Comparison of Trenchless Technologies and Open Cut Methods in New Residential Land Development

by

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Abstract

Nowadays, with the expansion of population in urban areas, development of new residential and commercial areas is essential to meet the needs of this ever-expanding population. Urban water and wastewater systems are fundamental infrastructure in this development, and are very important for high quality of life and strong urban economy. Also, there is growing attention to consider different factors, such as environmental, cost, social impacts, safety and seasonality in the development of infrastructures. It is considered indispensable to improve construction practices and develop infrastructures in ways that considers all above mentioned concerns in urban construction.

As the world moves towards providing a better and cleaner environment for future generations, there is an urgent need to quantify and reduce the emission footprints of industries. The construction industry, which consumes a large quantity of fossil fuels, is one of the targeted industries for which researchers aim to evaluate proper alternatives to traditional construction methods in order to reduce these emissions. Underground utility installations, especially in the development of residential communities in urban areas, are one of the largest construction projects across North America and, consequently, one major source of emissions.

Moreover, studying cost as essential element is important in the development of underground infrastructure. Project owners and decision makers look for economical methods for installing underground infrastructure and renewing underground utility pipes.

This dissertation demonstrates a comparison between the traditional open cut option in underground utility projects and trenchless methods (auger boring and HDD) through two case studies in new residential development area in Edmonton, Alberta, which consists of three main lines: water, sanitary, and storm. The results show that GHG emissions generated from open cut were significantly higher compared to the estimated trenchless alternatives. Also compared to open trench, trenchless techniques are more expensive in Edmonton, Alberta. However, productivity, and constructability of trenchless methods in in cold areas such as Alberta, these technologies would be considerable alternatives to open cut.

Dedicated

To

My lovely parents and my dear brother, HamidReza

for their supports and love.

&

My precious grandparents who watch over me from heaven

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Table of Contents

List of Tables

List of Figures

1. Introduction

1.1 New Residential Land development

With ever increasing population in urban areas, there is a crucial need to develop new lifelines as the municipal areas expand, also to rehabilitate aging underground infrastructures to meet the essential needs. There are two aspects with regards to underground lifelines; installing of new facilities and rehabilitating of the old underground utilities. Challenges to install new infrastructures include emission footprint, social inconveniences, economic impacts, and safety concerns.

On the one hand, with the growth of urban areas in Canada, especially in cold provinces like Alberta, there is a need in order to overcome the adverse impacts of abovementioned challenges. On the other hand, due to inclement weather condition, the construction season is very short. Thus, it is vital to find sustainable solutions to let contractors continue construction activities even in extreme weather conditions while the construction method get minimally affected by seasonality.

1.2. Underground Development in New Residential Urban Areas

New underground utility infrastructure continues to be installed, and the wide range of water and wastewater infrastructure in North America is getting old and approaching the end of its useful life. Therefore, several new installation, rehabilitation and renewing projects are required, and there are a multitude of large-scale construction works to fulfill these needs.

Open cut methods are traditionally used to install and rehabilitate underground infrastructure. This method involves surface excavation to reach the pipe, installation of new equipment, replacement of excavated material, and reinstatement of the surface. Open cut methods are associated with high environmental, economic, and social impacts, particularly in densely populated areas (Sullivan 2012).

In the past 20 years, a group of new technologies have been developed, which are known as trenchless methods. These alternative methods of installing and replacing of underground utility pipes have been created to facilitate underground utility construction with minimal surface disruption and social inconveniences (Najafi 2004). As there is minimal excavation, trenchless methods have less construction foot print and are more environmentally friendly. These methods also provide safer work environment, and are becoming increasingly more common to use in place of traditional open cut methods. Some trenchless methods are pipe ramming, horizontal auger boring, micro tunneling, horizontal directional drilling (HDD), cured-in-place pipe lining (CIPP), and pipe bursting (Ariaratnam et al. 2013).

With growing attention to consider sustainability factors, such as environmental, cost, and social, when developing infrastructures (Ding 2008), responsible management is also needed to protect the natural environment from irreversible and remarkable effects, such as air and water pollutions, and waste. Dissipating non-renewable natural resources is a harmful loss for future generations (Ofori et al. 2000). As a result, it is considered indispensable to improve construction practices and develop infrastructures in ways that facilitate sustainable construction.

Seasonal constructability is another challenge in developing infrastructure especially in areas with extreme weather conditions. Interruptions in construction projects caused by climate would increase project time and delay activities, and it also creates more costs for project. Installation methods with applicability in most weather conditions are more admirable by construction decision makers.

1.2.1. Environmental Aspect

Global focus on environmental pillars and demand for clean energy by the United Nations Environmental Program (UNEP), the environmental protection agencies of many nations and environmental non-governmental organizations (NGOs) are notable and increasing. As the world moves towards providing a better and cleaner environment for future generations, there is an urgent need to quantify and reduce the emission footprints of industries. Reducing the amount of greenhouse gas (GHG) emissions is a worldwide concern due to the significant environmental, health, and economic impacts. Increasing amounts of GHG have led to global warming, a phenomenon with numerous environmental impacts, such as loss of snow cover and an increase in the frequency and severity of storms.

In Canada, the total amount of GHG emissions in 2015 was 722 megatons (Mt) of carbon dioxide equivalent (CO_2 eq), which is 18 percent higher than the 1990 emissions level of 611 Mt CO_2 eq. During the first 10 years of this period, the annual emissions increased steadily, but there were some fluctuations between 2000 and 2008, and it dropped in 2009. However, the annual emissions have gradually increased since 2009. As a result, the Canadian government committed to decrease the amount of future GHG emissions. Canada has targeted to reduce its GHG emissions to 523 Mt by 2030, which is expected to be between 697 and 790 Mt of carbon dioxide equivalent (Mt CO_2 eq) (Figure 1-2) (Government of Canada, 2016).

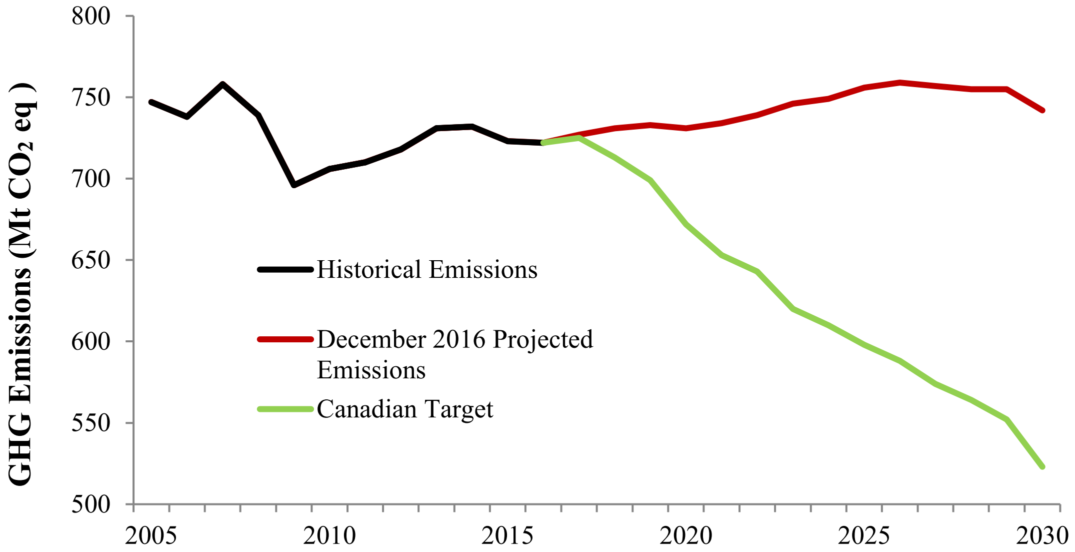

Figure 1-1- Pathway to Canada’s 2030 GHG emission target

Emissions vary significantly by province in Canada, based on factors such as population, energy sources, and economic base. Figure 1-3 shows the provincial and territorial greenhouse gas emissions breakdown from east to west for the years 1990, 2005, and 2015. GHG emissions for Ontario and Quebec were lower in 2015 than 1990; however, emissions in Saskatchewan, Alberta, and British Colombia were higher in 2015 than in 1990. In 2015, Alberta's emissions had increased 56 percent since 1990. Of Canada’s national total GHG emissions of 722 Mt CO_2 eq in 2015, Alberta emitted 274.1 Mt of CO_2 eql, making it the province with the highest emissions (Government of Canada, 2016).

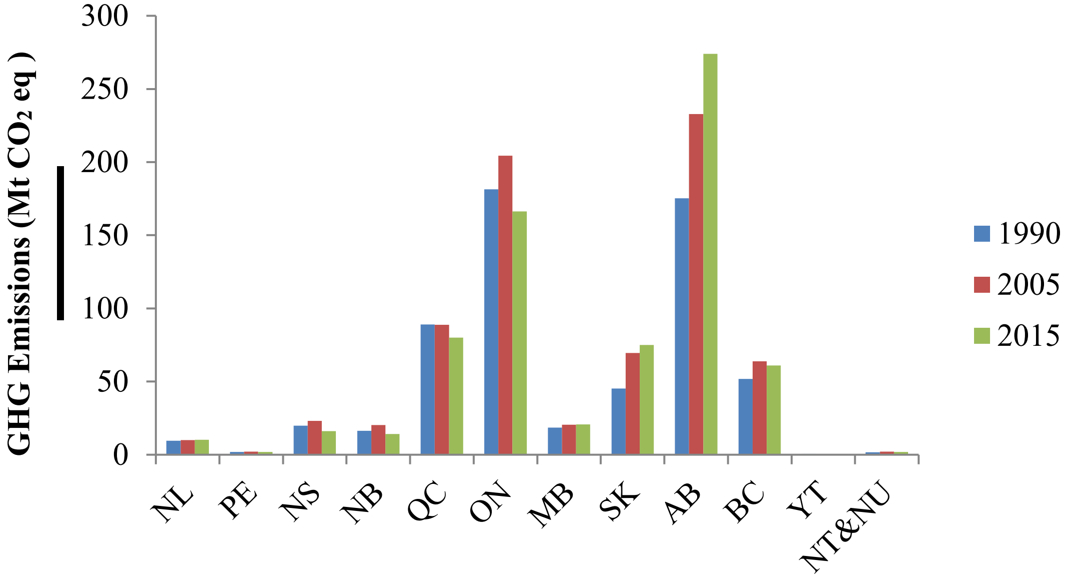

Figure 1-2-Greenhouse gas emissions by province and territory, Canada, 1990, 2005, and 2015

The Pan-Canadian Framework established on December 9, 2016 on clean growth, resilient economy, and climate change, is a commitment in all provinces and territories in Canada to adopt clean energy and technologies. This framework includes some short term and long term milestones to achieve the targeted plan of meeting, or exceeding, Canada's 2030 goal to reduce GHG emissions to 30 percent below the 2005 levels. Canada’s 2016 Fall Economic Statement and Budget 2017 included commitments to invest in green infrastructure. The Federal Government announced some sources of funding in Budget 2017 to support national, provincial, and municipal green infrastructure and other improvements in demonstration and adoption of clean technologies (Government of Canada 2016).

