additionally, the machine has a lubrication nozzle at the rear end to decrease friction between the casings and soil. The Eliminator has an overcut of 3.8cm (1.5 inches) to minimize the required jacking force. The length of the Eliminator’s is 124.5cm (49 inches), and its weight is 680 kg (1500 lbs).

Figure 2.12. Camera mounted on a theodolite in the launch shaft

Figure 2.13. Steering shoe located on the top of the Eliminator (Akkerman, 2013)

Figure 2.14. Jetting nozzle at the face of the Eliminator

The second stage of the Eliminator's installation process is the same as the third step in the conventional PTMT process. The auger casings develop the desired line and grade, and an adapter (PRH or a PCH) is used to connect the first pipe section to the final auger casing. The crew then begins replacing the installed auger casings with the product pipe.

2.4. Productivity analysis

Productivity plays a fundamental role in many project management functions such as estimation, scheduling, plan implementation, monitoring and control, and post-project performance review (Song et al., 2004). Tt is argued that research efforts should be performed on micro-datasets at the level of the individual construction projects (Bröchner and Olofsson, 2012; Crawford and Vogl 2006). Traditionally, contractors have relied on their experience and engineering intuition in making decisions related to their projects (Tavakoli, 1985); however, quantitative methods are currently the main tool for analysis of construction operations. Productivity measurement assists owners in evaluating the performance of contractors on their capital facility projects, while helping contractors to improve through internal or external benchmarking (Park et al., 2005). Measuring productivity is challenging due to difficulties in reaching an agreement for the exact definition of productivity for various working situations (Hancher, 1985).

Productivity can be illustrated by an association between an output and an input. Two types of productivity were used in previous studies: (1) productivity = output/input and (2) productivity = input/output (Park et al., 2005), and the first definition is used in this study. No productivity analysis has been performed for the Eliminator, and very few studies have been performed for conventional PTMT. Olson and Lueke (2013) studied cycle time frequency and cumulative installation length against time for all three stages of recorded data from two PTMT projects. Cycle time frequency analysis is useful in monitoring progress, perceiving productivity, and assessing project impacts (Olson and Lueke, 2013). Olson and Lueke (2013)'s study showed that the average productivity of pilot tubes installation was 31 m/hr, auger casings installation was 4.3 m/hr, and product pipe installation was upwards of 22.9 m/hr .

2.5. Risk analysis

The significance of risk management has been recognized in various industries. Specifically, the construction industry and its clients are widely associated with a high degree of risk due to the nature of activities, processes, and the environments involved (Akintoye and MacLeod, 1997). Risk manifests itself in unforeseen circumstances which are not accounted for in the planning stage. In the construction industry, the common practice for determination of this expenditure is the addition of a single contingency amount (usually as a percentage) to the base estimate (Mak and Picken, 2000). However, the contingency for above ground construction is not applicable for underground construction (Wagner, 2004). The geologic uncertainty in underground construction has a significant effect on the project cost (Ioannou, 1989), consequently performance of risk assessment for each underground construction technique is necessary. Major projects have been subject to missing cost targets or schedule deadlines due to improper risk assessment(Senesi et al., 2012). Risk assessment can be defined as a unified procedure including identification, analysis, evaluation, and managing of the associated risk (Choi et al., 2004). This study is focused on the first two steps: risk identification and analysis. Risk identification is a process to understand risk events and identify their characteristics, which has considerable significance in the remainder of the process as it defines the risk events to be included throughout the assessment (Choi et al., 2004). Raftery mentioned that many professionals experienced in risk assessment find that the identification stage is the most time-consuming (Choudhry et al., 2008). The identified potential risks can be analyzed in terms of probability and impact. Quantitatively, the effect of each risk event can be calculated by product of the probability of an event and the given damage or consequence (Zio, 2007). Practically, the perception of risk is such that the effect of consequence is greater than its probability of occurrence.

Lueke et al. (2012) conducted a survey on 22 PTMT contractors across North America, representing 450 projects completed between 2006 and 2010. The contractors were asked to rate risk associated with certain factors and conditions affecting PTMT installation. The survey results showed that the risk associated with damaging the product pipe and adjacent utilities had the lowest ranking due to the technology's high accuracy of installation. Ground movements resulting from PTMT installations as well as clay and silty soil conditions were also perceived as a low risk conditions. Surface movements due to PTMT installations are more likely as large diameter pipes are installed at shallow depths. High groundwater table was ranked as a moderate to high risk of PTMT installation, while Sand and gravel as well as cobble and boulders soil conditions were perceived as high risk conditions. The ranking of each risk factor is shown in Table 2.2.

Table 2.2. Risk factors and conditions for PTMT installation (Lueke et al., 2012)

Risk factor	Rating
Cobble and boulders	9.5
Sand and gravel soils	6
Maintaining grade	4.8
High groundwater	4.5
Ground movements	2.7
Clay and silty soils	2.7
Damaging adjacent utilities	2.4
Damaging product pipe	2.2

2.6. Jacking force analysis

Jacking force is the one of most crucial factors in pipe jacking engineering (Bai et al., 2013). The construction of microtunneling shafts has a significant impact on the total cost of projects (Staheli, 2006). Jacking force prediction has similar significance for PTMT and Eliminator projects due to similarity of the mechanical operation of these technologies. The maximum applied jacking force affects several factors in the project design such as the type of jacking frame capable of applying the maximum jacking force, the maximum distance between the launch and reception shafts, and the lunch shaft's structural requirements to withstand the maximum jacking force. Prediction of the required jacking force is also important in preventing damage to pipe and joints from excessive stress concentrations (Chapman and Ichioka, 1999). Jacking force prediction is critical in determining the number of rely stations, especially in long distance pipe jacking construction (Bai et al., 2013).

2.1.1. Face resistance

The total jacking load should overcome the face resistance (penetration resistance) at the shield and the frictional resistance of the pipe string (Marshall, 1998). Depending on the method of jacking, three types of penetration resistance are possible: cutting edge resistance (P_S), contact pressure (P_A), and support force (P_{ST}) (Stein, 2005). The cutting edge resistance exists when the excavation tool is jacked through the ground, and it is due to creation of shear failure-like zones of soil flow at the front of the cutting edge (Stein et al., 1989). Herzog (1985) determined the cutting edge resistance Ps as a product of cutting edge area and tip resistance in the soil as follows:

$$\boldsymbol{P_s = \pi \times D_m \times t \times p_s} \tag{2.1}$$

where D_m is the cutting edge diameter, t is the cutting edge thickness, and p_s is the tip resistance. The guide value for P_S is shown in Table 2.3. Since Herzog (1985) measured these values by monitoring cast-in-place piles and not pipe jacking operations, the values suggested are too low when passive soil pressure is assumed in place of tip resistance (Stein et al., 1989).

Table 2.3. Tip resistance based on soil type (Herzog, 1985)

Soil Type	**P_S [kN/m^2]**
Rock-like soil	12000
Gravel	7000
Sand, dense bedding	6000
Sand, medium dense bedding	4000
Sand, loose bedding	2000
Marl	3000
Tertiary clay	1000
Silt, quaternary clay	400

Weber (1981) proposed two formulas for calculation of the cutting edge resistance for the boring head behind and ahead of the cutting edge. When the boring head is position behind the cutting edge, the cutting edge resistance is calculated as follows:

$$\boldsymbol{P_S = \lambda \pi D_a t(c + \gamma h \, tan \, \emptyset)} \qquad \textbf{(2.2)}$$

where γ is the density of the soil [kN/m^3], c is the cohesion of the soil [kN/m^2], D_a is the external diameter of the pipe, h is the height of cover [m], φ is the friction angle of the soil [°], and λ is the carrying capacity coefficient which is equivalent to the bearing capacity reduction factor and with an increasing trend from approximately 0.05 at φ=0°, to 0.02 at φ=25°, to 0.75 at φ=40°, and 1at φ=42° (Bennett, 1998). When the boring head is located ahead of the cutting edge, Weber proposed the following equation to calculate the cutting edge resistance:

$$\boldsymbol{P_S = (c + \gamma \times 1).\lambda.\pi.D_a.t} \qquad \textbf{(2.3)}$$

The contact pressure force is the force that presses the excavation tool in the direction of boring, and can be calculated from:

$$\boldsymbol{P_A = A_1.p_A} \qquad \textbf{(2.4)}$$

where A_1 is the area of the bore head and p_A is the support pressure of the bore head. The support force is the force supporting the earth pressure at the face, which is applied with mechanical support, compressed air, fluid support, earth pressure balance, or natural support (Stein, 2005). This force can be calculated by product of the required support pressure and the working face area. For calculation of the contact pressure, since neither settlement nor heave of ground surface is allowed during the installation, a value between active and passive Rankin earth pressure can be used as an estimate (Staheli, 2006). Bennett (1998) recommended the average of these two pressures for microtunneling projects. A summary of the penetration resistance with regard to the type of microtunneling is shown in Table 2.4.

Table 2.4. Summary of the penetration resistance with regard to the type of microtunneling or shield machine (Stein, 2005)

P_E			Method
P_A	P_B		
	P_A	P_{ST}	
√	√	√	Shield machine with partial excavation and compressed air support
√		√	Hand shields with compressed air support (unstable soil); shield machines with hydraulic partial excavation; open shield machines with mechanical partial excavation and partial support
√	√		Open, mechanical partial excavation shield machines (usually with fixed installed excavator) and natural support of the working face
	√	√	All microtunneling methods except microtunneling with auger spoil removal and drive of the cutting head the spiral conveyor, shield machines with full face excavation (except open full face excavation shield machines with natural support, shield machines with mechanical partial excavation and compressed air support)
√			Auger boring methods, microtunneling with auger spoil removal and drive of the cutting head with the spiral conveyor, open hand shields with natural support
	√		Open, mechanical partial excavation as well as open, full excavation shield machines both with natural support
		√	Hand shield with compressed air support
			Hand shield with natural support (working face without support) in solid rock

2.1.2. Frictional resistance

Frictional resistance results from the skin friction acting on the external surface pipe string and the machine (Marshall, 1998). The frictional resistance depends on several factors such as the nature and condition of the soil, the type of the pipe surface, the depth of installation, size of the overcut, lubrication, and stoppage in jacking (FSTT, 2006). The frictional resistance can be calculated as follows (Stein et al., 1989):

$$\boldsymbol{F_r = R \times D \times \pi \times L} \qquad \textbf{(2.5)}$$

where F_r is the frictional resistance [kN], R is the skin friction [kN/m^2], D is the pipe or shield outside diameter [m], and L is the jacking distance [m]. The skin friction can be calculated based on the law of friction:

$$\boldsymbol{R = \mu \times N} \tag{2.6}$$

where μ is the coefficient of friction and N is the normal force acting on the pipe. The coefficient of friction is determined as a function of the wall friction angle δ by:

$$\boldsymbol{\mu = tan\,\delta} \tag{2.7}$$

Scherle, as reported by Stein (2005), provided a guide value for concrete and fibre cement pipes on clay, gravel, and sand soil, as shown in Table 2.5.

Table 2.5. Guide value for the friction coefficient (Stein, 2005)

Pipe type/soil condition	**Adhesive friction μ**	**Sliding friction (without lubricant) μ**	**Sliding friction (with lubricant) μ**
Concrete on gravel or sand	0.5 to 0.6	0.3 to 0.4	For fluid friction when using a Bentonite suspension as lubricant dependent on the liquid limit of the Bentonite suspension 0.1<μ<0.3
Concrete on clay	0.3 to 0.4	0.2 to 0.3	
Fiber cement on gravel or sand	0.3 to 0.4	0.2 to 0.3	
Fiber cement on clay	0.2 to 0.3	0.1 to 0.2	

For steel or cast iron, Stein (2005) suggested a guide value for coefficients of friction, as shown in Table 2.6:

Table 2.6. Coefficients of friction for steel or cast iron pipes to (Stein, 2005)

Type of soil	Coefficient of friction μ
Dense soil	0.5
Moist soil	0.33
Fine round gravel	0.6
Round gravel	0.5
Gravel	0.6
Clay	0.2 to 0.5
Sand	0.5
Common soil or moist sand	0.2 to 0.33

Iscimen (2004) measured peak and residual friction coefficients for different pipe materials sheared against Ottawa 20/30 and Atlanta Blasting sand. Staheli (2006) developed interface friction for a wide range of granular soil based on experiments performed by Iscimen (2004), as shown in Table 2.7:

Table 2.7. Pipe-soil interface friction coefficients for different pipe materials (Staheli, 2006)

Soil at interface	Interface friction coefficient between soil and pipe					
Residual friction angles	Hobas	Polycrete	Permalok Steel	Wet Cast Concrete	Verified Clay Pipe	Packerhead Concrete
25	0.37	0.40	0.38	0.43	0.42	0.49
26	0.39	0.41	0.40	0.45	0.44	0.50
27	0.41	0.42	0.42	0.47	0.46	0.52
27.9 Ottawa 20/30	0.43	0.43	0.44	0.48	0.48	0.53
28	0.43	0.43	0.44	0.48	0.48	0.53
29	0.45	0.44	0.46	0.50	0.50	0.55
30	0.47	0.45	0.48	0.51	0.52	0.56
31	0.49	0.46	0.51	0.53	0.54	0.57
32	0.51	0.47	0.53	0.55	0.56	0.59

33	0.53	0.48	0.55	0.56	0.58	0.60
34	0.55	0.49	0.57	0.58	0.60	0.61
34.6 Atlanta Blasting	0.56	0.49	0.58	0.59	0.61	0.62
35	0.57	0.49	0.59	0.60	0.62	0.63
36	0.59	0.50	0.61	0.61	0.64	0.64
37	0.61	0.51	0.63	0.63	0.66	0.65
38	0.62	0.52	0.65	0.65	0.68	0.67
39	0.64	0.53	0.67	0.66	0.70	0.68
40	0.66	0.54	0.69	0.68	0.72	0.69

The next influential factor on the frictional resistance is the normal stress acting on the pipe. Earth load pressure is transferred to the pipe by the deformation of the soil around the borehole. This deformation results in a cavity filled with sloughing soil above the borehole. The sloughing process continues until equilibrium is reached and the sloughed soil is stiff enough to resist further sloughing. This bulking state results in reducing the earth load applied to the pipe. Hence, prism load is not applicable anymore. This phenomenon is called arching (ASTM, 2012). Different calculation methods have been developed for consideration of the arching effect. Table 2.8 shows different methods of calculation of the vertical and horizontal stress on the crown of the pipe.