Construction industries cause environmental problems, including the use of global resources and polluting surrounding environments with building operations. The United States Environmental Protection Agency (EPA) identified construction as the third highest source of GHG emissions among industrial factors (Truitt 2009). Achieving the goal of sustainable development necessitates considering some assessments at early stages of projects to select more environmentally friendly designs and methods of implementation (Ding 2008).

The main source of air pollution in construction projects is the combustion of fossil fuels, which account for 76 percent of emissions produced on construction sites. This includes the combustion of fossil fuels generated from gas and diesel on-and-off-road transportation; transportation of site equipment; as well as natural gas used for field office power, heat, and tools. Underground construction plays a major role in producing GHG emissions in the construction sector (Truitt 2009). Due to the use of emission producing equipment in underground construction projects, it is challenging to reduce the amount of GHG emissions produced through underground construction projects.

As mentioned above, many countries are trying to develop sustainably; therefore, there is a global trend to monitor the environmental impacts of projects, including underground infrastructure projects, and to minimize the environmental impact whenever possible (Khan et al. 2015). Therefore, construction industry decision makers and executers in underground projects have been actively trying to adopt innovative technologies for the installation of these infrastructure systems.

1.2.2. Economic Development

Cost is an essential element in the development of infrastructures, and the World Trade Organization (WTO) and the Organization for Economic Cooperation and Development (OECD) focus mostly on economic growth. Canada’s economic objective aims to ensure prosperity and rising living standards for all Canadians, and the new Government of Canada is taking a fundamentally different approach to grow the economy for the benefit of every Canadian. The

Canadian's Sustainable Economic Growth Strategy seeks to create sustainable, long-term economic growth that will increase a generation of revenue (Government of Canada 2016).

The Government of Canada announced the long-term vision for its infrastructure plan in Budget 2017 and committed to invest an additional \$81 billion through to 2027–2028 in public transit, social infrastructure, green infrastructure, rural and northern communities, transportation and trade infrastructure, and introduced the Smart Cities Challenge. Considering existing infrastructure programs, the government will be investing more than \$180 billion through to 2027–2028. This sustainable approach requires proper project budgeting and efficient use of these financial resources when developing infrastructures (Government of Canada 2016).

Therefore, cost-efficient construction methods are more acceptable, and project owners and decision makers look for economical methods in all industries. Accordingly, there is a growing trend to use effective alternatives in construction. The cost effectiveness of a construction method necessitates a clear definition and understanding of all cost factors associated with the method.

1.2.3. Social Impact

Social impact nature is subjective, and includes damages to the environment and inconveniences to the surrounding area. Organizations such as the Economic Cooperation and Development (OECD) give attention to social impacts and try to optimize quality of life for the whole world.

Growth of public awareness about quality of life and protecting the environment has resulted in more research and studies to quantify the social costs of different construction methods. Various modeling techniques have been developed by researchers based on the percentage of occurrence and level of impact for determining socials aspects.

1.3. Problem statement

Developing new residential and commercial areas is substantial in urban enlargement. Consequently, expansion of infrastructures is required as a fundamental part of this development. Nowadays, different construction and installation methods including traditional open cut and innovative trenchless methods are available to grow these infrastructure in urban residential areas. Development of these infrastructure requires urban planners, managers, and engineers to overcome different challenges including: environmental adaptability, cost effectiveness, safety, social conveniences and seasonal constructability challenges in selecting appropriate construction method.. As a result, the main focus of this research is to identify and evaluate these challenges in using trenchless technologies in comparison with traditional open cut installation methods.

1.4. Objectives

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

- Perform a literature review on new residential land development necessity, specifically, on underground pipeline installations that consider challenges associated with current underground engineering practice in traditional open cut and trenchless technology methods;
- Identify the potential environmental and social impacts, cost factors, and seasonal constructability challenges associated with each installation method;
- Compare traditional open cut installation in underground pipelines with trenchless alternatives to determine the most applicable method for development of sewer and water main lines in new residential land development.

1.5. Thesis Structure

This thesis is presented with the following organization:

- Chapter 1 – Introduction: In this chapter, a brief background on new residential urban development is provided. The global plans and specifically the Canadian government strategic target on new underground development are introduced. In addition, the need to perform a comprehensive study on construction in underground development is propounded. The objectives, methodology, and organization of the thesis are also described.

- Chapter 2 – Literature Review: In this chapter, general information related to studies in underground pipe line installation in new residential land development, traditional open cut, and trenchless technologies, are introduced. A detailed literature review on environmental, economic, and social impacts of trenchless technologies is also performed.

- Chapter 3 – Study of Environmental Impacts of Trenchless Technologies and Open Cut Methods in New Residential Land Development: This chapter aims to compare the greenhouse gas (GHG) emissions of open cut methods and trenchless technologies through a case study, which consists of three main lines: water, sanitary, and storm. The indices used to evaluate the performance of each method are carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM), nitrogen oxide (NOx), sulfur dioxide (SO_2), and hydrocarbons (HC) emissions as measured by the United States Environmental Protection Agency (EPA).

- Chapter 4 – Cost Comparison of Trenchless Technologies and Open Cut Methods in New Residential Land Development: This chapter compares the construction costs and social impacts of traditional open cut, auger boring, and HDD in underground utility projects. The research aims to estimate the costs associated with different construction methods, including open cut methods and trenchless technologies, through a case study, which consists of a 460 m storm line, a 250 m sanitary line, and a 325 m water line.

- Chapter 5 – Conclusions: In this chapter, the research approach and the findings of the studies are summarized, and future research topics are proposed.

2. Previous Research

2.1. New Residential Land Development

Nowadays, with the expansion of population in urban areas, the existing urban housing and infrastructure is insufficient in addressing housing needs in many countries. Development of new residential and commercial areas are essential to meet the diverse needs of this ever-expanding population. New urban residential developments are closely linked to developments in infrastructure construction (Shi et al. 2014).

Infrastructure plays essential roles in the cities development, improvement in the quality of people lives and overall growth of economies (Brown et al. 2010).Basic infrastructural services such as access road, drainage systems, water supply, and electricity are essential needs to have to be provided for residential developments.

The global urbanization, together with population expansion, is increasing the pressure upon urban areas leading to develop underground infrastructures (Delmastro 2016). In September 2015, the 2030 Agenda for Sustainable Development was adopted by the United Nations (UN) member states consisting of 17 Sustainable Development Goals (SDG) including clean water and sanitation, sustainable cities and communities, and industry and infrastructure. This Agenda provides the framework for future development, integrating environmental, economic, and social aspects.

The growth of cities in North America, and the aging infrastructure in older cities, are creating a strong demand for new underground solutions and new underground infrastructures. The American Society of Civil Engineers (ASCE) report card rates the overall condition of the infrastructure system in the United States a failing grade (ASCE 2005). New underground utility infrastructure continues to be installed, and the wide range of water and wastewater infrastructure is getting old and approaching the end of its service life. Therefore, vast underground projects to replace or rehabilitate the existing underground water and wastewater lines are currently being performed and are expected to continue in the near future (Betti 2010).

In Canada, the Federal Sustainable Development Strategy (FSDS) sets out Canada's sustainable development priorities, establishes goals and targets, identifies actions to achieve them, and is the primary vehicle for infrastructure development planning and reporting. One of the greatest challenges facing municipal engineers in Canada is the weather condition. In Canada, especially in Alberta, as a result of prolong winters, the duration of constriction is limited to the months of May to October each year. This limitation leads to construction constrains in terms of utility installation in new development areas as well as rehabilitation in developed areas. To overcome this challenge, the method of utility installation should be compatible with seasonality changes (Davis 2017).

The construction industry's transition from the traditional paradigm towards sustainable development has received global attention (Zhang et al. 2014). There are different studies focusing on significant and detrimental effects of construction. Moreover, municipalities seek innovative technologies that can provide cost savings in addressing their underground infrastructure needs.

Development of infrastructures in new residential and commercial areas is associated with different challenges these days. Environmental adaptability, cost effectiveness, safety, and social conveniences during construction are some of these challenges which should be considered in selecting of construction methods (Zhang et al. 2014).

The literature review on the abovementioned challenges in infrastructure related construction projects were generally conducted in this research study regardless of the field conditions as there were very limited number of studies found on developing of lifelines in new residential and commercial sites.

2.2. Underground Construction

2.2.1. Traditional open cut

The conventional method for construction, replacement, and repair of underground utilities is the open cut method. The open cut process includes direct installation of utility systems into open cut trenches. Over a century ago, this solution may have been considered economically appropriate for the installation of potable water networks and wastewater networks below ground because there were no alternatives available.

Research has shown that some contemporary water utilities contractors still have a strong preference for using conventional open cut replacement techniques when rehabilitating water pipes in urban areas (Hunt 2014), which can be costly and disruptive to the surrounding environment, particularly in highly populated areas. Since the advent of trenchless technologies in the 1980s, the problems associated with traditional methods have gradually been resolved. Municipal owners and engineers are actively exploring the adoption of innovative technologies for the installation of these critical systems.

Nowadays, trenchless technologies are known as innovative and effective methods for underground construction. There are different studies (explored further in the coming sections) confirming that stakeholders and societies would benefit from shorter construction times, less construction costs, and especially, less social impacts and pollutant emissions by applying trenchless methods. There are several papers and research studies which compare conventional open cut construction with trenchless technologies. These comparisons cover a wide range of areas, including planning and engineering methods, construction issues, environmental and social impacts, and cost and economical concerns. The importance of incorporating sustainable development methods, such as trenchless technologies, is not effectively understood by project owners since there is still a massive public tendency to use the traditional open cut methods in underground construction.

2.2.2. Trenchless Technologies

Trenchless technologies are effective alternatives to traditional open trench construction, as these methods require minimum excavation. Applying trenchless technologies to install and repair underground infrastructure prevents digging a trench or open cutting (Ezeokonkwo and Nwoji 2014). The North American Society for Trenchless Technology (NASTT) defines trenchless technology as a family of methods, materials, and equipment capable of the installation of new lines, replacing old lines, or rehabilitating existing underground infrastructure with minimal disruption to surface traffic, business, and other activities. Trenchless methods have many advantages such as:

- Minimal disruption to existing environment, residential and businesses areas.
- Low risk of interfering with existing piping and utilities.
- Safer working area for both workers and the community because of less requirement of open exposed installation.

Trenchless technologies methods are categorized in two main areas: trenchless construction methods and trenchless renewal methods (Najafi 2005). Trenchless construction method includes all techniques for installation of new pipelines and conduits below grade without an open-cut trench. Some trenchless construction methods are horizontal auger boring, horizontal directional drilling (HDD), pipe ramming, and pilot tube micro tunneling. (Table2-1)

Table 2-1-Trenchless construction methods (Najafi 2005)

Method	Diameter (in)	Maximum installation (ft)	Pipe material	Typical application	Accuracy
Auger boring	4–60	600	Steel, PVC	Pressure and gravity pipe	±12 in
HDD	2–12	Up to 600	PE, steel, PVC, clay, FRP	Pressure pipe/cable	Varies
	12–24	Up to 1000	PE, steel, ductile iron	Pressure pipe	Varies
	24–48	Up to 6000	PE, steel	Pressure pipe	Varies
Pilot tube Micro tunneling	10–136	500–1500	RCP, GRP, VCP DIP, Steel, PCP	Gravity pipe	±1 in
Pipe ramming	Up to 120	400	Steel	Road and rail crossing	Dependent on setup

Auger boring is a very popular method among trenchless technologies for underground pipeline installations ranging from 4-60 in. up to 600 ft. Guided auger boring is a tunneling technique that uses a guided boring machine (GBM) to bore a hole through the earth while removing spoil through auger flights. This method consists of three stages. The first stage is the installation of a pilot tube with a rotating head for steering, and a theodolite guidance system for accurate installation. The second stage is the installation of a reaming head and auger tube sections behind the pilot tubes after the steering head has reached the reception shaft. A section of pilot tube is removed in the reception shaft with the addition of each section of auger and tube in the launch shaft. The process is continued until all pilot sections have been detached. Finally, in the third stage, the product pipe is installed. A pipe adapter is attached to the last auger casing section, and subsequent product pipes are pushed into place while the auger tubes are removed from the other shaft.

Horizontal directional drilling (HDD) is a trenchless method with the capability of installing pipelines over 6,000 ft. with diameters ranging from 2 to 48 in. HDD has a low construction footprint compared to other techniques so is ideal for installations in urban environments. HDD process consists of an initial pilot hole boring to the target location along the proposed alignment, reaming the borehole to a larger diameter, and pulling back the product pipe. A transmitter tracker is used to inspect the line and grade. The transmitter is directly behind the drill head, which is tracked by a surface walkover locator, and can be adjusted in the preferred direction by rotating the pilot rod string to orient the bit on the lead rod. At the exit, a reamer and a swivel system are used to attach the product pipe to the pilot rod string and to carve a borehole to insert the larger product pipe. Multiple reaming passes may be needed depending on site characteristics and the diameter of the product pipe (Ariaratnam 2013).

Pipe ramming (also called pipe jacking) is typically used for utilities installation up to 120 in. with maximum length of 400 ft. under road and rail crossing. In this method an air compressor drives a steel casing pipe inside the earth from a drive pit. Pipe ramming can be applied in a wide variety of soils; however, it is a little difficult in medium to dense sands and not suitable for solid rock. This method has become quite common in Europe and parts of Asia but is still hardly used yet in North America. Compared to horizontal directional drilling and auger boring, pipe ramming can be used in soils with loose rock and cobble, or extremely fine sands where these two methods are not effective or efficient. (Simicevic,2001)

The pilot tube method of micro tunneling (PTMT) was introduced in the united states in 1995 (Najafi, 2005), and now is mostly used to install pipe diameters up to 136 in and drive lengths in the range of 500-1500 LF. In PTMT augers excavate and remove the soil, and the jacking system pushes the pipe. It uses a guidance system with camera mounted theodolite and electric light emitting diodes (LEDs) to secure high accuracy in line and grade. This method requires a small workspace and has an accuracy of 0.25 in for 300-ft pipe installations. It is less costly than conventional open-cut methods and solve engineering problems such as poor soils condition, utility obstacles, high ground water and deep installations. (Boschert, 2007).

PTMT is applicable in a variety of soft soil conditions. However, there are some challenges to use this method in hard soil with relatively large boulders and rocks, running sands and unstable soils. Using different types of reaming heads for different soil conditions assists performance of PTMT in challenging soil.

2.3. Environmental impacts

The construction industry is considered an environmental polluter, and the promotion of sustainable construction practices are meant to encourage the use of environmentally friendly techniques in construction projects.

As a critical phase in urban development, underground pipe construction involves activities such as the demolition of any surface materials, excavation, pipe installation works, and backfilling, which all take time and use heavy construction equipment and techniques. Therefore, underground pipeline construction accounts for a considerable amount of GHG emissions. Measurement and control of greenhouse gas emissions and harmful substances, such as carbon monoxide, nitrogen oxide, and particulate matter emissions that are released into the atmosphere, can lead to a considerable reduction in emission levels.

GHG emission analysis is becoming more popular in every industry, and it is critical to estimate emissions for engineering projects. The investigation and quantification of the amount of GHG emissions was conducted during previous years in several studies, and various efforts to estimate emissions from construction operations can be found in the literature. Key models are the EPA's Nonroad model (EPA 2010), and the California off-road model.

Sihabbudin and Ariaratnam (2009a) applied the EPA Nonroad model to estimate the emissions generated by equipment and transportation in a utility installation project employing HDD. Project emissions were calculated by an emissions calculator based on the EPA model, and the site details and equipment usage hours that were collected onsite were used as inputs in the calculator to estimate the total number of emissions. The developed model could be used by policy makers to select the proper construction methods based on estimated emissions. This initial estimation would be helpful to narrow and mitigate airborne pollution in future construction projects.

In a different study, Sihabbudin and Ariaratnam (2009b) used the same model to compare trenchless pipe replacement, horizontal directional drilling, trenchers, and traditional open cut in terms of generated GHG. Three project sites for each method were visited to collect the data on the activities for each utility installation method to use as inputs for the calculator. The results reinforced that trenchless construction technologies produce fewer emissions compared to open cut installations.

Ariaratnam and Sihabbudin (2009) compared the emissions of two construction methods, open cut and pipe bursting, in wastewater line installations. The results indicated that the trenchless method resulted in 80 percent fewer emissions compared to the open cut method. Ariaratnam and Sihabbudin also recommended that for future construction projects, emission estimator tools be used to compare various construction methods regarding their emitted pollution. This could help achieve acceptable emission levels by choosing the proper construction option.

Piratla et al. (2012) focused on comparing the CO_2 emissions of open cut pipeline construction and HDD in the construction of a 12 inch potable waterline and its attached structures in an urban residential street in Bowling Green, Ohio, United States. A spreadsheet model based on the EPA data base was developed to calculate the CO_2 emitted by construction machinery in both open cut and HDD scenarios. Transportation trucks and construction equipment used in the construction were the two categories of construction machinery considered in the study. The construction activity data and daily outputs were collected from the actual construction site and adjusted by a local contractor in the area. They concluded that HDD reduced the CO_2 emissions by 47.6 percent. This huge reduction was mainly because less excavation, backfill, pavement demolishment, and restoration were needed in HDD compared to open cut.

Ariaratnam (2013) studied four common construction methods in the installation of underground utilities in different aspects, including environmental impact, cost, and social impact. Open cut, pilot tube micro-tunneling (PTMT), HDD, and vacuum micro tunneling (VMT) were investigated in this research. The study introduced a sustainability index rating to evaluate utility installation projects and assist decision makers in quantifying environmental impacts of proposed technologies. In the mentioned research, an emission calculator was used to quantify airborne emissions. The results demonstrated that PTMT generates the lowest emissions, followed by VMT, HDD, and open cut, and the percentage reductions of using trenchless methods compared to open-cut are 48.36 percent, 42.68 percent, and 31.65 percent.

2.4. Cost and Social Impacts

As stated before, cost effectiveness and social impacts of construction methods are important factors in selecting the appropriate option in each project for sustainable development. Clear definition of all costs and impact items would help the designer have impressive economic and social evaluations of the project. As will be discussed below, there are varoius prevoius studies that have compared conventional open cut construction with trenchless technologies and focused on different aspects of this criteria.

Tighe et al. (1999) studied traffic delay cost savings associated with trenchless technologies. The study focused on cost savings in trenchless methods from eliminating the traffic disruptions associated with excavation and trenching compared to the conventional open cut method. Tighe et al. (1999) suggested a methodology to consider the cost of traffic delays associated with trenching methods. The results showed that eliminating traffic disruption in trenchless technologies make them the most economical alternative to open cut.

Tighe et al. (2002) also performed a study to compare the overall project costs of the traditional open cut method with trenchless technologies. They considered different factors, such as performance, future maintenance costs, and user-delay costs in the study. It was concluded that surface restoration costs were comparable, and trenchless construction methods are an effective alternative to open trench options, especially in developed urban areas. The results indicated that traditional open cut methods reduce the life of pavement about 30 percent and increase the maintenance and rehabilitation costs of pavement from 85 CAD/m^2 to 146 CAD/m^2. However, trenchless technologies have fewer costs associated with pavement disruptions.