Table 2.8. Summary of the calculations for normal stress on the pipe

Author	Vertical stress on the crown of the pipe (σ_v)	Horizontal stress at the level of the pipe crown(σ_H)	Symbols
Terzaghi (1943)	$\sigma_V = B_1 \frac{\gamma - \frac{c}{B_1}}{K.tan\varphi}\left(1 - e^{-K.tan\varphi \frac{h}{B_1}}\right)$ where $B_1 = \left[\frac{D_a}{2} + H.\tan\left(\frac{\pi}{4} - \frac{\emptyset}{2}\right)\right]$		K = earth pressure coefficient = 1 r = Pipe radius [m] Υ' = soil average effective unit weight [kN / m^3] H=Height of tunnel
Pipe Jacking Association (PJA) (Craig, 1982)	$\sigma_v = \frac{\gamma.B}{K.tan\varphi}\left(1 - e^{-K.tan\emptyset.\frac{H}{B}}\right)$	$\sigma_h = k(\sigma_V + 0.5\gamma D_a)$	K = earth pressure coefficient ($K = \frac{(1-\sin\emptyset)}{(1+\sin\emptyset)}$) B = silo width ($B = \frac{D_a}{2}\tan\left(45° - \frac{\emptyset}{2}\right) + \frac{D_a}{2\sin\left(45°+\frac{\emptyset}{2}\right)}$)
ASCE-27 (2000)	$W_e = [VAF]\gamma \frac{B_{Th} * h}{12}$ where $[VAF] = \frac{1 - 2.718^{-\alpha}}{12}$ $\alpha = 24K'_{\mu}\frac{h}{B_{Th}}$ For cohesive soils `$[VAF_R] = (1 - \frac{24 * c}{\gamma * B_{th}})$[VAF]	$P_{eh} = [HAF]\gamma\frac{B_{Th} * h}{12}$ Where $[HAF] = K_2[VAF]$ For cohesive Soils $[HAF] = K_2[VAF_R]$	B_{Th} = maximum span of tunnel bore for jacked pipe [inch] see Table 2.9 for K_2 Soil type — K'_{μ} Granular (no cohesion) 0.192 Sand and Gravel 0.165 Saturated top soil 0.15 Ordinary clay 0.13 Saturated clay 0.11

ATV A 161 (GAA, 1990)	$P_{EV} = b\frac{(\gamma - \frac{2c}{b})}{2K_1 \tan\delta} \times \left(1 - e^{-2Ktan\delta\frac{h}{b}}\right)$	$P_{Eh} = \left(P_{Ev} + \frac{D_a}{2} \times \gamma\right) \times K_2$	K_1 = coefficient of horizontal soil pressure above at silo wall = 0.5 b = ideal silo width ($b = \sqrt{3} \times D_a$) [m] δ = one half angle of wall friction in plane of shear ($\delta = \emptyset'/2$) [°] $0.3 < K_2 < 0.5$

Table 2.9. Ratio of lateral force to vertical load and bottom bedding angle for common jacked pipe installation conditions (ASCE, 2000)

Installation	**Ratio of lateral force to vertical load K_2**	**Bedding angle, β (°)**
Without grout, bentonite or other lubricant	0.25	45
Without grout with annular space filled with bentonite or other lubricant.	0.33	75
With annular space filled with grout	0.5	120

Different methods to calculate frictional resistance can be developed by product of the normal stress on the pipe and the proper coefficient of friction based on the pipe's type and surrounding soil. The total maximum jacking force during a project can be determined by summing the calculated frictional resistance with face resistance estimated through various recommended methods.

2.1.3. Jacking force predictive models

In this section, different jacking force predictive models for both microtunneling and pipe jacking methods are discussed. As mentioned previously, Weber (1981) proposed two formulas to calculate the cutting edge resistance for microtunneling projects in two states: when the boring head is located behind and ahead of the cutting edge. For calculation of the frictional resistance, Weber (1981) proposed the following equation:

$$\boldsymbol{F_r = \mu\ \sqrt{p_v p_h}.A_p L} \qquad (2.8)$$

Weber (1981) suggested 0.49 for μ, p_v and p_h as the vertical and horizontal earth pressures [kPa] and A_p as the pipe circumference [m]. By summing the face and frictional components, the total jacking force can then be calculated.

Bennett (1998) developed a model for prediction of frictional resistance in both cohesive and granular soils. He assumed the normal force on the pipe is independent of the depth of installation, but rather it varies with as the soil's unit weight and pipe diameter differs. He also proposed an arching and friction reduction factor for different types of soil. Bennett's (1998) predictive model for frictional resistance is shown below:

$$\boldsymbol{F_r = C_a \gamma D_a\, tan(C_f \phi_r) A_p L} \qquad (2.9)$$

where C_a is the arching factor and C_f is the friction reduction factor. By reviewing the case histories in his research, he concluded that C_a varies between $\frac{1}{3}$ and 3, with most cases ranging between ½ and $1\frac{1}{2}$. As shown in Table 2.10, he suggested an upper, perfect, and lower bound for estimation of normal stress on the pipe. The upper bound should be used for design as it provides a conservative but reasonable estimation. The best fit is what is expected to act on the pipe in the field. The lower bound can be used to evaluate the applicability of contractor claims by the owner. Bennett's suggested values for C_f are mentioned in Table 2.11.

Table 2.10. Values of arching factor (C_a) (Bennett, 1998)

Soil type		Non-lubricated interval	Lubricated interval
Sands	Upper Bound	1.5	1
	Best Fit	1	0.66
	Lower Bound	0.75	0.5
Stiff to hard clay	Upper Bound	1	0.66
	Best Fit	0.66	0.5
	Lower Bound	0.33	0.5
Soft to medium clay	Upper Bound	1	3
	Best Fit	0.66	1.5
	Lower Bound	0.5	1

Table 2.11. Values of friction reduction factor (C_f) (Bennett, 1998)

Ground condition	Un-lubricated		Lubricated	
	Range	Median	Range	Median
Sand	1	1	0.5 to 1	0.66
Stiff to hard clay	1	1	0.5 to 0.66	0.5
Soft to medium silt and clay	1	1	0.5 to 1	0.75

Chapman and Ichioka (1999) studied data from 398 microtunneling projects to provide a jacking force predictive model. They suggested three models for slurry shield machines, auger machines, and push-in machines. For slurry machines, 236 projects were studied, but a total of 47 projects were removed due to abnormalities. The required jacking force for all three types of machines can be calculated as follows:

$$F = (D_0)^2 \frac{\pi}{4} P_0 + \pi D_a R L \qquad (2.10)$$

where F is the total jacking [kN], R is the frictional resistance along the pipe run [kN/m^2], D_0 is the outer diameter of the excavation [m], and P_0 is the face resistance (kN/m^2). For 60 percent of coverage with slurry machines, P_0 is equal to 500 kN/m^2 (50T/m^2), and for 90 percent of data coverage, P_0 is considered 900 kN/m^2 (90T/m^2). Chapman and Ichioka (1999) suggested R [kN/m^2] as follows for slurry machines:

$$\boldsymbol{R = a + 3.77D} \qquad (2.11)$$

in clay soil a = 1.524 , in sand a = 2.421, and for sand and gravel a = 3.418.

For auger machines, Chapman and Ichioka (1999) initially considered data from 113 projects, but 44 projects were removed due to abnormalities. For 80 percent coverage of data with auger machines, operations in clay soil equate P_0 = 500 kN/m^2 (50T/m^2) and P =7 kN/m^2 (0.70 T/m^2); in sand, sand, and gravel, P_0 = 700 kN/m^2 (70T/m^2) and P = 7.5 kN/m^2 (0.75 T/m^2).

Chapman and Ichioka (1999) studied 49 push-in machines projects, which is equivalent to PTMT or pilot pipe jacking technologies. They recommended P_0 = 2000 kN/m^2 (200 T/m^2) for 90 percent of coverage and P_0 = 4000 kN/m^2 (400 T/m^2) in pipe installation, For pipes with a diameter of ($0.1 < D_a < 0.25$) in clay soils, R = - 22.9D + 16.9, and for in sandy soils, R = - 24.9D + 18.9.

ASCE-27 (2000) is a standard practice for direct design of precast concrete pipe for jacking in trenchless construction. This standard is applicable to precast concrete pipe with circular shape used for conveyance of sewage, industrial waste, storm water, and drainage. ASCE-27 provides typical frictional resistance for different ground conditions, as shown in Table 2.12. ASCE-27 does not suggest any value for face resistance.

Table 2.12. Frictional resistance for different ground conditions (ASCE, 2000)

Ground condition	Resistance, psi of surface area	Resistance, kPa of surface area
Rock	0.3-0.4	2-3
Boulder clay	0.7-2.6	5-18
Firm clay	0.7-2.9	5-20
Wet clay	1.4-2.2	10-15
Silt	0.7-2.9	5-20
Dry loose sand	3.6-6.5	25-45
Fill	Up to 6.5	Up to 45

For prediction of jacking force in microtunneling in granular soils, Kimberlie Staheli (2006) developed a formula based on an interface friction approach. She stated that the frictional component of the jacking force in microtunneling follows this formula (Staheli, 2006):

$$\boldsymbol{F_r = \mu \times \frac{\gamma\, r \cos\left(45+\frac{\emptyset}{2}\right)}{\tan \emptyset_r}} \qquad \textbf{(2.12)}$$

where μ can be derived from Table 2.7. Staheli derived this formula from the Terzaghi (1943) equation for situations when the depth of installation is sufficient for the complete occurrence of the arching effect.

3. Chapter 3: Field Assessment of Pipeline Installation Using the Eliminator: A New Guided Boring Machine[1]

3.1. Introduction

In the past 40 years, techniques available to install, maintain, repair, and renew underground utility systems have changed drastically (Lueke & Ariaratnam, 2001; Sterling, 2010). An increasing number of metropolitan public works departments are realizing that trenchless technologies can reduce both tangible and intangible costs of construction in comparison to open-cut methods (Ariaratnam et al., 2006, 2013; Bruce, 2004; Jung & Sinha, 2007; Matthews & Monsalve, 2012). Pilot Tube Microtunneling (PTMT) originated more than two decades ago in Europe for trenchless installation of 10.2 and 15.2 cm (4 and 6 inch) house connections (Bruce, 2004; Haslinger et al., 2007). PTMT has become increasingly popular worldwide for a variety of reasons. Firstly, PTMT is as accurate as conventional microtunneling; however it has significantly lower equipment costs (Haslinger et al., 2007). Secondly, PTMT requires smaller shafts, which decreases the project's footprint. Thirdly, it is safer for crews than conventional open cut or hand-tunneling methods, and the environmental impacts are lower (Sewing et al., 2009). Lastly, PTMT provides societal benefits such as the reduction of traffic delays, road closures, and citizen complaints (Haslinger et al., 2007). Effective use of PTMT necessitates in-depth understanding of factors affecting pipeline installation productivity (Tang et al., 2013). Detailed construction productivity data facilitates the control of the construction process to achieve ideal productivity (Ali et al., 2007; Tang et al., 2013).

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[1] A version of this chapter has been submitted to Canadian Journal of Civil Engineering, Authors: Mahmood Ranjbar, Yaolin Yi, Leon Gay, and Alireza Bayat

The PTMT installation process (Figure 3.1) generally consists of three stages (Lueke et al., 2012; Olson & Lueke, 2013): pilot tube installation, reaming and auger casing installation, and product pipe installation. In the first stage, the desired line and grade is determined by the installation of the pilot tubes. In the second stage, the borehole diameter increases from the pilot tubes' diameter, usually 10.2 cm (4 inch), to the casings' diameter, between 30.5 to 40.6 cm (12 to 16 inch). During this stage, auger casings are pushed through the soil and replaced with the installed pilot tubes. To perform the replacement, a reaming head or a cutter head is attached to the last pilot tube to increase the borehole diameter to be slightly larger than that of the auger casing. At the end of this stage, all pilot tubes are removed from the reception shaft and a stem of augers is installed between the reception and launch shafts. In the third stage, the installed auger casings are replaced with the final product pipes. The final auger casing is attached to the first pipe section using an adapter. In case the diameter of the product pipe is larger than the installed casing, a Powered Reaming Head (PRH) or a Powered Cutter Head (PCH) is used to increase the borehole's diameter. The PRH's rear end is attached to the lead end of the first pipe, while the PRH's front end is attached to the final auger casing. Typically, a PRH is used for pipe diameters ranging 40.6 to 50.8 cm (16 to 20 inch) and a PCH is used for diameters ranging 50.8 to 111.8 cm (20 to 44 inch). When a PRH or PCH is used, the spoils are removed from the reception shaft.

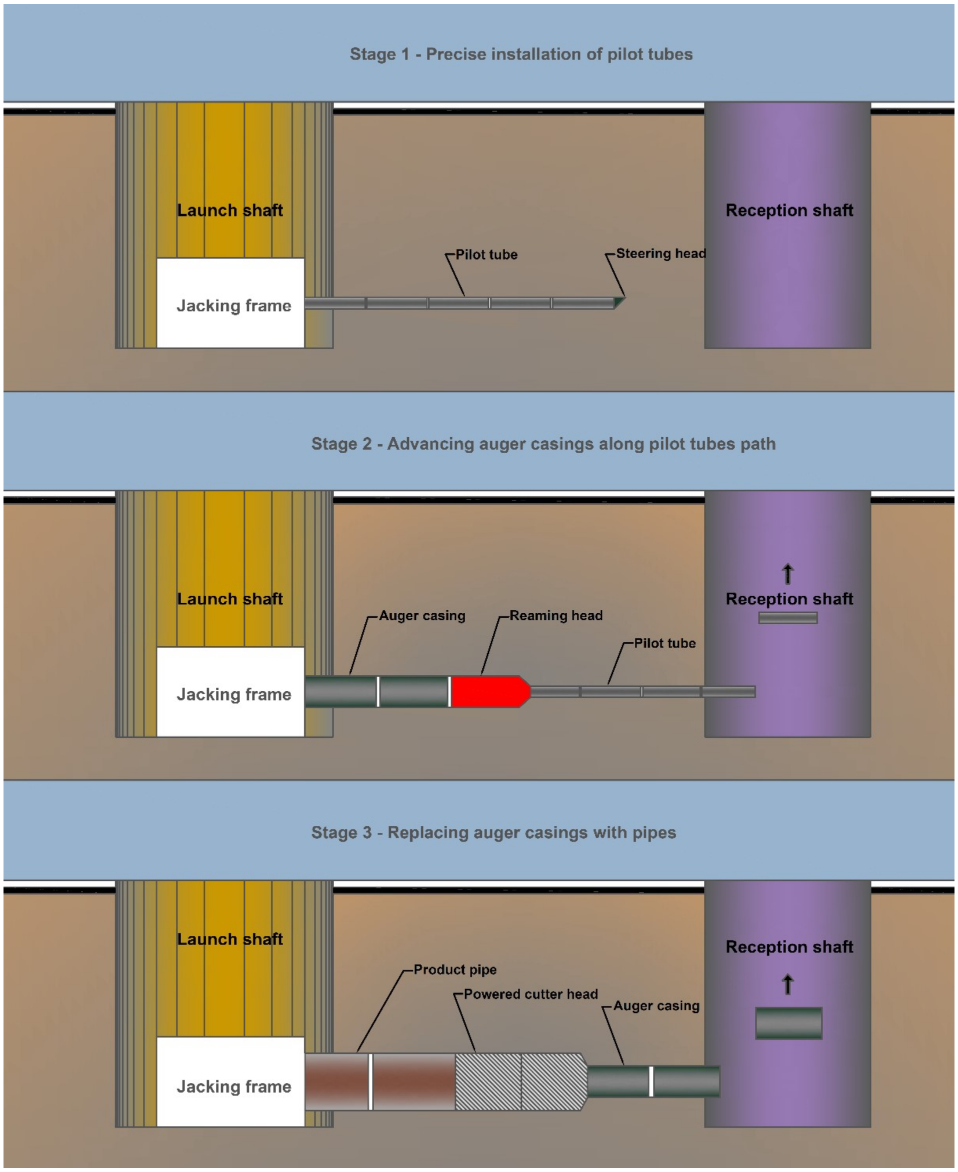


Figure 3.1. PTMT installation process

PTMT was originally used for pipes with diameters between 10.2 to 30.5 cm (4 to 12 inch), performing maximum drive lengths up to 75 m (250 feet) (Boschert, 2007). Nowadays, PTMT can be used to install pipe with diameters between 10.2 and 121.9 cm (4 and 48 inch) at lengths of up to 175 m (575 feet) in a single drive (Lueke et al., 2012). Line and grade accuracy of 6.4 mm (0.25 inch) is also possible for 90 m (300ft) drives using PTMT (Lueke et al., 2012). Nevertheless, PTMT is still limited to installations of specialty sectional jacking pipe material

(Ariaratnam et al., 2014) and is applicable only in displaceable soils with Standard Penetration Test (SPT) values lower than 50 (Gill, 2010).