Najafi and Kim (2004) compared conventional open cut construction with trenchless options. The study comprised all engineering, capital, and social costs of construction in both methods. They concluded that trenchless methods were generally cheaper, especially compared to life-cycle costs. They also deduced that, because of lower initial construction costs of traditional open cut, local agencies, municipalities, and consulting and design engineers are slow in identifying the benefits of trenchless technologies. However, a life-cycle-costs analysis would reflect the real advantages of trenchless methods.

Yeh et al. (2008) developed cost functions applicable to open cut and jacking methods, and construction techniques of sewer systems. The cost functions use the pipe size and excavation depth to estimate the construction costs of sewer systems. The proposed cost function proved to be a very useful tool, allowing both governments and contractors to estimate quickly sewer construction budgets.

Kulkarni et al. (2011) studied a cost comparison of HDD with traditional open cut installation methods in three different projects. These projects included installation of a 100 mm and a 150 mm PVC pipe in Texas, and a 150 mm PVC pipe in Florida. The results of the cost analysis indicated that HDD was more cost efficient than the open cut method for installation of the small diameter PVC pipelines, with an average of 39 percent more efficiency in these case studies.

This study compared only the base cost associated with PVC pipe installation and the suggested cost depends on the project. There would be a series of other costs, which should be added to the base cost to have the total cost estimation.

In 2013 Ariaratnam et al. studied environmental impact, costs, and social impacts of four common construction techniques in the installation of underground utility infrastructure: open cut, pilot tube micro-tunneling, horizontal directional drilling, and vacuum micro-tunneling technology. They developed an overall underground sustainability index rating (USIR) through case studies based on the aforementioned factors. The application of USIR was demonstrated using an installation project in Portland, Oregon as a case study. The project consisted of 313 m of 400 mm PVC sewer line. All cost factors related to this project were considered to estimate the capital cost of the project, and a subjective evaluation quantified social impacts. The results confirmed the advantages of trenchless methods in these areas.

Ariaratnam et al. (2014) also investigated using trenchless technologies, especially pipe bursting trends, for underground systems replacement and renewal projects. They studied a survey questionnaire examining 886 projects from 2007 to 2010 in Canada and the United States, and the results supported the advantages of trenchless technologies. In 2014, Islam et al. evaluated social costs in trenchless projects and compared them to traditional trenching methods through five case histories in different countries, including the United States, Austria, Italy, and Belgium. The Social Cost Calculator (SCC) of the Trenchless Technology Center (TTC) at Louisiana Tech University was used in their study, and the results showed that trenchless alternatives reduced the project's associated social costs significantly compared to the open cut method by a factor of 5 to 17.

Matthews et al. (2015) studied social cost impact assessment of pipeline infrastructure projects. Their research identified the eight most important social cost categories through two pipe line construction case studies and presented mathematical methods for calculating them. The social cost categories in this study are travel delay, vehicle operating costs, lost business revenue, loss of parking revenue, decreased road surface value, noise pollution, and cost of dust control and worker safety. Both case studies took place in high density urban areas with significant social impact. For these case histories, travel delay costs were the most important social cost category, followed by vehicle operating costs with the second largest share, and business revenue as the third. Other mentioned social costs have a more limited economic impact.

In 2015, a study by Whitehead et al. discussed various challenges of the underground pipeline installation in a heavily populated area through a case study in the Southern Delivery System (SDS) in Colorado. They identified a number of challenges containing traffic, safety, noise, dust, and vibration. The study emphasized that trenchless alternatives saved considerable amounts of time and money in this project, and also allowed a safer project with fewer social inconveniences.

Rashid et al. (2016) analyzed tender documents and reports from construction projects in the cities of Niagara Falls and Waterloo, Ontario, Canada over 28 years from 1980 to 2008. They used compiled information from tender packages and combined them with the data from the RS Means construction cost database to compute unit costs and estimate inflation in their construction costs of water main and sanitary sewer projects.

Younis et al. (2016) presented a method to forecast the unit price of water and wastewater pipeline capital works. They developed the method by studying inflation in the construction price, and tried to quantify the markup in order to consider factors such as overhead, profit, and market conditions and risks that contractors need to consider bidding successfully on a project.

Tavakoli et al. (2017) compared the generation of respirable suspended particulate matter (RSPM) between open cut and trenchless technology methods. In this study, they measured RSPM in site using a personal exposure sampler on six open cut and three trenchless sites. The amount of RSPM was sampled using filter papers in each of the sites. The results of their study indicated that using trenchless technology alternatives in underground projects significantly reduced construction workers' and the general public's exposure to RSPM.

3. Study of Environmental Impacts of Trenchless Technologies and Open Cut Methods in New Residential Land Development [1]

Abstract: As the world moves towards providing a better and cleaner environment for future generations, there is an urgent need to quantify and reduce emission footprints of industries. The construction industry, which consumes a large quantity of fossil fuels, is one of the targeted industries for which researchers aim to evaluate proper alternatives to traditional construction methods in order to reduce these emissions. Underground utility installations, especially in the development of residential communities in urban areas, are one of the largest construction projects across North America and, consequently, one major source of emissions. This study demonstrates an environmental impacts comparison between the traditional open cut option in underground utility projects and trenchless methods (auger boring and HDD). The presented research aims to compare the greenhouse gas (GHG) emissions of open cut methods and that of trenchless technologies through a case study, which consists of three main lines: water, sanitary, and storm. The indices used to evaluate the performance of each method are carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM), nitrogen oxide (NOx), sulfur dioxide (SO_2), and hydrocarbon (HC) emissions, as measured by the United States Environmental Protection Agency (EPA). Significant reduction in emissions of GHG was observed in augur boring and HDD methods compared to the open cut method. It is concluded that trenchless methods are more environmentally beneficial, as evident by the major reduction in airborne emissions compared to open cut.

3.1. Introduction

Growing concerns about global warming has led to an urgent need to quantify and reduce the emission footprint of industries. Many countries now have pre-determined pollutant targets and

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[1] This chapter has been submitted to Journal of Green Building and under review.

are making efforts to transition to low-carbon economies by the middle of this century. Legislation, such as the “Federal Sustainable Development Strategy for Canada” (Canada), the “U.S. Clean Energy Security Act” (United States of America), the “Climate Change Bill” (United Kingdom), the “National Greenhouse Gas and Energy Reporting Act” (Australia), and the “Strategic Energy Technology Plan” (European Union), are intended to reduce pollution.

A variety of programs by the Government of Canada support clean technologies. Canadian Federal Sustainable Development Strategy (FSDS) is the primary measure for sustainable development planning and reporting. FSDS sets out priorities and targets for sustainable development and identifies actions to achieve them. The Government of Canada also supports the efforts of provinces and territories to achieve their own greenhouse gas (GHG) emissions reduction targets. Moreover, businesses and individuals are encouraged to lower their respective emissions (Canada’s Emissions Trends 2013). As of July 1, 2007, the Alberta government required all industrial facilities emitting more than 100,000 tonnes of GHG per year to decrease emissions by at least 12 percent (Government of Alberta 2008).

Based on a World Bank report, the amount of CO_2 emissions generated from Canadian manufacturing and construction industries in 2011 was 101.24 million metric tons (World Bank 2011), which accounted for 14.5 percent of all CO_2 emissions in Canada that year. Alberta was the largest producer of GHG among Canadian provinces, producing 243 million metric tons of carbon dioxide equivalents in 2012. The main source of air pollution in construction projects is the combustion of fossil fuels, accounting for 76 percent of emissions produced on construction sites. This includes the combustion of fossil fuels generated from gas and diesel on-and-off road (transportation and site) equipment, as well as natural gas used for field office power, heat, and tools (Canada’s Emissions Trends 2013).

Underground construction plays a major role in producing GHG emissions in the construction sector. The construction of water lines, sewer lines, and related structures, with many construction activities involving the installation of underground pipes, is the third largest producer of GHG (Truitt 2009).

Today, engineers are developing construction options that are both cost effective and consider environmental sensitivities to create a sustainable solution. The reduction of six significant airborne pollutants (carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO_X), hydrocarbon (HC), sulfur oxide (SO_X), and particulate matter (PM)) have been identified by the United States Environmental Protection Agency as critical to sustainable development (EPA 2010).

3.2. Underground Construction

Globally, nations face a major issue in addressing aging underground utility infrastructure systems. Many of these systems need to be rehabilitated, while others require the installation of new product pipes. Due to the use of emission producing equipment in underground construction projects, it is challenging to reduce the amount of GHG emissions produced through underground construction projects.

As new underground utility infrastructure continues to be installed, it is imperative that factors other than lowest cost be considered in the selection of the construction method. Currently, there is a growing trend toward using sustainable methods in infrastructure development. Factors such as environmental impact, cost, and social impact form the pillars of sustainability and are considerations in infrastructure development (Ariaratnam 2013).

3.2.1. Traditional Open Cut

The conventional method for construction, replacement, and repair of underground utilities is the open cut method. The open cut process includes direct installation of utility systems into open cut trenches. Over a century ago, this solution may have been considered economically appropriate for the installation of potable water networks and wastewater networks below ground because there were no alternatives available.

Research has shown that some contemporary water utilities contractors still have a strong preference for using conventional open cut replacement techniques when rehabilitating water pipes in urban areas (Hunt 2014). Since the advent of trenchless technologies in the 1980s, the problems associated with traditional methods have gradually been resolved. Municipal owners and engineers are actively exploring the adoption of innovative technologies for the installation of these critical systems.

3.2.2. Trenchless Technologies

Trenchless technologies are effective alternatives to traditional open trench construction, as these methods require minimum excavation. Applying trenchless technologies to install and repair underground infrastructure prevents digging a trench or open cutting (Ezeokonkwo and Nwoji 2014). The North American Society for Trenchless Technology (NASTT) defines trenchless technology as a family of methods, materials, and equipment capable of the installation of new lines, replacing old lines, or rehabilitating existing underground infrastructure with minimal disruption to surface traffic, business, and other activities. There are many advantages offered by trenchless methods, including the reduction of noise, dust, pollution, and other environmental impacts.