3.2. The Eliminator

The Eliminator is a new guided boring machine (Figure 3.2) developed to address the market need for PTMT in non-displaceable soils. It works as a cutter head installed at the front of the auger casings providing the desired line and grade. Since the Eliminator has steering capabilities, it eliminates the need for the installation of pilot tubes in developing the desired line and grade. The Eliminator is equipped with a jetting nozzle (Figure 3.2) at the face to ease the excavation process and facilitate soil removal. In addition, this machine has a lubrication nozzle at its rear end to decrease friction between the casings and soil. The eliminator has an overcut of 3.8cm (1.5 inch) to minimize the required jacking force. The length of the Eliminator's is 124.5cm (49 inch), and its weight is 680 kg (1500 pound).

The Eliminator

The steering shoe located on the top of the Eliminator

Jetting nozzle at the face

Figure 3.2. The Eliminator

The installation process using the Eliminator includes two stages (Figure 3.3): auger casing installation and pipe installation. In the first stage, the Eliminator is attached to the front of an auger casing as a lead tool to make a 40.6-cm (16-inch) diameter borehole along the desired line and grade. The Eliminator advances with a combination of rotation and thrust provided by the jacking frame and transferred via the auger casings. Since the soil can be cut and removed (not displaced), the Eliminator is applicable in non-displaceable ground with SPT values above 50. Spoils are moved by the auger casings to the launch shaft and removed via a bucket. The first stage is completed when the Eliminator is removed from the reception shaft, and the auger casings are installed on the desired alignment. The second stage, installation of the pipe, is the same as that of the conventional PTMT method.

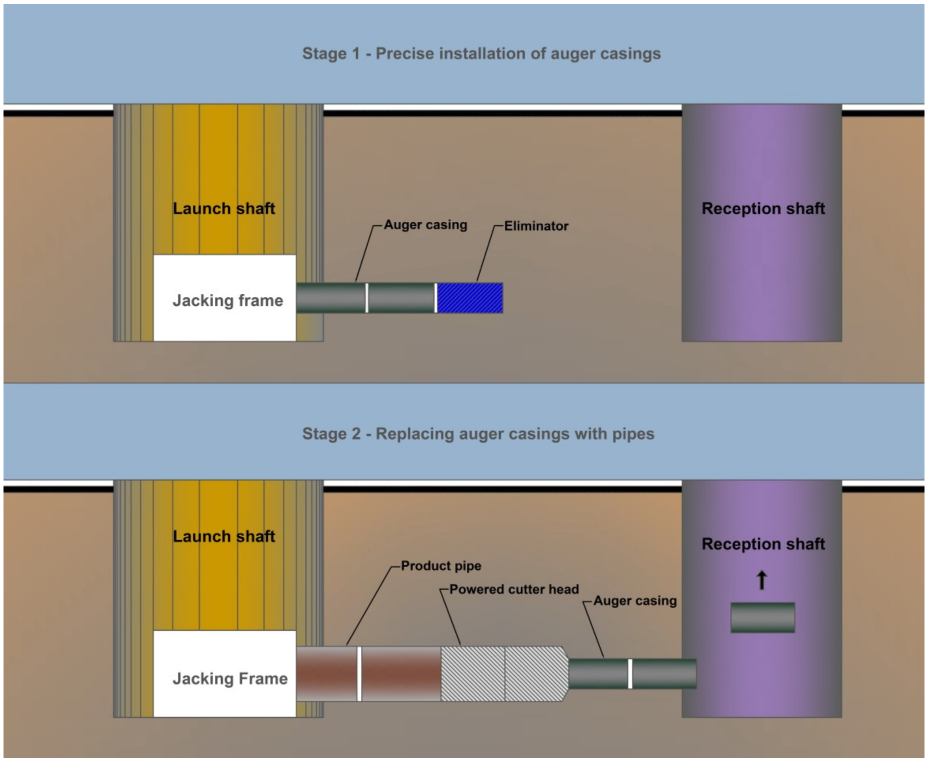


Figure 3.3. The Eliminator installation process

In conventional PTMT, the desired line and grade is provided by rotation of a slanted-face steering head on the front end of the pilot tubes (i.e., the pilot tubes advance displacing the soil, not excavating it). Additionally, there is a battery-powered, LED-illuminated target inside the steering head. Before beginning pilot tube installation, a camera mounted on the top of a theodolite is oriented in the jacking shaft to develop the desired line and grade. Using this camera, the illuminated target can be seen through the hollow stem of the pilot tubes. The target is displayed on a monitor in the jacking shaft and shows the head position and its steering direction (Gottipati, 2011). The Eliminator's guidance system is similar to that of the conventional PTMT method: there is an illuminated target inside the cutter head which can be seen through the string of hollow stem augers. As in conventional PTMT, the target is viewed by a camera mounted on a theodolite. The Eliminator uses three independent controllers (steering shoes) to steer, which are located on the top and lower ends of the Eliminator, as shown in Figure 3.2.

The Eliminator was developed by Akkerman Inc. in 2012, and only a few projects have been performed with the machine to date. The Eliminator was firstly used in a sewer line installation project in Edmonton, Alberta, Canada. In this paper, the use of the Eliminator for this project is introduced; a productivity analysis is performed to compare the Eliminator with the conventional PTMT method, and risk events associated with this new technology are also discussed.

3.3. Sewer line installation using the Eliminator

The project was located in a residential area around the intersection of 66th Street and 165th Avenue in Edmonton, Alberta, Canada. This sewer line project, performed by the City of Edmonton, installed Vitrified Clay Pipe (VCP) with an Internal Diameter (ID) of 68.6 cm (27 inch). Four sections of the project sewer line were installed using the Eliminator. Data was collected from two of those four sections in the summer and fall of 2013. The length of the first monitored section was 61 m (200 feet), with an installation depth varying between 12.4 to 13.3 m (40 to 43 feet). This section was located above the ground water table. The length of the second section was 48 m (157 feet) with a water table 5 to 6 m (16.4 to 19.7 feet) below the surface. The installation depth for the second section varied between 11.7 to 12.4 (38 to 40 feet). According to the project's geotechnical report, a layer of very stiff to hard green clay with an SPT value of 25 and moisture content of 32.6 percent existed along the sewer line alignment. This layer was located between two layers of hard clay shale bedrocks, which were highly plastic and within close vicinity to the installation alignment. The top bedrock layer had a moisture content of 33 percent, and the lower layer had a moisture content of 23 percent. Although the SPT value of the project's soil was in the range of conventional PTMT application, the Eliminator was chosen due to the hard ground conditions expected near the pipeline alignment.

The Eliminator site setup starts with mobilization and shaft excavation. Two shafts with diameters of 4.5 and 3.2 m (14.8 and 10.6 feet) were drilled as the launch and reception shafts, respectively. The launch shaft was stabilized with rib and lagging, and the reception shaft was stabilized with Corrugated Metal Pipe (CMP). Since the ground water table level in the project's location was high, concrete slabs were poured at the bottom of both shafts. The next step in the process was the setup of the jacking frame and the power pack. An Akkerman P275T power pack was used to provide hydraulic power for the Akkerman 4812A jacking frame in the launch shaft during both auger casing and pipe installation stages. Next, the camera was set along the desired line and grade. Auger casing installation (the first stage, as shown in Figure 3.3) starts after determining the alignment. The LED target was placed inside the cutter head. The battery for the target lasts about 11 days; consequently, the crew has a time limitation for finishing the first stage of installation. After installation of the LED target, the first auger casing was connected to the Eliminator on the ground surface. Then, the eliminator and the first auger casing were lowered into the launch shaft to begin the installation. As mentioned previously, the Eliminator excavates along the desired line and grade while installing the auger casings.

During pipe installation (the second stage, as shown in Figure 3.3) an Akkerman PCH (Figure 3.4) with an outer diameter of 83.8 cm (33 inch) was used to install the final product pipe. An adapter was required to connect a PCH to the final auger casing. The adapter itself was installed similarly to an auger casing, as shown in Figure 3.5. When it was fully pushed into the soil, the PCH was connected to the rear end of the adapter. The PCH had four jetting nozzles on its face to increase cutting performance and facilitate spoils removal. There are also independent ports for pipe lubrication at the rear end of the PCH to decrease the friction between the soil and the outer surface of the pipes.

Figure 3.4. PCH installation

Figure 3.5. PCH adapter installation

For each pipe installed in the launch shaft, one auger casing is removed in the reception shaft. During the second stage of the project, one crew worked in the launch shaft to prepare and install pipe sections, while another worked in the reception shaft to disassemble the removed auger casings. For the installation of the last three pipes, the PCH was removed in the reception shaft. Since the diameter of the opening in the wall of the reception shaft was equal to the casings' diameter, before removing the PCH, the crew had to enlarge the opening by the time it hit the CMP stabilizing the reception shaft walls.

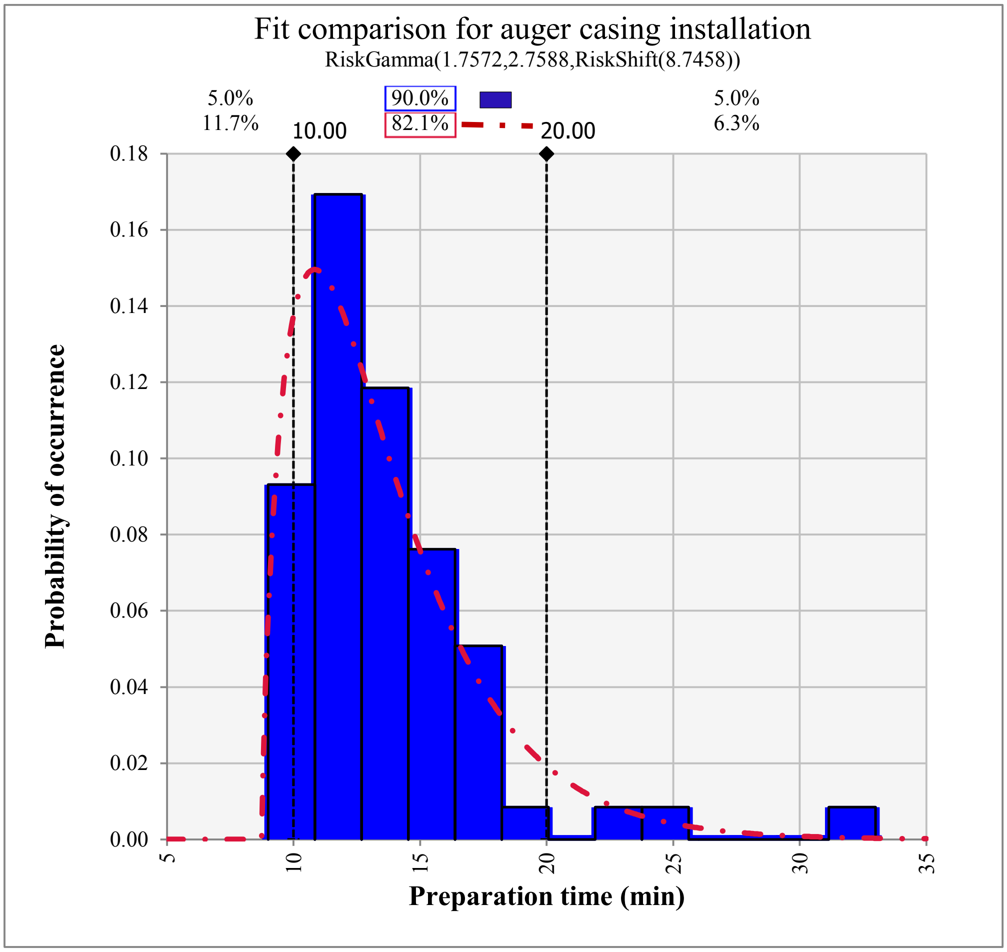
It took 72 days to complete the first section of sewer line installation and 134 days for the second section. Hand tunneling, the most commonly used technique for pipeline installation in Edmonton, was used for the other sections of the project. Compared to hand-tunneling, it was found that the Eliminator provided a variety of advantages for the project, including reduction of heavy trucks in residential areas, societal costs, dewatering requirement, and environmental impacts.

3.4. Productivity analysis

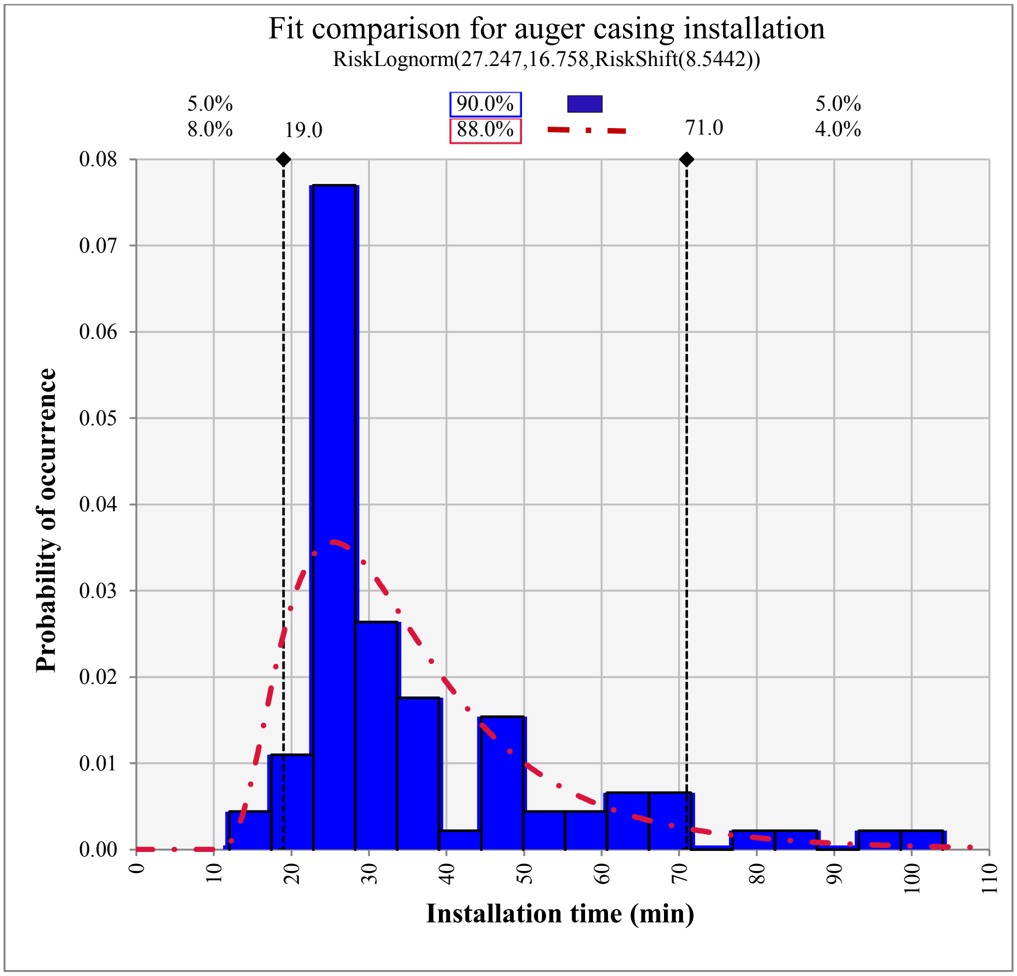
As a new technology, the Eliminator's productivity is of interest to the industry, and the factors and risks affecting productivity need to be evaluated (Ali et al., 2007; Tang et al., 2013). The productivity of the Eliminator was analyzed for four installation steps: auger casing preparation, auger casing installation, pipe preparation, and pipe installation. Auger casing preparation time included removing the launching bucket dirt from the launch shaft, emptying the dirt bucket, returning the dirt bucket, sending a new auger casing down to the launch shaft, and attaching the new auger casing to the previous. The duration of auger casing preparation was kept separate from auger casing installation duration to facilitate the risk analysis. Auger casing installation duration consisted of only the time spent installing an auger casing into the ground. Pipe preparation time included removing and emptying the dirt from the exit shaft, returning the dirt bucket down to the exit shaft, disconnecting and connecting the lubrication hoses, lowering a new pipe section to the launch shaft, and fitting the new pipe section to the previously installed section. Pipe installation time comprised the time required to push a given pipe section into the ground. Since the preparation and installation of auger casings and pipes were both a cyclic process, a cycle time frequency analysis was performed on their durations. Cycle time frequency analyses are useful in monitoring progress, perceiving productivity, and assessing project impacts (Olson & Lueke, 2013). Curve fitting was also performed on the frequency analysis results, which can be used as a beginning point for future projects' scheduling and simulation. The generated information on productivity and risks of using the Eliminator is considered approximate, since there have only been a few projects using this technology thus far.

During the project, hydraulic pressures applied by the power pack were recorded in time series and were used for productivity analysis as suggested by Olson & Lueke (2013). Additionally, field notes were also used in the analysis. The preparation and installation durations for both auger casings and pipes were determined from the recorded data. Durations excessively longer than reasonable values were considered outliers and were not included in the productivity analysis. For auger casing and pipe preparation, durations higher than 60 minutes were disregarded. Auger casing installation durations higher than 120 minutes were also omitted from the analysis. For pipe installation, durations higher than 40 minutes were not considered in the analysis. Curve fitting was provided by @RISK: an "add-in" to Microsoft Excel developed by Palisade Corporation that allows the program risk analysis capabilities. This "add-in" ranks different probability density functions for the sample data based on a goodness-of-fit test. In this analysis, Chi-Square test was selected as the method for fitting different distributions.

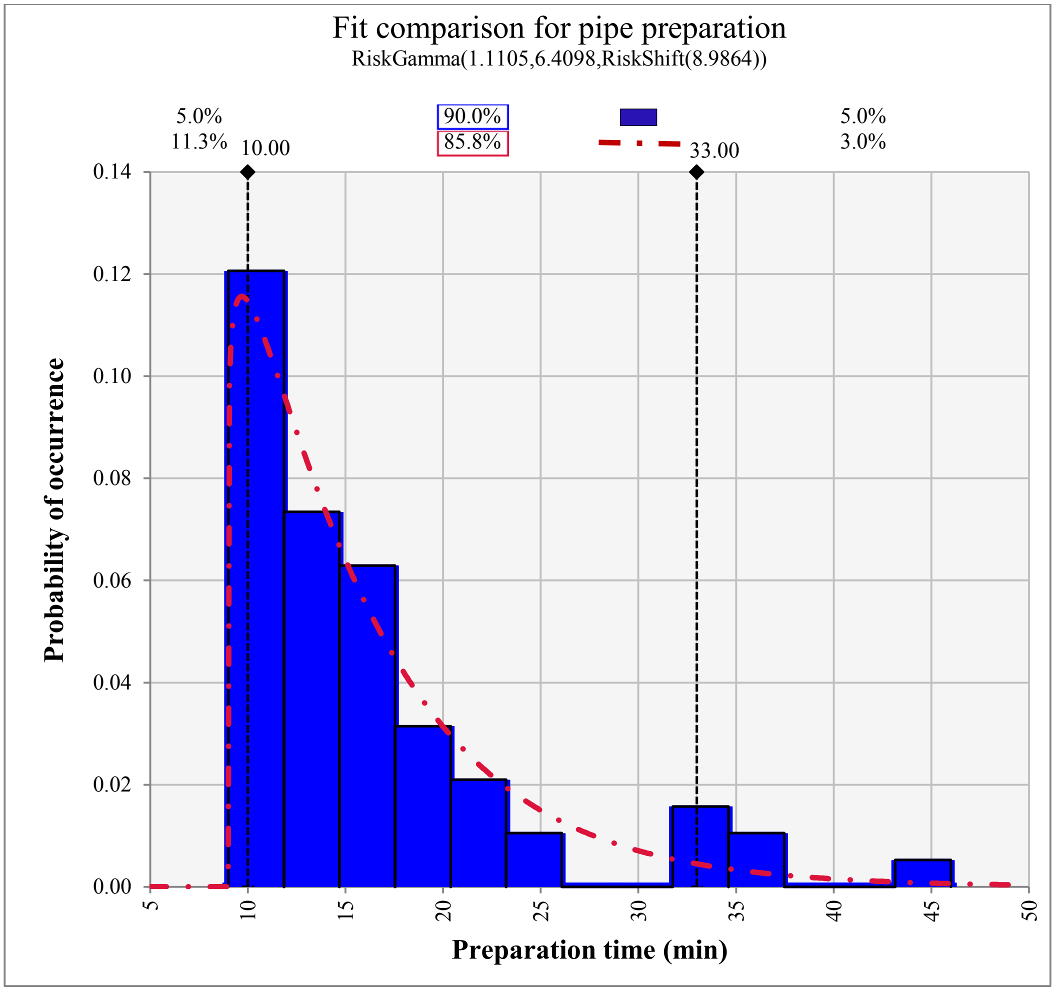
Data from the two monitored sections of the project were considered in the productivity analysis. Figure 3.6 a-d shows the best distributions fitted for the durations of auger casing preparation and installation as well as pipe preparation and installation, respectively. As more data is collected in future projects, expected productivity and risks will be refined.


Fit comparison for auger casing installation
RiskGamma(1.7572,2.7588,RiskShift(8.7458))
5.0%
11.7%
90.0%
82.1%
5.0%
6.3%
10.00
20.00
Probability of occurrence
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
5
10
15
20
25
30
35
Preparation time (min)

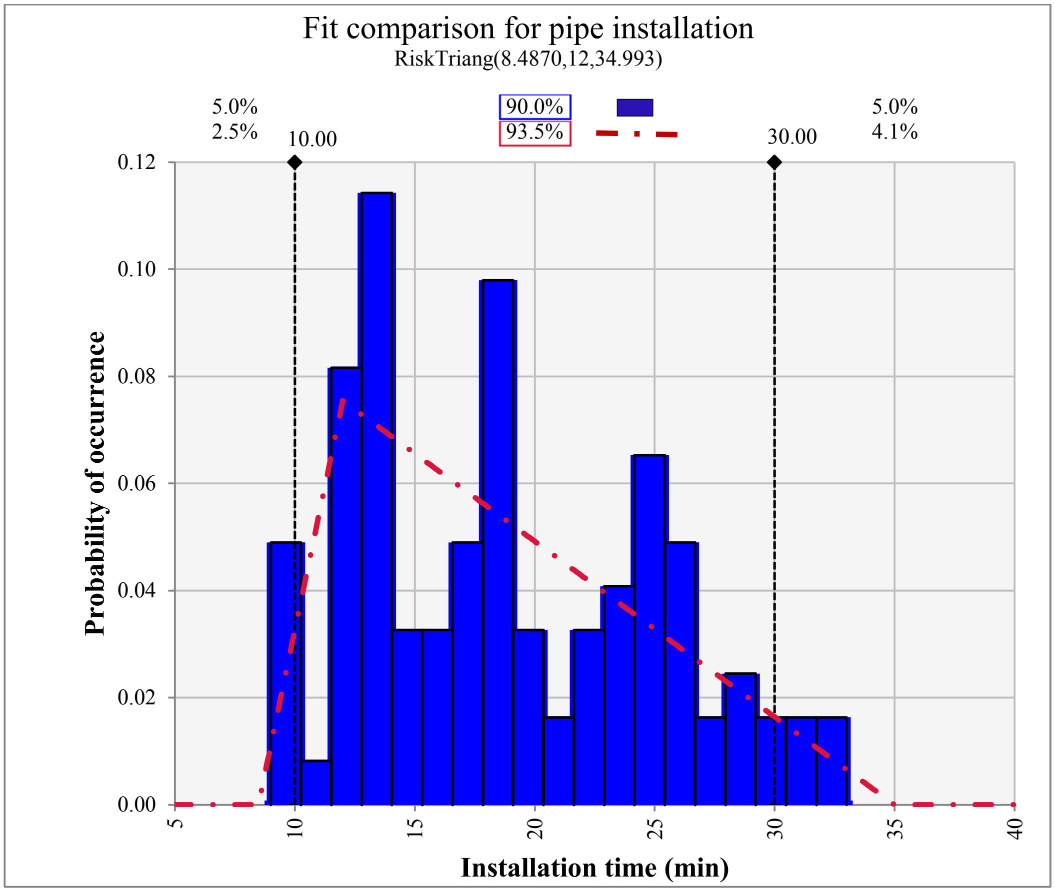
(a)


Fit comparison for auger casing installation
RiskLognorm(27.247,16.758,RiskShift(8.5442))
5.0%
8.0%
19.0
90.0%
88.0%
71.0
5.0%
4.0%
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Probability of occurrence
0
10
20
30
40
50
60
70
80
90
100
110
Installation time (min)

(b)


Fit comparison for pipe preparation
RiskGamma(1.1105,6.4098,RiskShift(8.9864))
5.0%
11.3%
10.00
90.0%
85.8%
33.00
5.0%
3.0%
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Probability of occurrence
5
10
15
20
25
30
35
40
45
50
Preparation time (min)

(c)



(d)

Figure 3.6. Frequency analysis results for: (a) auger casing preparation, (b) auger casing installation, (c) pipe preparation, and (d) pipe installation.

As shown in Figure 3.6 a, the auger casing preparation duration varies typically mainly between 10 to 18 minutes, and only five percent of durations are greater than 20 minutes. The auger casing preparation time depended on the launch shaft depth and the crew productivity in connecting and disconnecting the auger casings. For projects with harsh weather condition that affected the crew's productivity or projects with deeper shafts, higher preparation durations are expected. However, for both monitored sections, similar weather conditions existed and the same launch shaft was used, which led to similar preparation durations.

It can be observed from Figure 3.6 b that the installation duration for auger casings generally lies between 20 to 40 minutes. From field notes, it was also observed that installation durations lasting more than 40 minutes were due to the occurrence of risk events. The most common risk that affected auger casing installation was pilot hole deviation, which occurred when the operator corrected the project's line and grade by pulling back the installed augers. This line and grade correction increased the installation time significantly; however, some alignment correction is expected in all guided boring methods.

As shown in Figure 3.6 c, the pipe preparation duration is generally less than 18 minutes. This time depends on crew productivity in both shafts as well as the depth of the shaft, which were similar for both monitored sections. Long preparation times typically happened during the second section. This can be accredited to seasonal conditions, as the second section was installed during late fall, while the first section was installed in spring; the drop in temperature lead to lower crew productivity onsite.

Figure 3.6 d indicates that the pipe installation duration varies significantly between 10 to 33 minutes. This is due to several factors affecting the jacking force required for pushing the pipe, such as soil conditions, lubrication, and ground water table. The ground water table of the second section was higher than that of the first section, leading to lower jacking requirements and faster pipe installation.

A statistical analysis summary of project activities is shown in Table 3.1. For each activity, the best distribution fit is shown along with the mean times, standard deviation, and minimum and maximum values for the actual observed data and the fitted distribution.