3.2.2.1 Auger Boring Method

Auger boring is a very popular method among trenchless technologies for providing underground water and gravity pipeline installations. Complex networks of buried underground utilities are creating a necessity to achieve grade accuracy and precise lines in pipe installations. Guided auger boring is a tunneling technique that uses a guided boring machine (GBM) to bore a hole through the earth while removing spoil through auger flights. This method consists of three stages. The first stage is the installation of a pilot tube, which employs a rotating head for steering, and a specially designed theodolite guidance system. The theodolite helps in the accurate installation of casing through video surveillance. The second stage is the installation of a reaming head and auger tube sections behind the pilot tubes after the steering head has reached the reception shaft. A section of pilot tube is removed in the reception shaft with the addition of each section of auger and tube in the launch shaft. The process is continued until all pilot sections have been detached. Finally, in the third stage, the product pipe is installed. A pipe adapter is attached to the last auger casing section, and subsequent product pipes are pushed into place while the auger tubes are removed from the other shaft (Figure 3-1).

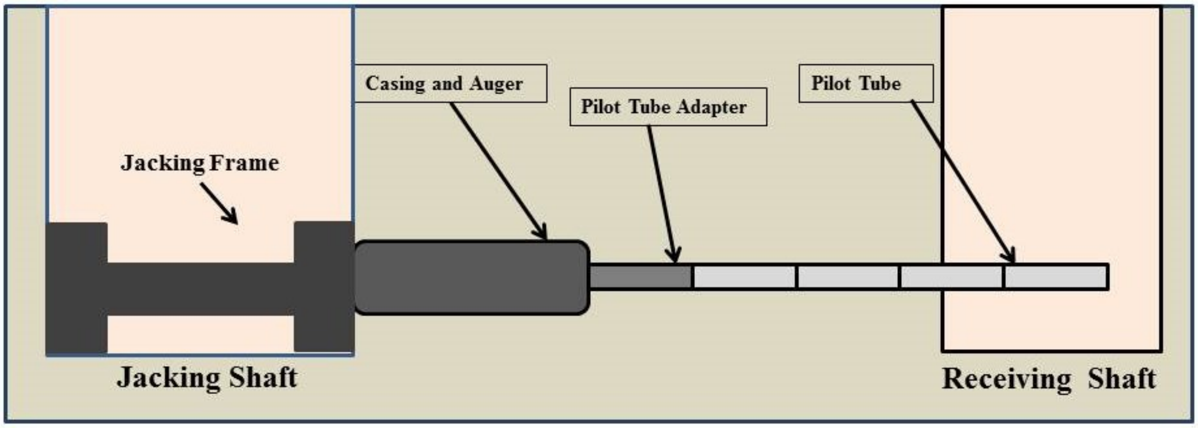

Figure 3-1- Schematic picture of auger boring

3.2.2.2 Horizontal Directional Drilling

Horizontal directional drilling (HDD) is a trenchless method with the capability of installing pipelines over 3,000 m, with diameters ranging from 50 mm to 1,650 mm (Bennett and Ariaratnam 2008). HDD has a low construction footprint compared to other techniques so is ideal for installations in urban environments. Figure 3-2 shows the installation procedure using HDD, which consists of an initial pilot hole boring to the target location along the proposed alignment, reaming the borehole to a larger diameter, and pulling back the product pipe. A transmitter tracker is used to inspect the line and grade. The transmitter is directly behind the drill head, which is tracked by a surface walkover locator, and can be adjusted in the preferred direction by rotating the pilot rod string to orient the bit on the lead rod. At the exit, a reamer and a swivel system are used to attach the product pipe to the pilot rod string and to carve a borehole to insert the larger product pipe. Multiple reaming passes may be needed depending on site characteristics and the diameter of the product pipe (Ariaratnam 2013).

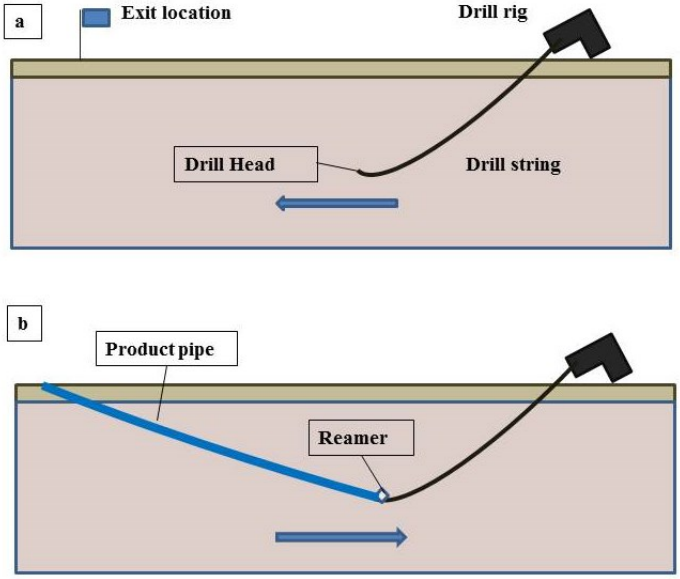

Figure 3-2- Horizontal directional drilling (HDD)

3.2.3. GHG Emission Quantification of Underground Construction

In order to quantify the amount of construction process emissions, several databases have been created. The EPA has developed the standard emission modeling method in North America, which has been used to evaluate the GHG emissions of construction in recent studies.

Sihabbudin and Ariaratnam (2009a) applied the EPA Nonroad model to estimate the emissions generated by equipment and transportation in a utility installation project using HDD. Project emissions were calculated by an emissions calculator based on the EPA model, and the site details and equipment usage hours that were collected onsite were used as inputs in the calculator to estimate the total number of emissions. The developed model could be used by policy makers to select the proper construction methods based on estimated emissions. This initial estimation would be helpful to narrow and mitigate airborne pollution in future construction projects.

In a different study, Sihabbudin and Ariaratnam (2009b) used the same model to compare trenchless pipe replacement, horizontal directional drilling, trenchers, and traditional open cut in terms of generated GHG. Three project sites for each method were visited to collect the data for each utility installation method to use as inputs for the calculator. The results reinforced that trenchless construction technologies produce fewer emissions compared to open cut installations.

Ariaratnam and Sihabbudin (2009) compared the emissions of two construction methods in wastewater line installations: open cut and pipe bursting. The results indicated that the trenchless method resulted in 80 percent fewer emissions compared to the open cut method. Ariaratnam and Sihabbudin also recommended that for future construction projects, emission estimator tools be used to compare various construction methods regarding their emitted pollution. This could help achieve acceptable emission levels by choosing the proper construction option.

Ariaratnam (2013) studied four common construction methods in the installation of underground utilities in different aspects, including environmental impact, cost, and social impact. Open cut, PTMT, HDD, and VMT were investigated in this research. The study introduced a sustainability index rating to evaluate utility installation projects and assist decision makers in quantifying the environmental impacts of proposed technologies. In Ariaratnam's research, an emission calculator was used to quantify airborne emissions. The results demonstrated that PTMT generated the lowest emissions, followed by VMT, HDD, and open cut, and the reduction percentages of trenchless methods compared to open cut are 48.36 percent, 42.68 percent, and 31.65 percent.

The current study focuses on the environmental impacts of the traditional open cut option in underground utility projects and compares it with auger boring and HDD. In this case study, the open cut method was used in a project that installed new storm lines, sanitary lines, and water lines in Edmonton, Alberta. Contractor estimators were consulted to provide project productivity estimates if the project had been completed using auger boring and HDD. The GHG emissions associated with each trenchless installation method have been calculated based on one estimation from contractors for each method.

3.3. Research Methodology

In this methodology, the total emissions from the project are calculated from the summation of emissions from all the construction equipment and transports used in the project. The main input for emission calculation is the emission factor. The most commonly used reference for emission factor sources is the "Crankcase Emission Factors for Non-Road Engine Modeling-Compression-Ignition" (EPA 2010a), which all emission factors in this research (HC, CO_2, CO, PM, NOx, and SO_2) are based. The emission factors for all pollutants are calculated for each piece of construction equipment and transportation source, and the determined emission factor is multiplied by load factor, horsepower, and hours of use to estimate construction emissions, while the transportation emissions are quantified by multiplying the haul and return distance by the transportation emission factor.

3.3.1 Construction Equipment Emissions

Based on empirical observations, the EPA has developed an equation to calculate the amount of gas emissions produced by construction equipment (EPA 2010b). Equation (3-1) is detailed below:

$$\text{Emissions } i = EFi \times HRS \times HP \times LF \qquad (3\text{-}1)$$

where Emissions i is the emission amount generated by the equipment i (g), EFi is the emission factor for the impact i (g/hp-hr), i is the type of pollutant (CO_2, SO_2, NO_X, CO, PM, HC), HRS is the hours of use, HP is the average rated horsepower of the equipment, and LF is the load factor (operating hp/maximum rated HP).

Table 3-1 shows the emission factor formulas used for construction equipment for HC, CO, NO_X, PM, CO_2, and SO_2 (EPA 2010a and 2010b).

3.3.2. Emissions from Transporting Materials To and From Site

After calculating emission factors for construction equipment, the transportation footprint is calculated using Equation (3-2) (Sihabbudin and Ariaratnam 2009a):

$$\text{Emissions}_{ti} = EF_i \times n \times (D_O + D_R) \qquad (3\text{-}2)$$

where Emissions_{ti} is the transportation emission, EF_i is the transportation emission factor from pollutant i (g/mi), n is the number of trips required to transport materials and equipment, D_O is the one-way distance hauling to the site, and D_R is the return distance from the site.

The emission factor formulas of transportation are presented in Table 3-2 for different pollutants (EPA 2010a and 2010b).