Table 3.1. Statistical analysis results for preparation and installation activities

Activity	Best distribution	Data type	Mean duration (min)	Standard deviation (min)	Min. (min)	Max. (min)
Auger casing preparation	Gamma	Actual	13.6	3.9	9.0	33.0
		Best fit	13.6	3.7	8.7	+∞
Auger casing installation	Lognormal	Actual	36.0	18.2	12.0	104.0
		Best fit	35.8	16.8	8.5	+∞
Pipe preparation	Gamma	Actual	16.1	7.5	9.0	46.0
		Best fit	016.1	6.8	9.0	+∞
Pipe installation	Triangle	Actual	18.9	6.2	9.0	33.0
		Best fit	18.5	5.9	8.5	35.0

Olson (2013) performed a productivity analysis on auger casing installation for four conventional PTMT projects. He observed that auger casing installation and preparation for a 21-inch nominal ID pipe generally took between 25 to 30 minutes, with an average installation time of 34.4 minutes. For the Eliminator, the average total cycle duration is 49.6 minutes, which means the equivalent auger casing installation rate is about 1.2 m/hr. There are a number of reasons for increased installation duration using the Eliminator. First, the Eliminator was used in hard ground conditions (an SPT value of approximately 25 for this project), while Olson (2013) had a SPT value between 4 and 5. Therefore, hard ground conditions slowed the installation process significantly. Gottipati (2011) reported that 72 percent of contractors believed ground condition was a major factor in productivity of PTMT. Second, the Eliminator operator had to steer and correct the line and grade during auger casing installation. In conventional PTMT, line and grade is developed in the first stage via pilot tube installation, and the crew uses the auger casings to increase the borehole diameter and remove the excavated soil only.

Regarding pipe installation during conventional PTMT, Olson (2013) concluded that the average duration was about 7.5 minutes. With the Eliminator, the average installation time was 35 minutes, for an equivalent pipe installation rate of about 1.7 m/hr. The significant difference between these values is also due to a variety of reasons. First, in the project studied by Olson (2013), no excavation was performed during pipe installation as all excavation was performed during the auger casing installation. Conversely, excavation in the Eliminator project was performed by the PCH during pipe installation. Further excavation extended the installation process duration significantly. Second, harder ground conditions at the Eliminator site caused slower installation due to higher jacking forces. Finally, the ID for pipes in the Eliminator's project was 27 inches, which is a 50-percent increase in pipe weight compared to pipe used in Olson (2013). It is also important to consider that projects performed with the Eliminator have two stages, while conventional PTMT projects have three.

Figure 3.7 shows the cumulative installation time for auger casing and pipe installation in both sections of the project. The slope of each curve represents the installation rate. As observed in Figure 3.7, the installation rate was fairly uniform in the first section. The spikes in the auger casing installation curves (primarily section 2) are caused by a risk item and produce an abrupt change in the installation rate. It was expected that the auger casing and pipe installations would have similar slopes in each section, since the installation rate mainly depends on the ground condition and the water table level. Although the installation slopes for pipe and auger casing installation were similar in the first section, the slopes for the second section are different, contrary to expectation. The slopes for the second section are different due to several stoppages that occurred during the auger casing installation and between auger casing and pipe installations. Additionally, a significant amount of water was pumped out of the launch shaft between auger casing and pipe installations, and this affected the ground water level, leading to varying installation rates.

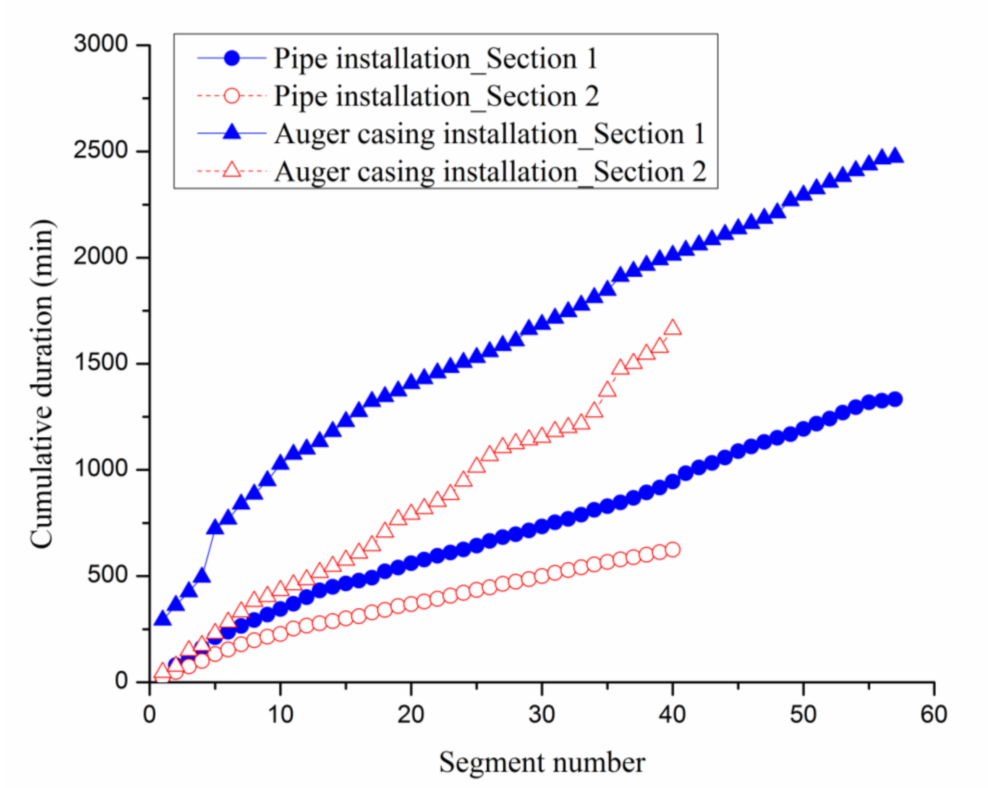


Figure 3.7. Cumulative times for auger casing and pipe installations

3.5. Risk analysis

Quantitatively, risk can be calculated by multiplying the probability of an event by the given damage or consequence (Zio, 2007). Practically, the perception of risk is such that the effect of consequences is greater than its probability of occurrence. Since two sections of installation are not enough for assessing the probability (frequency) of occurrence, the analysis in this paper is focused on the consequences (damage) of risk events on the project's schedule. The first step of this analysis is risk identification. A total of 13 risk items were identified through examining recorded data as well as field notes, as shown in Table 3.2.

Table 3.2. Risk items description

Code	Risk item	Description
R1	Control panel malfunction	The control panel in the shaft had to be restarted at least every 30 seconds, otherwise crews may experience lower steering capability or mechanical problems.
R2	Trouble in PCH connection with the last auger	The previously installed auger connection to PCH is cumbersome. In this project, the crew had to pull out the last installed auger for connection to the PCH.
R3	Wait for the reception shaft during pipe installation	In case the distance between the walls of the shafts is not designed appropriately, the crew could not work simultaneously in both shafts; when a pipe section is fully pushed into the ground in the reception shaft, an auger casing is not fully pushed out of the ground.
R4	Theodolite stand movement	The theodolite stand should not touch the jacking frame or the shaft wall. If this is not addressed sufficiently or the stand is installed on a slab which is shared with the jacking frame, the camera may move or tilt.
R5	Severe weather conditions	Lightning, heavy rain, or very low temperature can cause project interruptions.
R6	Stoppage due to lack of contingency plan	Some stoppages happened during these projects because the onsite crew waited for the contract engineers to make decisions regarding risks.
R7	Pilot hole deviation	When the Eliminator deviated from the desired line and grade, the crew had to pull back all installed auger casings and reinstall them.
R8	Stoppage due to lack of monitoring of pipe sections	Prior to the preparation of pipes for installation, the pipes should be inspected onsite at both ends for any damage incurred during transportation, unloading, and handling (No-Dig install guide). If any flaw is found during installation, the crew must disconnect and remove all hoses from all pipes.
R9	Optical distortions	The further the LED target goes, the smaller it appears on the display. Additionally, when the LED target is far from the launch shaft, reflections of the LED target can be seen in the display; the operator might mistakenly follow the reflection instead of the real signal.
R10	Jacking frame movement	If the jacking frame is not properly fixed, its movement may cause interruptions in pipe installation.

R11	Steering problem due to small auger diameter	Free space between an auger and a casing should be limited (less than 1/8 inch) to help steer by pushing the casings in the desired direction, otherwise steering problems are likely.
R12	Theodolite malfunction	The camera is mounted on a theodolite. If any parts of this theodolite, such as the horizontal movement knob, breaks, stoppage will occur in the project.
R13	Auger drive motor and hydraulic pumps malfunction	Failure in auger drive motor or the hydraulic pumps results in interruption of project operations. This failure occurs when the cutter head becomes stuck in the soil and is unable to rotate.
R14	Laser blocked by auger casings curving down	During auger casing installation, soft soil in the middle of the installation causes casings to curve downwards, and this leads to the loss of the target.
R15	Locating existing utilities	Prior to digging a rescue shaft, the crew had to locate existing utilities to prevent damages and associated repair costs. This process caused stoppage in the project.
R16	PCH adapter failure	An adapter should be used to attach the PCH to the previously installed auger casing. This adapter can break down if it does not bear the forces applied by the jacking frame.

By reviewing the recorded data, daily reports, and field notes, the time at which a stoppage occurred and its duration were calculated. Next, the summation of all risk events' durations was calculated and was subtracted from their total final durations to calculate the ideal construction time. Then the effect of each risk event was calculated in terms of percentage with respect to the project's total duration. Additionally, causes of each risk item were investigated to determine whether the item is preventable and controllable in future projects.

The risk analysis results for the two sections of this project are presented in Tables 3.3 and 3.4, which indicate that 93.4 percent and 65.5 percent of total risk events are preventable for the first and second sections, respectively. Considering both sections together, 72.8 percent of total risk events are preventable. All preventable risk items are due to the crew's lack of experience with the Eliminator; as more projects are completed, these items will become easier to identify and prevent. As shown in Tables 3.3 and 3.4, none of preventable risk items in the first section reoccurred in the second section, except lack of contingency planning. To establish an effective contingency plan, contractors must perform more projects to gain familiarity with the new technology.

Table 3.3. Risk analysis results for the first section

Code	Duration (Hr)	% of Total project duration	Preventable
R1	5	0.9	√
R2	5	0.9	√
R3	2	0.4	√
R4	5	0.9	
R5	5.5	1.0	
R6	5	0.9	√
R7	6	1.1	
R8	2	0.4	√
R9	224	40.3	√
Total	259.5	46.7	

Table 3.4. Risk Analysis results for the second section

Code	Duration (Hr)	% of Total project duration	Preventable
R5	4	0.4	
R6	14	1.4	√
R7	5	0.5	
R10	96	9.4	√
R11	63	6.2	√
R12	3	0.3	
R13	61	6.0	√
R14	248	24.4	√
R15	58	5.7	
R16	184	18.1	
Total	736+	72.4	

In terms of consequences, the most significant risk items in both sections are R9, R10, R14 and R16. R9 is a preventable risk item, which can be avoided by following the target on the display. Additionally, dry nitrogen can be used to solve optical problems arising from the condensation of air inside of the hollow augers. R10 can be avoided by welding vertical beams behind and adjacent to the backstop for stability. Four reinforcements can also welding in each corner of the jacking frame to prevent any rotational movement. The occurrence of R14 is possible in very specific ground conditions, where soft ground exists between two hard sections. This risk item can be avoided by implementing better steering, which results in reducing the need for pulling back installed auger casings and their subsequent re-installation in soft sections. R16 is a type of equipment failure, which is addressed by the manufacturer.

3.6. Conclusion

This paper introduced the Eliminator: a new guided auger boring machine developed to address the market need for PTMT pipe installations in non-displaceable soils. The Eliminator construction process was presented through a sewer line installation project in Edmonton. Compared to hand-tunneling, there were a variety of advantages to using the Eliminator, including reduction in transit of heavy trucks in residential areas, lower societal costs, decrease of dewatering requirements, and reduction of environmental impacts.

A productivity analysis was conducted on the Eliminator's performance in two sections of this project, and the best distribution patterns and statistical durations for the auger casing preparation and installation, as well as pipe preparation and installation were provided. The auger casing and pipe installation rates were approximately 1.2 m/hr and 1.7 m/hr, respectively. These results can be used as an approximation for scheduling future projects using the Eliminator. In the two monitored sections, there were a relatively high number of risk events that considerably delayed project completion for an estimated 46.7 and 72.4 percent in the first and the second sections, respectively. However, 72.8 percent of the total risk was identified as preventable following the risk analysis. The high incidence of risk can primarily be accredited to inexperience with the Eliminator. In order to improve the accuracy of the productivity and to reduce the impact of risk on future Eliminator projects, further project-based investigation is suggested.

4. Chapter 4: Jacking Force Analysis of Pipeline Installation Using the Eliminator[2]

4.1 Introduction

A majority of underground utilities in North America were installed during the 1950s and 1960s postwar construction boom. These systems, constructed in fields and sparsely developed areas, presented few impediments to large-scale open-cut trenching that was standard practice at the time (Mckim, 1997). Although open-cut trenching was traditionally the cheapest method for pipeline installation, the need for utility service line replacement or repairs with minimum surface disruption has increased, promoting the use of trenchless technologies as a consequence (Hegab et al., 2006). Trenchless technology is defined as "techniques for utility line installation, replacement, rehabilitation, renovation, repair, inspection, location and leak detection, with minimum excavation from the ground surface" (NASTT, 2014). An increasing number of metropolitan public works departments are recognizing that the tangible and intangible costs of trenchless construction can be lower in comparison to open-trench construction (Bruce, 2002).

Different trenchless technologies have been developed for various applications such as pipe jacking, microtunneling, and Pilot Tube Microtunneling (PTMT). Pipe jacking uses hydraulic jacks to push pipe sections through the ground while excavation is performed at the shield's face (Rahjoo et al., 2012). The Inner Diameter (ID) of the jacking pipes is usually greater than 1200 mm (Stein, 2005), which limits the application of pipe jacking in projects with smaller-diameter pipes. Microtunneling is a guided pipe-jacking method that does not require

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[2] A version of this paper was submitted to Tunnelling and Underground Space Technology, Authors: Mahmood Ranjbar, Yaolin Yi, and Alireza Bayat

personnel entry into the tunnel (Bennett, 1998). Microtunneling is controlled remotely from an operator's console at the surface, while pipe jacking is typically controlled by an operator inside the pipe (Bennett, 1998). Microtunneling is used for pipe diameters ranging from 300 to 2500 mm (FSTT, 2006). PTMT has evolved as a combination of three existing trenchless technologies, namely microtunneling, horizontal directional drilling, and auger boring (Lueke et al., 2012). The PTMT installation process consists of three stages: 1) pilot tubes installation, 2) reaming and auger casings installation, and 3) product pipe installation. PTMT has been applied successfully in weak soils where other methods, such as open-cut and auger boring, are unsuccessful (Boschert, 2007). The method has been gaining popularity since it was introduced to the United States in 1995 (Haslinger et al., 2007). The primary reason for PTMT's popularity is that installations can be as accurate as conventional microtunneling but have significantly lower equipment costs (Haslinger et al., 2007). Microtunneling's margin of error is 2 cm (0.75 in) per 100 m (330 ft) (Ueki et al., 1999) while PTMT's accuracy is less than 0.6 cm (0.25 in) per 90 m (300 ft). Additionally, a limited footprint, increased worker safety, deep installation potential, and minimal environmental impacts also contribute to the popularity of the PTMT method (Sewing et al., 2009). PTMT is applicable for pipe with Outer Diameters (OD) ranging from 100 to 1100 mm, but can only be used in displaceable soils with Standard Penetration Test (SPT) N-values less than 50 (Gill, 2010) as pilot tube cannot advance through non-displaceable soils.