Table 3-1- The construction equipment emission factor formulas (EPA 2010)

Symbol	Description	Formula
$\mathrm{EF(HC, CO, NO_x)}$	HC, CO, and NO_X emission factor	$\mathrm{EF_{SS} \times TAF \times DF}$
$\mathrm{EF(PM)}$	PM emission factor	$\mathrm{EF_{SS} \times TAF \times DF - S_{PMadj.}}$
$\mathrm{EF(CO_2)}$	CO_2 emission factor	$\frac{\mathrm{44gCO_2}}{\mathrm{12gC}} \times 0.87 \times (\mathrm{BSFC \times TAF} \times 453.6 - \mathrm{HC})$
$\mathrm{EF(SO_2)}$	SO_2 emission factor	$\frac{\mathrm{64gSO_2}}{\mathrm{32gS}} \times 0.01 \times \mathrm{SO_xdsl} \times (\mathrm{BSFC \times TAF} \times 453.6 \times (1 - \mathrm{SO_xconv}) - \mathrm{HC})$

EFSS: Steady-state emission factor; TAF: Transient adjustment factor; DF: Deterioration factor; BSFC: Brake-specific fuel consumption; SPmadj: Sulfur content adjustment to PM emission factor; SOx dsl: Episodic fuel sulfur percentage; SOx conv: Fraction of fuel sulfur converted to PM.

Table 3-2-The transportation emission factor formulas (EPA 2010)

Symbol	Description	Formula
$\mathrm{EF_t(HC, CO, N}O_x\mathrm{)}$	HC, CO, and NO_X transportation emission factor	$\left\{\mathrm{EF_{ZM(HC,CO,Nox)}} + \left(\mathrm{D} \times \frac{\mathrm{M}}{10{,}000}\right)\right\} \times \mathrm{AF} \times \mathrm{C_F}$

$EF_t(PM)$	PM transportation emission factor	$EF_{ZM(PM)} + \left(D \times \frac{M}{10{,}000}\right)$
$EF_t(CO_2)$	CO_2 transportation emission factor	$\frac{44gCO_2}{12gC} \times 0.87 \times (\frac{F_D}{F_E} \times 453.6 - HC)$
$EF_t(SO_2)$	SO_2 transportation emission factor	$\frac{64gSO_2}{32gS} \times 0.01 \times SO_x dsl \times (\frac{F_D}{F_E} \times 453.6 \times (1 - SO_x conv) - HC)$

EF ZM: Zero-mile emission factor; D: Deterioration; M: Mileage; AF: Altitude adjustment factor; CF: Conversion factor; FD: Field density; FE: Fuel economy.

3.4. Case Study and Results Analysis

3.4.1 Case Description

To compare open cut installation with trenchless methods, a case study was monitored and analyzed. In this case study, the open cut method was used in an installation project of a new 300 mm diameter storm line, a 250 mm sanitary line, and a 200 mm water line, with an overburden depth of 2 m to 5 m, and lengths of 460 m, 250 m, and 325 m in Edmonton, Alberta (Table 3-3). Equipment and activity data were collected onsite by monitoring the construction operation. In this study, the emissions from construction equipment were considered.

Table 3-3- The project main lines: storm, sanitary, and water lines

Work Package	Line	Diameter (mm)	Length (m)	Slope (%)	Depth (m)
	Storm	300	460	0.36-4	2-5

	Sanitary	200	250	0.40-0.43	2-5
	Water	200	325	-	2-4
		Diameter (mm)	Quantity	Distance (m)	
	Man Hole	900	15	20-90	3-5
	Catch Basin	600	3	17.5-25	3-5

3.4.2. Open Cut Field Data and Calculation

The on-site construction operation for installing new lines using open cut consists of trench excavation, bedding, placing and joining the pipes, embedment, backfill, and compaction of the soil. The average daily equipment operating times and usage were recorded through observation and the gathering of equipment specific records onsite. The results are presented in Table 3-4, which also shows the equipment name, make, model year, tier category, and list of activities.

Table 3-4- The actual equipment daily operating times and usage in open cut process

Equipment	Make	Model	Tier	Power (hp)	Activity	Daily Hours of Use (hr)
Hydraulic Excavator	Caterpillar320D	2009	3	140	1.Compaction 2.Bedding 3.Pipe Installation 4.Embeding	8

					5.Back fill	
Wheel Loader	Caterpillar930H	2010	3	149	1.Bedding	8
					2.Pipe Installation	
					3.Embeding	
Hydraulic Excavator	Caterpillar336 DL	2009	3	268	1.Excavation	8
					2.Back fill	
Track Loader	Caterpillar963C	2010	3	158	1.Back fill	8
Excavator	John Deere 450D	2010	3	384	1.Excavation	4
					2.Back fill	
Single Drum Vibratory Rollers	BOMAG BW211D-50	2009	3	120	1.Compaction	8
Plate Compactor	Subaru-PB147	2012	4	6	1.Compaction	6

The average daily progress of the line installation was calculated and is presented in Table 3-5. The progress shown in this table are for the days that the crew were completely involved in line installations and there were minimal interruptions and shutdowns due to weather conditions and equipment repairs. The water main lines work under pressure; therefore, the pipe installation was at the same level the length of the line. However, the installation of sewer lines had to follow the designed grades and slopes. Consequently, the daily progress of water main installation was greater, near to 9.46 m/hr compared to 8.38 m/hr in sewer lines.

Table 3-5- Sample daily progress of line installation

Date	**Working Time (hr)**	**Installation(m)**	**Line**
15 Aug	11	97	Storm-Sanitary
16 Aug	11	85	Storm
17 Aug	11	92	Storm
18 Aug	11	90	Storm
19 Aug	11	97	Storm
Average (m/hr)		8.38	
26 Aug	10.5	98	Water
27 Aug	8	76	Water
28 Aug	11.5	110	Water
Average (m/hr)		9.46	

Project details, including equipment specifications, model year, and engine power, were used to determine the emissions factors mentioned in the EPA methodology. To facilitate the calculations for various methods, a spreadsheet was developed using Equation 1. The daily emissions of equipment were estimated based on hours of use, and the total daily estimated emissions generated by the open cut process are illustrated in Table 3-6.

Considering the average progress of installations illustrated in Table 3-5, the average emissions from equipment per meter of storm, sanitary, and water line installations can be calculated. Table 3-7 shows the average emissions for open cut line installation. As mentioned above, due to different installation specifications for sewer and water lines, the daily progress and estimated emissions are different for each.

Table 3-6- Emission factors and footprint from construction equipment sources for the open cut project

Emission Factor (g/hp-hr)								**Emission (kg)**					
Equipment	**Make**	**HC**	**CO**	**NO$_X$**	**PM**	**CO$_2$**	**SO$_2$**	**HC**	**CO**	**NO$_X$**	**PM**	**CO$_2$**	**SO$_2$**
Hydraulic Excavator	**Caterpillar 320D**	0.20	1.52	2.62	0.47	535.72	1.08	0.13	1.00	1.73	0.31	354.01	0.72
Wheel Loader	**Caterpillar 930H**	0.43	2.42	3.04	0.66	625.27	1.26	0.30	1.70	2.14	0.47	439.74	0.89
Hydraulic Excavator	**Caterpillar 336 DL**	0.20	1.31	2.62	0.32	535.72	1.08	0.25	1.66	3.31	0.41	677.67	1.37
Track Loader	**Caterpillar 963C**	0.43	2.47	3.04	0.70	625.26	1.26	0.32	1.84	2.27	0.52	466.30	0.94
Excavator	**John Deere 450D**	0.18	1.40	2.61	0.28	535.79	1.08	0.15	1.15	2.14	0.23	440.03	0.89
Single Drum Vibratory Rollers	**BOMAG BW211D-50**	0.43	2.45	3.04	0.69	625.27	1.26	0.24	1.39	1.72	0.39	354.15	0.72
Plate Compactor	**Subaru-PB147**	0.55	4.22	4.31	0.30	588.60	1.19	0.01	0.07	0.07	0.00	9.11	0.02
Total		2.41	15.79	21.28	3.42	4071.63	8.23	2.79	18.03	28.31	4.83	2741.00	5.54

Table 3-7- The average emissions from construction equipment per meter of different lines during open cut installation

Line	**Emission (kg)**					
	HC	**CO**	**NO_X**	**PM**	**CO_2**	**SO_2**
Storm/Sanitary	0.04	0.27	0.42	0.07	40.89	0.08
Water	0.04	0.24	0.37	0.06	36.22	0.07

3.4.3. Trenchless Installation Alternatives

Contractor estimators in Edmonton were consulted to provide project productivity estimates had the project been completed using auger boring and HDD. Details of activity durations and the equipment required for construction were obtained from the contractors' estimates.

3.4.3.1. Auger Boring Methods

Based on data provided from contractors, the required equipment list is illustrated in Table 3-8. Some of the equipment in this list consume fuel and are sources of emissions. The above information is also used in augur boring, and data is tabulated in Table 3-9. Based on the contractors' estimations, the daily progress of auger boring in the installation of underground lines is about 25 m. Considering equipment specifications and provided estimations for daily progress, the total emissions from equipment were calculated and shown in Table 3-10. The last row of the table shows the total emissions (kg) per meter of auger boring pipe installation.

Table 03-8- The equipment list in auger boring

Number	Machinery	Activity
1	Guided Boring Machine	Excavation and pipe installation
2	Power Pack	Provides hydraulic power
3	Guidance System	Provides line and grade accuracy for the GBM system
4	Pilot Tube	Allows for fluid passage to the steering head
5	PRH Kit	Auger drive for spoil removal to reception shaft
6	Augers and Casings	Assembly and soil discharge
7	Lube Pump	Offers independent flow control of jetting and lubrication operations

Table 0-9- The specification and operating times of emission sources in auger boring

Equipment	Make	Model	Tier	HP	Activity	Daily Hours of Use
Power pack	Akkerman P150D	2014	4	154	Providing hydraulic power	8
Lube pump	Akkerman 2325D	2013	4	34	Flow control	8

Table 3-10- Emission factors and footprints from equipment for auger boring

Emission Factor (g/hp-hr)								**Emission (kg)**					
Equipment	Make	HC	CO	NO_X	PM	CO_2	SO_2	HC	CO	NO_X	PM	CO_2	SO_2
Power pack	Akkerman P150D	0.13	0.15	3.00	0.02	530.62	1.07	0.06	0.07	1.45	0.01	255.55	0.52
Lube Pump	Akkerman 2325D	0.13	0.09	0.28	0.01	589.95	1.19	0.01	0.01	0.02	0.00	44.65	0.09
Total		0.26	0.24	3.28	0.03	1120.57	2.27	0.07	0.08	1.47	0.01	300.20	0.61
Total Emission (kg) per meter of pipe installation								0.0029	0.0033	0.0587	0.0004	12.0078	0.0243

3.4.3.2 Horizontal Directional Drilling

The required equipment lists, and related activities provided by professional contractors in this area, are illustrated in Table 3-11. The specifications and operating times of emission sources in the HDD process, which are required to estimate the emission factors, are shown in Table 3-12. Based on the contractors' estimations, the daily progress of HDD in the installation of underground lines is about 100 m. Table 3-13 illustrates the estimated emissions per meter of pipe installation in HDD based on the daily progress of 100 m.