4.2 Jacking force prediction

Jacking force prediction for pipe installation using the three aforementioned methods plays a critical role in project planning. The required maximum jacking force affects several factors in project design, such as the type of jacking frame, the maximum distance between the launch and reception shafts, and lunch shaft's structural requirements for withstanding the jacking force. Prediction of the jacking force is also important to prevent damage to pipes and joints due to excessive stress concentrations (Chapman and Ichioka, 1999). Jacking force prediction is critical in determining the number of rely stations, especially in long-distance pipe jacking and microtunneling construction (Bai et al., 2013).

The total jacking load should overcome the face resistance (penetration resistance) at the shield and the frictional resistance of the pipes and auger casing string (Marshall, 1998). Depending on the installation technique, three types of penetration resistance are possible: cutting edge resistance, contact pressure, and support force (Stein, 2005). Cutting edge resistance develops due to the creation of shear failure like zones of soil flow at the front of the cutting edge when the excavation tool is jacked through the ground (Stein et al., 1989). Contact pressure force presses the excavation tool in the boring direction, while support force is the force supporting the earth pressure at the face, which is applied with mechanical support, compressed air, fluid support, earth pressure balance, or natural support (Stein, 2005). Frictional resistance results from the skin friction acting on the external surface of the pipe string and the boring head (Marshall, 1998).

For microtunneling projects, several researchers have proposed models to calculate the required jacking force. Weber (1981) proposed formulas to calculate the penetration and frictional resistances for microtunneling and auger boring project. Bennett (1998) assumed the normal force on the pipe was independent of the depth of installation, but varied with soil unit weight and pipe diameter. Accordingly, he proposed an arching and friction reduction factor for different types of soil. Chapman and Ichioka (1999) proposed a probability-based method to predict the jacking force, which stated that the skin friction has little correlation to the OD of the jacking pipe, and suggested constant values for the skin friction. ASCE-27 (2000) is considered standard practice for the design of precast concrete pipe for pipe jacking in trenchless construction projects. This standard suggests typical frictional resistance for different soils. Staheli (2006) developed a model based on an interface friction approach to calculate frictional resistance. For PTMT projects, Olson (2013) studied the applicability of three predictive models, including Staheli (2006), Chapman and Ichioka (1999), and Bennett (1998) in all three steps of installation. He concluded that the models defined by Staheli (2006) and Bennett (1998) are the most appropriate in predicting the jacking force required for installation of 21 in and 8 in Vitrified Clay Pipes (VCP), respectively.

4.3 The Eliminator

The Eliminator is a new guided boring machine developed to address the market need for PTMT in non-displaceable soils. It provides a desired line and grade for pipeline installations, performing as a boring head installed at the front of the auger casings. Since the Eliminator has steering capability, it eliminates the need for the installation of pilot tubes to develop the desired line and grade, which is the reason it is named the "Eliminator". The Eliminator's installation process includes two stages (Figure 4.1): 1) auger casings installation and 2) pipe installation. In the first stage, the Eliminator is attached to the front of an auger casing as a lead tool, and creates a 40.6-cm (16-in) diameter borehole along the desired line and grade. The Eliminator advances by a combination of rotation and thrust provided by the jacking frame and transferred via the auger casings. Since the soil can be cut and removed (not displaced), the Eliminator is applicable to non-displaceable ground with SPT values above 50. The second stage of the process is pipe installation, which is the same as that of conventional PTMT. In case the diameter of the product pipe is larger than the installed casing, a Powered Reaming Head (PRH) or a Powered Cutter Head (PCH) is used to increase the borehole's diameter. The PRH's rear end is attached to the lead end of the first pipe, while the PRH's front end is attached to the last installed auger casing. Typically a PRH is used for pipe diameters ranging 40.6 to 50.8 cm (16 to 20 in), and a PCH is used for pipe diameters ranging from 50.8 to 111.8 cm (20 to 44 in). When a PRH or PCH is used, resultant spoils are removed via the reception shaft.

The Eliminator was developed by Akkerman Inc. in 2012, and only a few projects have been performed with the machine to date. It was used in a sewer line installation project in Edmonton, Alberta, Canada, which was the first pipeline installation project using the Eliminator in the world. Similar to PTMT or microtunneling, jacking prediction is also important for the Eliminator; hence, this paper performs a jacking force analysis using data collected from this project. The applicability of several microtunneling and pipe jacking prediction models for the Eliminator are also studied.

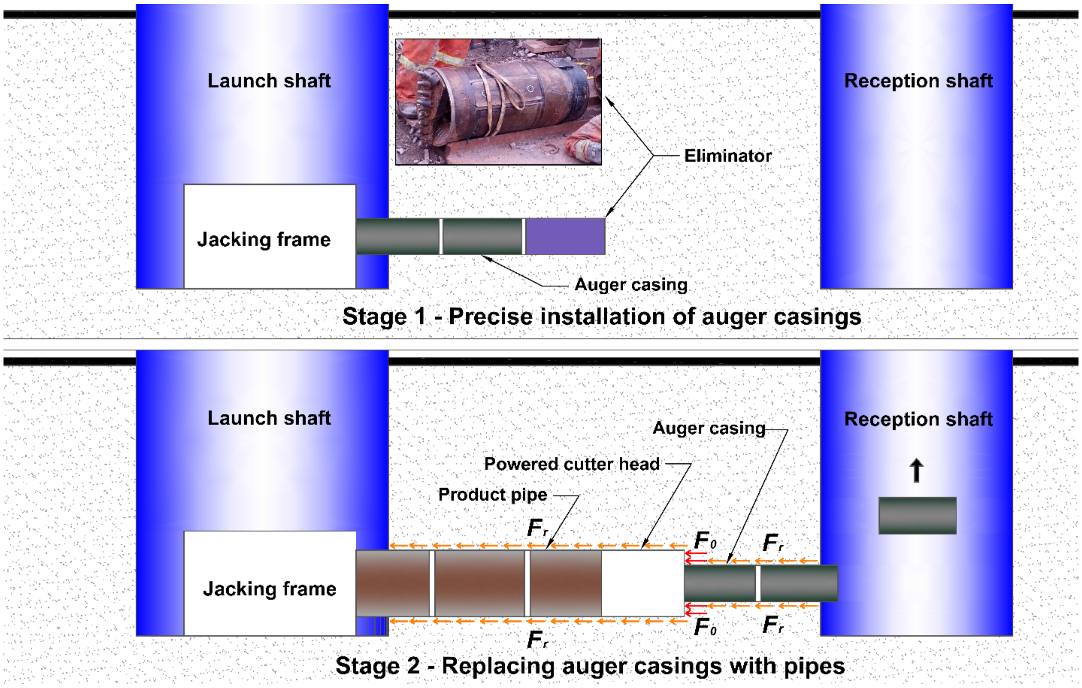


Figure 4.1. The Eliminator installation process

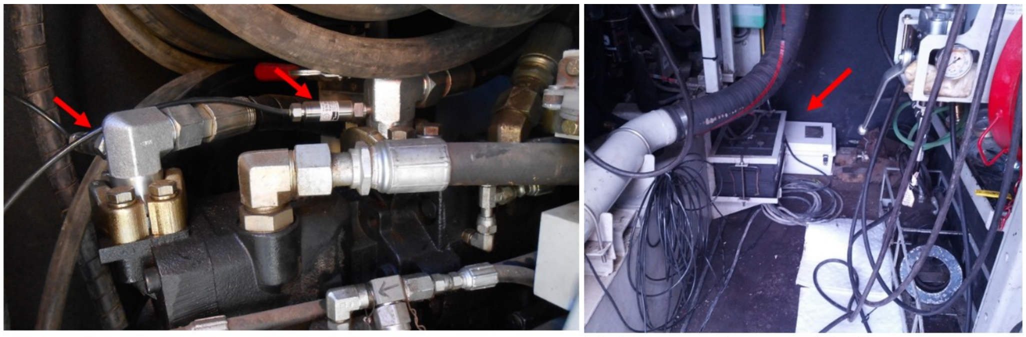
4.4 Field instrumentation and result analysis

4.4.1 Project overview

The project investigated in this paper was located in a residential area around the intersection of 66th Street and 165th Avenue, Edmonton, Alberta, Canada. Performed by the City of Edmonton, the project comprised the installation of VCP with an ID of 68.6 cm (27 in) for a sewer line system. An Akkerman P275T power pack was used to provide hydraulic power to the Akkerman 4812A jacking frame in the launch shaft. The distance between the centers of the shafts was 61 m (200 ft), and the depth of installation varied between 12.4 to 13.3 m (40.6 to 43.6 ft). The Groundwater table level was 5 to 6 m (16.4 to 19.7 ft) below the surface. According to the geotechnical report, a layer of very stiff to hard green clay existed along the sewer line alignment. This clay had a unit weight of 19 kN/m^3 and an effective friction angle of 25^o. The layer was located between two hard clay shale bedrocks, which were in close proximity to the installation alignment. The top bedrock layer had a moisture content of 33 percent, while the lower layer had a moisture content of 23 percent. Although the SPT value of the green clay was in the range of conventional PTMT's application, the Eliminator was chosen for this project due to the hard ground conditions (bedrock) near the pipeline alignment.

4.4.2 Instrumentation

Three hydraulic pressure transducers were installed on the power pack to measure the jacking force and rotational torque applied to the augers as well as the rotational torque applied to the PCH, as shown in Figure 4.2. The capacity of the pressure transducers was 68950 kPa (10000 psi), which is higher than the maximum hydraulic pressure of the power pack [41370 kPa (6000 psi)]. A CR-800 datalogger (Figure 3) from Campbell Scientific Canada, was used to record measurements from the pressure transducers. This datalogger collected data every 80 ms and recorded the maximum, minimum, and average values in 10-second intervals.



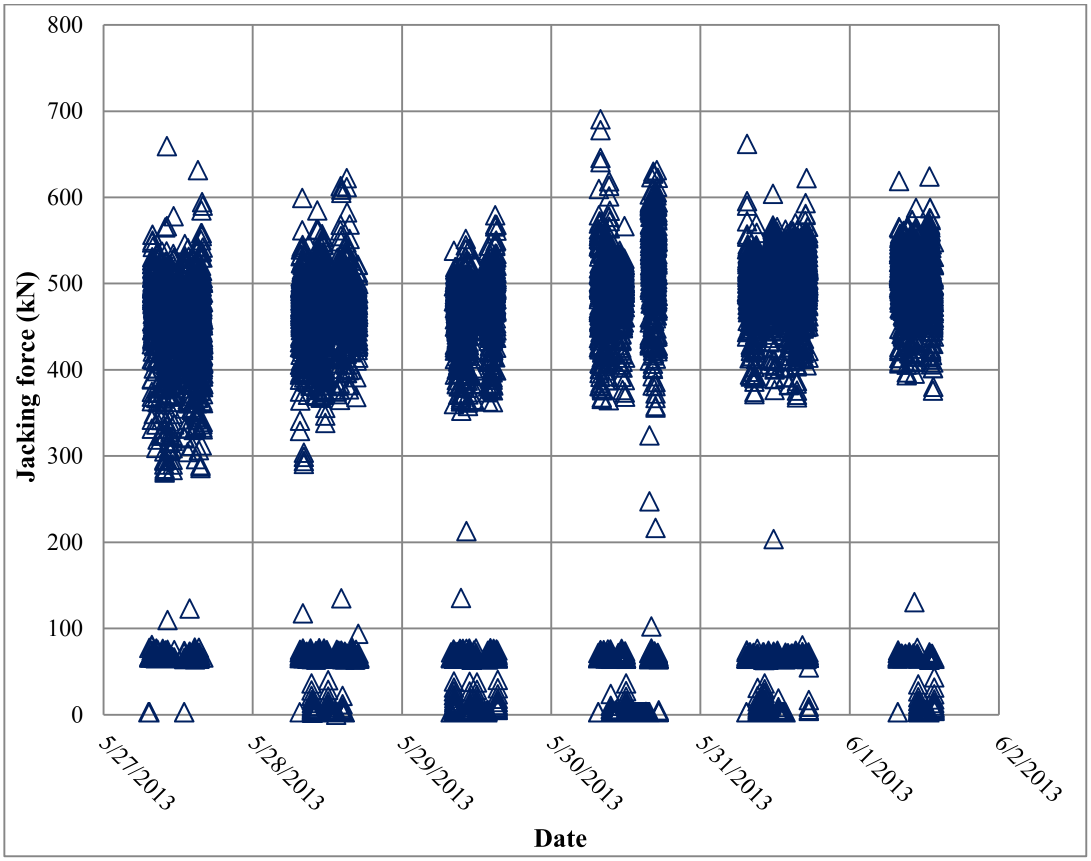
Pressure transducers installed on the power pack