Table 3-11- The equipment list for HDD

Number	Machinery	Activity
1	Dump Truck	Hauling excavations
2	Flatbed Trailer	Transportation
3	Horizontal Directional Drill	1-Boring pilot hole 2-Pre ream 3-Pull back
4	Mud Trailer	Supplying the drilling fluid
5	Pickup Truck	Transportation
6	Loader, Skid Steer	Excavation

Table 3-12- The specification and operating times of emission sources in HDD

Equipment	**Make**	**Model**	**Tier**	**HP**	**Activity**	**Daily Hours of Use**
Horizontal Directional Drill	Vermeer D40x55 S3	2012	Tier 4	140	1-Boring pilot hole 2-Pre ream 3-Pull back	8
Mud Trailer	Vermeer MX240	2012	Tier 4	22	Supplying the drilling fluid	8
Loader, Skid Steer	Cat 416F	2010	Tier 3	88	Transportation	2
Vacuum Truck	DitchWitch FX25	2012	Tier 4	31	Excavation	2

Table 3-13- Emission factors and footprint from equipment sources for HDD

Emission Factor (g/hp-hr)								**Emission (kg)**					
Equip.	Make	HC	CO	NO_X	PM	CO_2	SO_2	HC	CO	NO_X	PM	CO_2	SO_2
Horizontal Directional Drill	Vermeer D40x55 S3	0.13	0.09	0.28	0.01	530.62	1.07	0.06	0.04	0.13	0.00	255.55	0.52
Mud Trailer	Vermeer MX240	0.44	2.22	4.45	0.31	588.97	1.19	0.03	0.17	0.34	0.02	44.57	0.09
Loader, Skid Steer	Cat 416F	0.47	6.28	3.64	0.39	695.12	1.41	0.02	0.23	0.13	0.01	25.69	0.05
Vacuum Truck	DitchWitch FX25	0.13	0.15	3.00	0.02	589.95	1.19	0.00	0.00	0.08	0.00	15.73	0.03
Total		1.18	8.75	11.36	0.73	2404.66	4.86	0.12	0.45	0.68	0.04	341.54	0.69
Total Emission (kg) per meter of pipe installation								0.0012	0.0045	0.0068	0.0004	3.4154	0.0069

3.4.4. Comparison of GHG Emissions between Open Cut and Trenchless Methods

The comparison of estimated GHG released from pipe installations using open cut, auger boring, and HDD is depicted in Figure 3-3. In this Figure, two open cut categories represent the installation of different underground lines, gravity storm and sanitary lines, and pressure water lines.

The results reveal that the trenchless construction options cause fewer airborne emissions compared to open cut. The average percentage of reduction in emissions, calculated based on the unit length of pipe installation, is 86.43 percent in auger boring and 95.59 percent in HDD compared to the traditional open cut method.

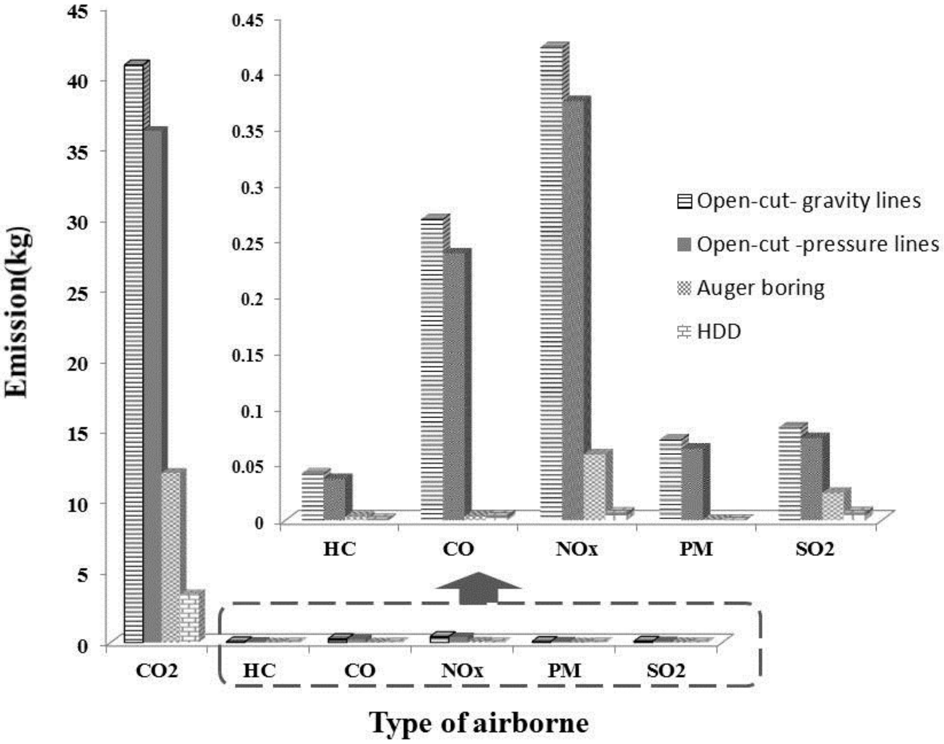

Figure 3-3- Emission comparison between open cut, auger boring, and HDD

In auger boring, the pilot tube steering system allows accurate installation of the desired line and grade, and it is recommended for the installation of storm and sanitary sewer pipes (Bruce 2002).

Water lines are generally not designed to be installed in specific slopes and usually work under flow pressure; therefore, trenchless construction methods with less accuracy in grades, such as HDD, are suitable for them. Thus, detailed comparisons between open cut installations for both groups of lines, with recommended trenchless methods for each of them, were performed and results are shown in Figure 3-4 and Figure 3-5.

Figure 3-4 shows that auger boring reduces all airborne particles by 70 percent to 99 percent compared to open cut installations. It can be seen that carbon dioxide (CO_2), which is the main component of GHG emissions, was reduced by 70.63 percent, and governs the emissions reductions from the quantity point of view (28.87 kg). The amounts of PM, CO, HC, and NO_X were decreased by 99.44 percent, 98.77 percent, 93.02 percent and 86.10 percent, respectively, when changing from open cut to auger boring. The lowest reduction occurred for SO_2, which was 69.61 percent.

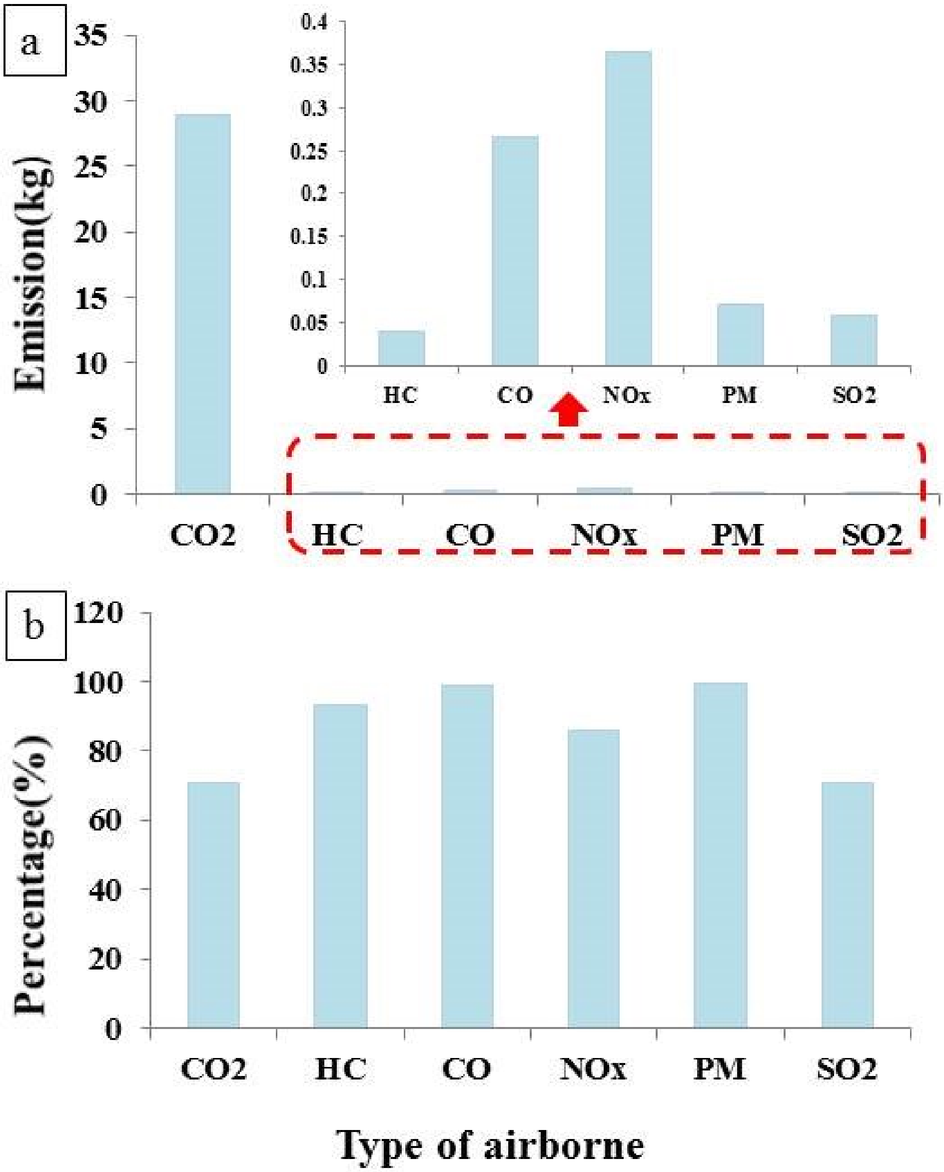

Figure 3-4- The reduction of emissions using auger boring compared to open cut. (a) The actual reduced amounts (b) Relative reduction (%)