Datalogger placement in the power pack

Figure 4.2 - Power pack instrumentation

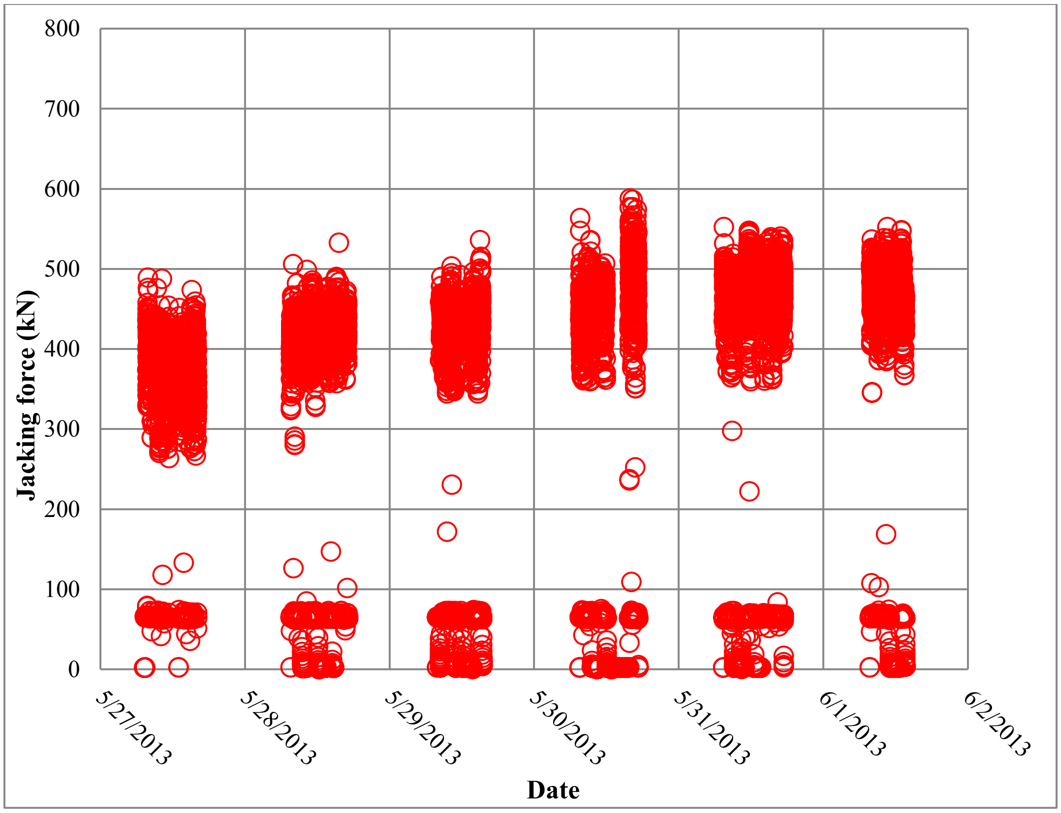
4.4.3 Result analysis

As discussed previously, the datalogger records the minimum, maximum, and average values in 10-second intervals. In jacking force analysis, only the minimum and maximum jacking pressures are used, and the recorded jacking pressures are converted to jacking forces with conversion tables provided in the jacking frame manual. The recorded maximum and minimum jacking forces for the entire second stage of the project (Stage 2 as shown in Figure 1) are shown in Figure 4.3. These results are similar to those obtained by Lueke and Olson (2012) for a conventional PTMT project. The results of the second stage did not produce significant information since the recorded jacking force varies between 0 and 700 kN without any evident trend, except that the plots generally cover two force ranges (i.e. 0-100 kN and 250-700 kN). Therefore, the raw data must be further analyzed and screened to eliminate non-jacking force data, e.g. idle force without installation.



800
700
600
500
400
300
200
100
0
Jacking force (kN)
5/27/2013
5/28/2013
5/29/2013
5/30/2013
5/31/2013
6/1/2013
6/2/2013
Date

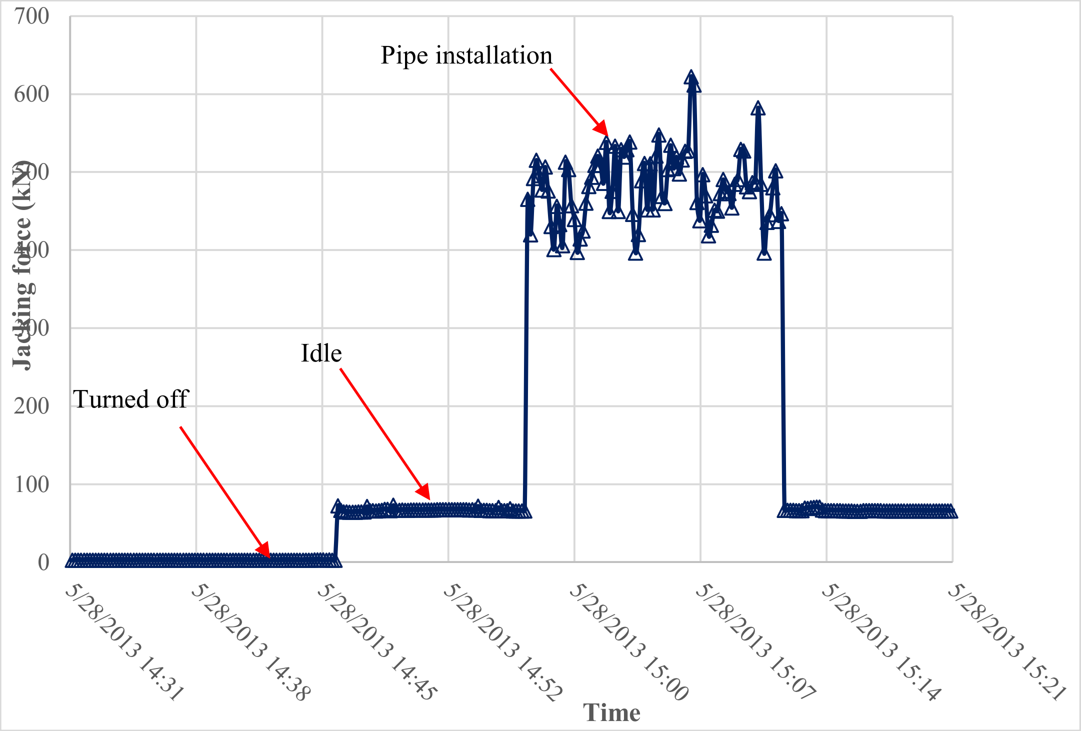
(a)



(b)

Figure 4.3 - Recorded a) maximum b) minimum jacking forces for pipe installation

To further analyze the recorded data, the maximum and minimum jacking forces for each pipe section were plotted against time, as shown in Figure 4.4. Evidently, the jacking force for each section is easily identifiable. The machine was turned off when the recorded jacking pressure was zero. Conversely, when the recorded jacking force was around 65 kN, the machine was turned on; however, the machine was idle, and no installation occurred. The stoppage and idle data is eliminated when analyzing the jacking force by subtracting the idle jacking force from the total jacking force. When a force jump occurs from 65 kN (Figure 4.4), it indicates the start of installation of a pipe section. Small variations exist in the recorded jacking force during the installation of the given pipe section, and the average and standard deviation values are used to represent the applied jacking force for installation of this section.



700
600
500
400
300
200
100
0
Jacking force (kN)
Pipe installation
Idle
Turned off
5/28/2013 14:31
5/28/2013 14:38
5/28/2013 14:45
5/28/2013 14:52
5/28/2013 15:00
5/28/2013 15:07
5/28/2013 15:14
5/28/2013 15:21
Time

(a)

(b)

Figure 4.4 – Recorded a) maximum b) minimum jacking force for a pipe section

Figure 4.5 shows the average and standard deviation of applied jacking force for all of the project's pipe sections. The applied jacking force in this project varies between 300 to 500 kN (30 to 50 tons). The trends for both minimum and maximum applied jacking force are similar; generally, the jacking force increases due to the increase in the frictional component of the total jacking force. However, the force-length curves, as seen in Figure 4.5, have very mild slopes due to the abundant application of lubrication during the project. In some sections, a temporary decrease in the applied jacking force is noticeable; these decreases are attributed to an abrupt change in soil condition. Figure 4.5 also indicates that a very small difference exists between the minimum and maximum recorded forces.

Hence, only the maximum recorded data are used to later validate the jacking force.

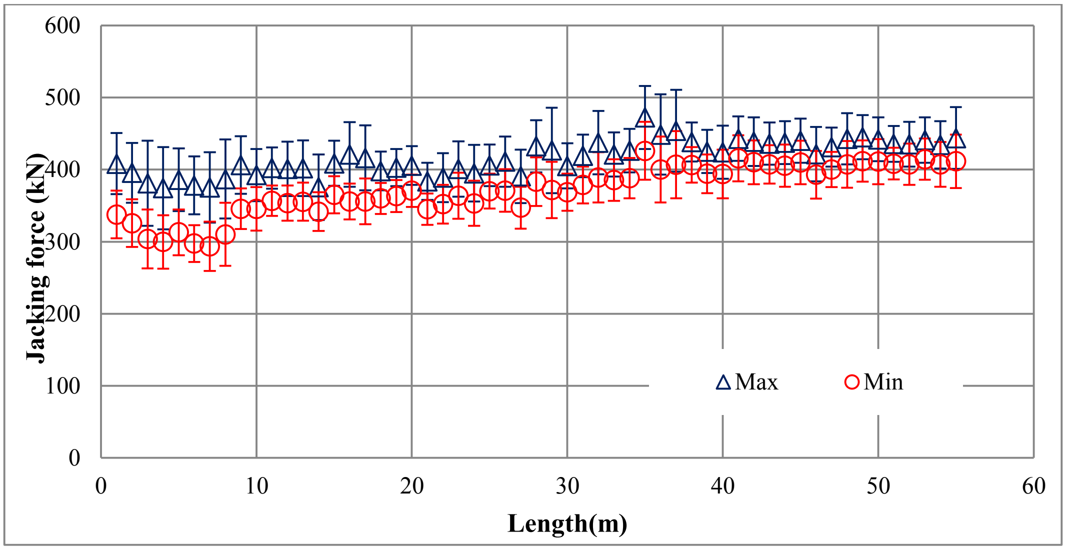


Figure 4.5 - Minimum and maximum recorded jacking force for each pipe segment

4.5 Jacking force prediction for the Eliminator

The jacking force required to install pipe sections is higher than that required to install augers casings; consequently, this study only focuses on the second stage of installation (pipe installation). Similar to microtunneling or PTMT, the total jacking load for the Eliminator is also comprised of two components, face resistance (F_0) and frictional resistance (F_r), as illustrated in Figure 4.1. According to Stein (2005), face resistance consists of cutting edge resistance and contact pressure for mechanical partial excavation shield machines. The mechanical performance of the PCH in the pipe installation stage is similar to the mechanical partial excavation shield machines with a fixed installed excavator; as a result, cutting edge resistance and contact pressure are considered for calculation of face resistance in the second stage of the Eliminator project.

In this section, five predictive models for microtunneling and pipe jacking, including Weber (1981), Bennett (1998), Chapman and Ichioka (1999), ASCE-27 (2000), and Staheli (2006), are used to predict the jacking force for the Eliminator project, the results of which are compared to the project's field measurement.

4.5.1 Weber (1981)

Weber (1981) proposed two formulas to calculate the cutting edge resistance for a microtunneling project in two states: with the boring head located behind and ahead of the cutting edge. As mentioned previously, in the pipe installation stage of Eliminator projects, a PCH (Figure 4.6) is used to increase the borehole's diameter. The boring head of the PCH is located inside the cutting edge, therefore Weber (1981)'s formula in which the boring head is behind the cutting edge applies. Equation (1) shows the cutting edge resistance proposed by Weber for this case.

PCH face **PCH installation in the launch shaft**

Figure 4.6 - PCH

$$\boldsymbol{P_S = \lambda \pi D_a t(c + \gamma h \tan \emptyset)} \tag{4.1}$$

Where P_s is the cutting edge resistance [kPa], γ is the density of the soil [kN/m^3], t is the thickness of the cutting edge [m], and c is the cohesion of the soil [kPa]. For this study, c is assumed to be 0 kPa considering a normally consolidated soil in an un-drained condition. D_a is the external diameter of the PCH, h is the height of cover, φ is the friction angle of the soil, and λ is the carrying capacity coefficient, which is the bearing capacity reduction factor with an increasing trend from approximately 0.05 at $\varphi = 0$ to 0.02 at $\varphi = 25°$, 0.75 at $\varphi = 40°$, and 1 at $\varphi = 42°$ (Bennett, 1998). As mentioned previously, the face resistance includes cutting edge resistance and contact pressure. Since the cutter head pushes soil to the front during installation, calculation of the contact pressure assumes that the passive Rankin pressure is distributed over the face of the PCH. As a result, the contact pressure (P_A) can be calculated with Equation (2).

$$\boldsymbol{P_A = \frac{\pi}{4}\left({D_a}^2 - {D_b}^2\right)p_a} \qquad \textbf{(4.2)}$$

Where D_b is the external diameter of casings [m] and p_a is the supporting pressure [kPa], which is assumed to be the passive Rankin pressure. The face resistance (F_0 [kN]) is the summation of the cutting edge resistance and the contact resistance. For calculation of the frictional resistance, Weber (1981) proposed the following equation:

$$\boldsymbol{F_r = \mu\sqrt{p_v p_h}A_p L} \qquad \textbf{(4.3)}$$

Where F_r is the frictional resistance [kN], μ is coefficient of friction equal to 0.49 as suggested by Weber (1981), p_v and p_h are the vertical and horizontal earth pressures [kPa], A_p is the pipe circumference [m], and L is the installation length [m]. For calculation of the vertical and horizontal earth pressure, ATV A 161 (1990), a German standard for structural calculation of driven pipes, proposed the following formulas (Stein, 2005):

$$\boldsymbol{P_v = b\,\frac{(\gamma - \frac{2c}{b})}{2K\tan\delta} \times \left(1 - e^{-2K tan\delta\frac{h}{b}}\right)} \qquad \textbf{(4.4)}$$

$$\boldsymbol{P_h = \left(P_{Ev} + \frac{D}{2} \times \gamma\right) \times K_2} \qquad \textbf{(4.5)}$$

Where δ is the wall friction angle ($\delta = \varphi'/2$) [°], K is the coefficient of earth pressure at the silo wall (K=0.5), K_2 is the coefficient of horizontal earth pressure at the level of the springing line of the pipe (for cohesive soils K_2 = 0.4), b is the ideal silo width ($b = \sqrt{3} \times D$) [m], and D is the pipe OD [m]. The summary of the project characteristics is shown in Table 4.1. By substituting these values in the aforementioned formulas, the total jacking force is then calculated.

Table 4.1. Project's soil and equipment specifications

D_b (cm)	D_a (cm)	Υ (kN/m^3)	$\emptyset$ (°)	c (kPa)	λ	t (cm)	h (m)
40.6	79.5	19	20	0	0.45	5	12.85

4.5.2 *Bennett (1998)*

Bennett (1998) provided a model for prediction of the frictional component of the total jacking force (F_r [kN]), as shown below:

$$F_r = C_a \gamma D \tan(C_f \emptyset) A_p L \tag{4.6}$$

Where C_a is the arching factor and C_f is the friction reduction factor. Bennett (1998) provided guide values for C_a and C_f in three states: upper bound, best fit, and lower bound. The upper bound can be used for the conservative design of projects, the best fit is appropriate for estimation of the expected values in the field, and the lower bound is useful for evaluation of the contractor's claims. In this paper, C_a and C_f are chosen for the best fit state since different models are compared with the field data. Bennett (1998) did not provide any model for the prediction of face resistance; however, he identified three methods for calculation of the face component in auger machines: Herzog (1985), Scherle (1977), and Weber (1981). For this project, the Weber (1981) formula was used to calculate face resistance.

4.5.3 Chapman and Ichioka (1999)

The following formula is suggested by Chapman and Ichioka (1999) for calculation of the face resistance (F_0):

$$\boldsymbol{F_0 = (D)^2\pi/4P_0} \qquad \textbf{(4.7)}$$

Where P_0 is the face pressure. Chapman and Ichioka (1999) performed a probability-based analysis on data recorded from 113 projects conducted using auger machines and for 80 percent coverage of the data they recommended 500 kN/m^2 (50T/m^2) for P_0 in clay soil. To calculate the frictional resistance, Chapman and Ichioka (1999) suggested 7 kN/m^2 (0.70 T/m^2) for a criterion of 80 percent coverage of the data in clay soil.

4.5.4 ASCE-27 (2000)

For pipeline installed through the pipe jacking method, ASCE-27 (2000) provides typical frictional resistance for different ground conditions. The suggested frictional resistance in firm clay is 5-20 kPa (0.7-2.9 psi). The average value of 12.5 kPa is used for jacking force analysis in this study. ASCE-27 does not suggest any value for face resistance, therefore Weber (1981)'s result is also used here.

4.5.5 Staheli (2006)

Staheli (2006) developed a model for the prediction of frictional resistance based on an interface friction approach. She stated that the frictional component of the jacking force (F_r) can be calculated as follows:

$$\boldsymbol{F_r = \mu \frac{\gamma r \cos\left(45+\frac{\emptyset}{2}\right)}{\tan\emptyset} A_p L} \qquad \textbf{(4.8)}$$

Where r is pipe diameter [m]. Iscimen (2004) measured peak and residual friction coefficients for different pipe materials sheared against Ottawa 20/30 and Atlanta Blasting sand. Staheli (2006) developed interface friction for a wide range of granular soils based on experiments performed by Iscimen (2004). Through extrapolation, the μ is identified as 0.28 for steel casings and 0.32 for VCP pipes with a soil with friction angle of 20°. Staheli (2006) did not provide any specific formula for calculation of the face resistance; consequently, Weber (1981)'s formula is used to calculate the face component, which is then added to the frictional component to calculate the total jacking force. During installation with the PCH, lubrication is applied generously. In such a situation, Staheli (2006) recommends using 10 percent of frictional resistance for non-lubricated drives. Bennett (1998) concluded that lubrication reduced the frictional resistance by 30 to 80 percent, with most calculated reductions ranging between 40 to 75 percent (Bennett, 1998). Likewise, ASCE-27 (2000) stated that lubrication may reduce the jacking force by more than 50 percent. As lubrication was used abundantly during this project, the lubrication effect is considered to reduce the frictional component by 50 percent.

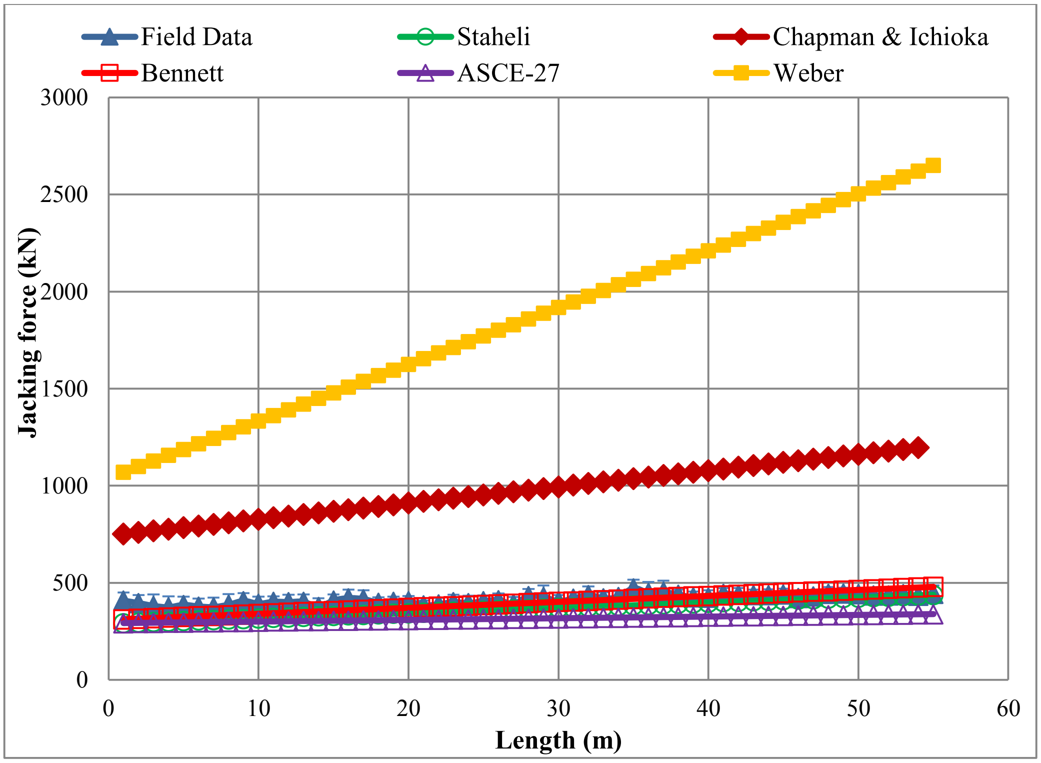


Figure 4.7 - Jacking forces as predicted by different models and measured in the field.

Figure 4.7 shows the jacking force predicted by all aforementioned models and the actual force measured in the field. The y intercept of this graph corresponds to the sum of the face resistance and the frictional resistance required to push the installed auger casings. In microtunneling projects, the jacking force required to overcome the frictional resistance is generally higher than that required to overcome the face resistance as the frictional component is caused by the outer surface of the installed sections, which is substantially larger than the area at the face (Bennett, 1998). However, in PTMT and Eliminator projects, the length of installation is significantly shorter than microtunneling projects, so the face component plays an essential role in the total required jacking force. Another factor which increases the influence of the face component for the project is the Eliminator's intent for projects with hard ground condition. Since the borehole's stability is greater in hard ground conditions, lubrication is applied generously and the frictional component of the total jacking force is consequently reduced.

As shown in Figure 4.7, Weber (1981) and Chapman & Ichioka's (1999) models are the most conservative, significantly over-predicting the project's jacking force. Although the face resistance for Weber (1981), Staheli (2006), Bennett (1998), and ASCE-27 (2000) are the same, the y intercept of Weber (1981)'s model is significantly higher than the others. The y intercept of Chapman & Ichioka (1999)'s model is about two times greater than the field result, also indicating conservativeness. The slopes of the Weber (1981) and Chapman & Ichioka (1999) models are the highest of all models, indicating that they predict greater frictional resistance. Although the process of pipe installation with a PCH is similar to that with auger machines, the Chapman & Ichioka (1999) model overestimated the required jacking force for this project.

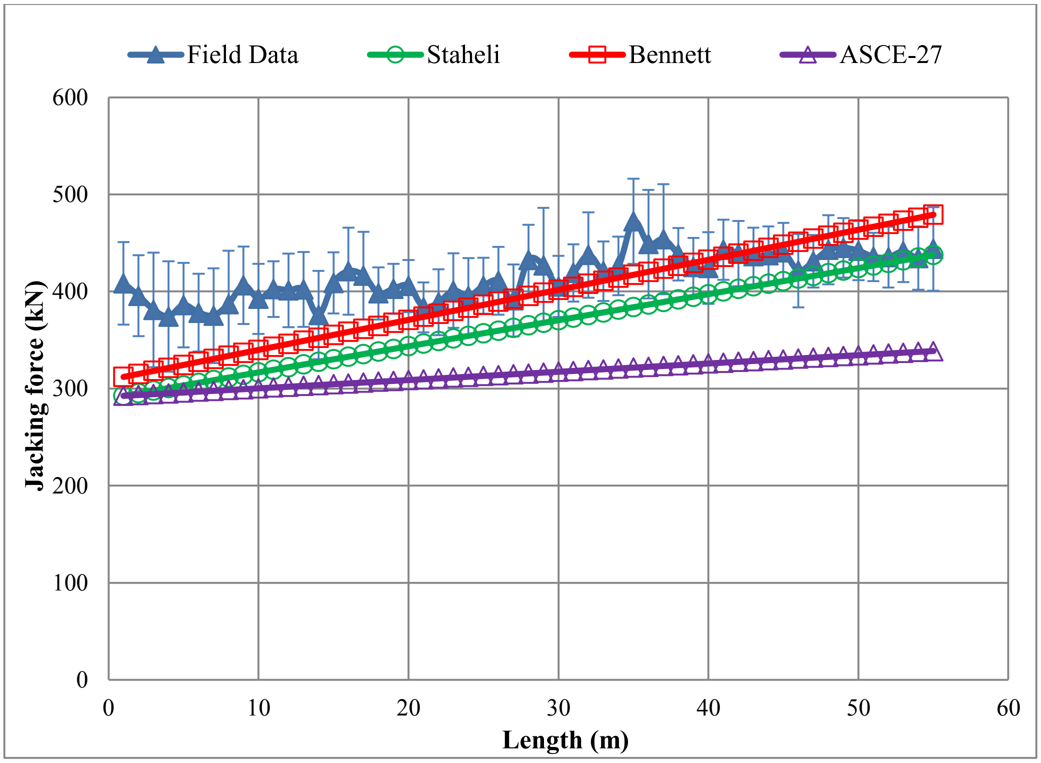


Figure 4.8 - Comparison of field data with jacking force predictive models

Figure 4.8 compares results of the predictive models. As shown in Figure 4.8, the y intercept of Staheli (2006), Bennett (1998), and ASCE-27 (2000) are close as the face components for these methods are calculated with Weber (1981)'s method. The ASCE-27 (2000)'s predictions are the lowest of all methods. The Bennett (1998) and Staheli (2006) methods are the best among the five methods studied in this paper, as their predictions are the closest result to actual field measurements.

4.6 Conclusion

This paper analyzes the first pipeline installation project completed with the Eliminator for the purposes of investigating the required jacking force by means of instrumentation and data collection. The results illustrated that the applied jacking force varied between 300 to 500 kN, and increased slightly with pipe length due to an abundance of lubrication. Five existing models for predicting the jacking force of technologies similar to the Eliminator were used for this project, and the results were compared to the field measurements. The comparison indicated that Bennett's best fit (1998) and Staheli (2006) most accurately predicted frictional resistance for this project. Additionally, it was found that the Weber (1981) and Chapman & Ichioka (1999) methods were the most conservative, and the ASCE-27 method was the least conservative of all methods. However, more field data is required to further validate these prediction models before they can be used in design.

5. Summary, Conclusions, and Recommendations

5.1 Summary

The Eliminator is a guided boring machine developed to address the market need for PTMT in non-displaceable soils. A literature review on the Eliminator and similar trenchless technologies, as well as a risk and productivity analysis, were performed. Moreover, different methods of jacking force analysis for these technologies are discussed in detail. There are few documented experiences with the Eliminator as it is a new technology. The first pipeline installation performed with the Eliminator for a project in Edmonton, Alberta was introduced. An overview of this project performed and its productivity and risk analysis results are presented, which can provide valuable insight into budget and time estimations of future Eliminator projects. Additionally, hydraulic pressure transducers were used to monitor the jacking force for this project. The recorded data was analyzed to determine the maximum applied jacking force. Moreover, five existing jacking force prediction models used for technologies similar to the Eliminator were used to predict the required jacking force for this project, and the results were compared to the force measured in the field.

5.2 Conclusions

The research results can be summarized as follows:

- Both sections of the project installed with the Eliminator were finished successfully, although their schedules were affected by different risk events.
- The auger casing and pipe preparation time depends on the depth of the shafts and the crew productivity working in the shafts. The auger casing preparation duration typically varies between 10 to 18 minutes, while the

installation duration typically varies between 20 to 40 minutes. The pipe preparation duration is generally less than 18 minutes, while the pipe installation duration varies significantly between 10 to 33 minutes.

- For scheduling of future projects with the Eliminator, the auger casing and pipe installation rates can be assumed to be 1.2 m/hr and 1.7 m/hr, respectively. In addition, for each activity, the best distribution fit, the mean times, standard deviation, and minimum and maximum values for the actual observed data and the fitted distribution are calculated.

- A total of 13 risk items were identified through examining recorded data and field notes, and the effect of each risk event was calculated in terms of percentage with respect to the project's total duration. Optical distortions, jacking frame movement, auger casings downward curvature, and PCH adapter failure are the most significant risk events occurring in this project. However, the first three risk events mentioned are preventable. In the two monitored sections, there were a relatively high number of risk events that delayed project completion considerably for an estimated 46.7 and 72.4 percent in the first and the second sections, respectively. However, 72.8 percent of the total risk was identified as preventable following the risk analysis.

- Three hydraulic pressure transducers were used to record the applied jacking force during this project. The applied jacking force for the first section of the project was measured. The recorded jacking force typically varied between 300 to 500 kN (30 to 50 Tons). The trends for both minimum and maximum applied jacking force are similar; generally, the jacking force increases due to the increase in the frictional component of the total jacking force. Since the length of installation is significantly lower in Eliminator projects than microtunneling projects, and the bore hole is more stable in hard ground conditions where the Eliminator is applicable, the face component of the total jacking force plays a significant role in the total required jacking force. The mechanical performance of the PCH necessitates the consideration of the cutting edge resistance and contact pressure for calculation of the face resistance. In order to estimate the cutting edge resistance of PCH, Weber's (1981) formula is recommended for situations when the boring head is behind the cutting edge . By summing the contact pressure and the cutting edge resistance, the face resistance component is calculated.

- Considering lubrication and the provided methods of face resistance calculation, it was concluded that Bennett (1998) and Staheli (2006) are the best methods of predicting the frictional resistance in the field. Weber (1981) and Chapman and Ichioka (1999) models can be used for conservative design of future projects, and the ASCE-27 (2000) method can be used to evaluate contractors' claims.

5.3 Future Research

The current study focused on productivity, risk, and jacking force analysis for Eliminator projects. However, this study was performed on two sections of a sewer line project in Edmonton, which limits the accuracy and applicability of the results for projects in different conditions. In addition, environmental and financial aspects of this new technology were not covered within the scope of this research. In order to improve the accuracy of future projects' predictions and to reduce the risk impact, further project-based investigation is suggested. Further study regarding the cost and CO_2 emissions of the Eliminator is also necessary for industry knowledge.

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