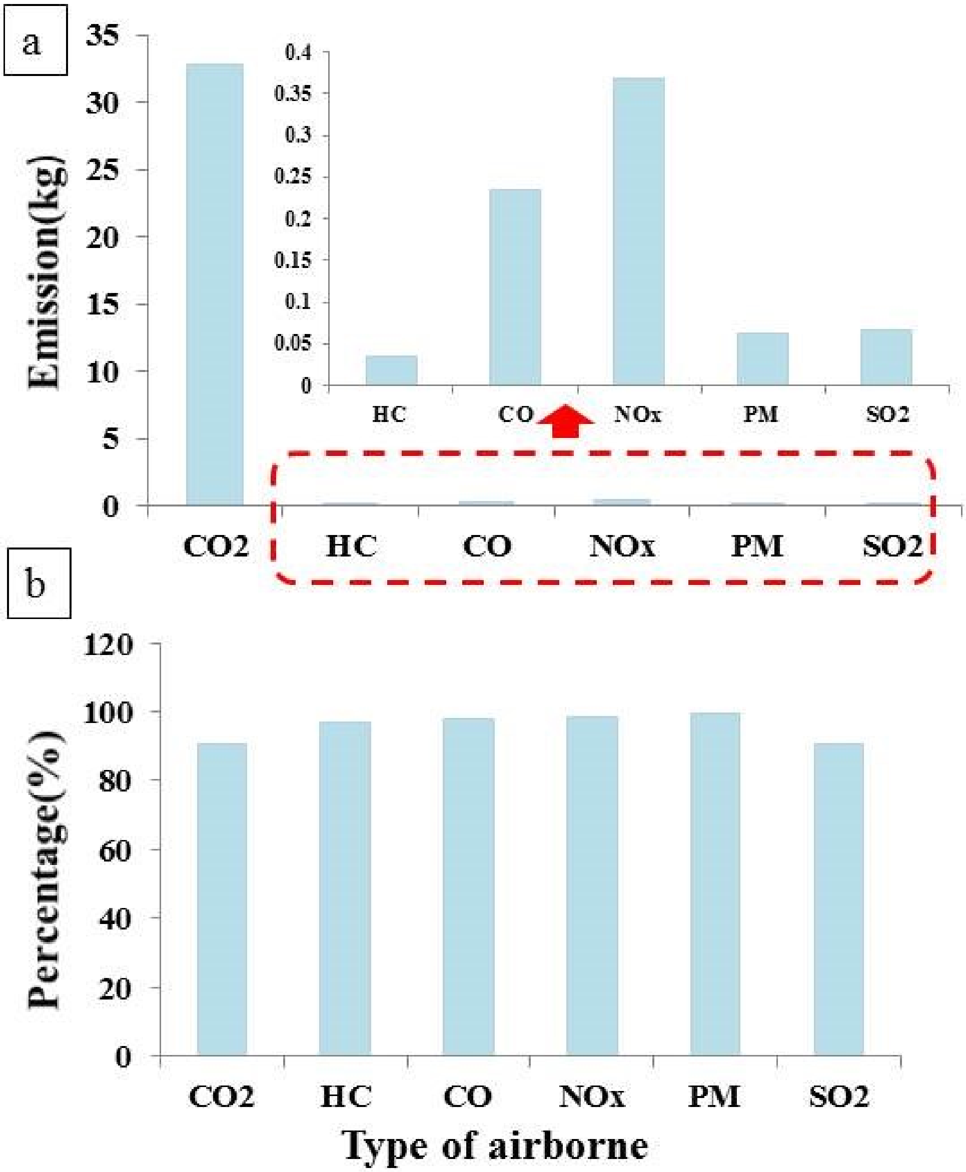

Figure 3-5- The reduction of emissions using HDD compared to open cut. (a) The actual reduced amounts (b) Relative reduction (%)

Figure 3-5 presents the emissions from the open cut installation of water lines compared to the trenchless HDD method. The results reveal that emissions decreased by approximately 90 percent to 99 percent when using HDD. For instance, HDD decreased the amount of CO_2 by 90.56 percent and 32.80 kg for each meter of pipe installed, which means a significant reduction in the whole project. Using HDD resulted in the amounts of PM, NO_X, CO, and HC diminishing by 99.37 percent, 98.18 percent, 98.11 percent, and 96.74 percent, respectively. The lowest depletion was 90.57 percent in SO_2.

3.5. Conclusions

With global commitment to achieve the GHG emission reduction target, there is an urgent need to quantify the emission footprints of industries and make more environmentally friendly technologies.

This study investigated an environmental impact comparison between traditional open cut, auger boring, and horizontal directional drilling (HDD) in underground utility projects by focusing on the emissions associated with them. The GHG indices were used to evaluate the performance of each method.

It was found that the GHG emissions generated from open cut were significantly higher compared to the trenchless options, and the total estimated amount of GHG emissions released into the environment was significantly reduced by 70 to 99 percent in auger boring, and by 90 to 99 percent in HDD, when compared to open cut. The results are inline with previous studies on emission foot print from trenchless methods. However, as the calculation is based on one estimation from one local contractor in Edmonton, Alberta, using these results and expanding them to other project locations would be limited.

Based on this study, higher GHG emissions in the open cut method is a result of longer project durations and more equipment requirements compared to smaller underground excavation when using the trenchless methods. Trenchless methods increase productivity as they require less excavation and are feasible in most weather conditions, resulting in fewer delays. Trenchless options also reduce equipment requirements, which yield a reduction in GHG emissions. Due to the scale of city projects, switching to a trenchless method in urban underground construction projects would lead to considerable reduction in GHG emissions.

4. Cost Comparison of Trenchless Technologies and Open Cut Methods in New Residential Land Development

Abstract: Sustainable development of underground infrastructure that considers environmental, social, and economical aspects is one of the main concerns in urban construction. It is important to study cost as an essential element in the sustainable development of underground infrastructure. Project owners and decision makers look for economical methods for underground installation and renewing of underground utility pipes. This study compares the construction costs and social impacts of traditional open cut, auger boring, and HDD in underground pipeline projects. The author estimated the costs associated with different construction methods, including open cut and trenchless technologies, through a case study, which consisted of a storm line (460 m), a sanitary line (250 m), and a water line (325 m). Study results indicated that, (1) considering the productivity and constructability of trenchless methods in all weather conditions, especially in a cold area such as Alberta, trenchless methods are cost beneficial alternatives to open trenching; and (2), using trenchless technologies with good construction practices can lead to a significant reduction in social inconveniences and impacts to local residential and business areas compared to open cut methods of underground construction.

4.1. Introduction

Sustainable development of underground infrastructure by considering environmental, social, and economical aspects is one of the main concerns in urban construction. Nowadays, ecofriendly and cost-efficient construction methods are more acceptable as there is a growing trend to use effective alternatives for underground construction rather than traditional open cut. The most applicable alternatives are trenchless technologies, which include all underground construction and renewal methods, which have minimum or no excavation and require minimal surface restoration (Ariaratnam et al. 2013).

In today's competing construction market, cost is an essential element. Decision makers and project owners look for economical methods for underground installation and renewal of underground utility pipes (Najafi and Kim 2004). Advancements in technology and improvements in trenchless construction options result in competition with traditional methods.

Generally, it is assumed that trenchless methods are more expensive than traditional open cut options since trenchless methods require expensive technical equipment, and execution of trenchless methods are assumed limited to expert contractors. However, considering environmental effects (cutting trees, removing green areas, and greenhouse gas emissions (GHG)), indirect costs and social inconvenience (traffic disruptions, pavement damage, dust, and noise) during open cut would make trenchless alternatives more efficient. Moreover, trenchless methods are generally faster than conventional methods and are applicable during most of the year in most weather conditions, which help project owners to reduce idle times, and, consequently, allow for faster operation and higher revenues (Hay 2014).

4.2. Previous Research

Researchers have compared conventional open cut construction with trenchless technologies and evaluated a wide range of areas, including planning and engineering methods, construction issues, environmental and social impacts, as well as cost and economical concerns.

Tighe et al. (1999) studied traffic delay cost savings associated with trenchless technologies. The study focused on cost savings in trenchless methods due to the elimination of traffic disruptions associated with excavation and trenching in conventional open cut methods. Tighe et al. suggested a methodology to consider the cost of traffic delays associated with open cut trenching methods. The results showed that eliminating traffic disruption in trenchless technologies makes them an economical alternative to open cut.

Tighe et al. also performed a study in 2002 to compare the overall project costs of traditional open cut methods with trenchless technologies. They considered different factors, such as performance, future maintenance costs, and user-delay costs in the study. It was concluded that surface restoration costs were comparable and trenchless construction methods a feasible alternative to open trenching options, especially in developed urban areas. The results indicated that traditional open cut methods reduce the life of pavement about 30 percent and also increase the maintenance and rehabilitation costs of pavement from 85CAD/m^2 to 146CAD/m^2. However, trenchless technologies have fewer costs associated with pavement disruptions.

Najafi and Kim (2004) compared conventional open cut construction with trenchless options. The study comprised all engineering, capital, and social costs of construction in both methods. They concluded that trenchless methods were generally cheaper, especially when comparing pavement lifecycle costs. Najafi and Kim also deduced that, because of lower initial construction costs of traditional open cut, local agencies, municipalities, consulting and design engineers are slow in identifying trenchless technology benefits. However, a lifecycle cost analysis would reflect the real advantages of trenchless methods.

Kulkarni et al. (2011) studied a cost comparison of horizontal directional drilling (HDD) with traditional open cut installation in three different projects. These projects included installation of a 100 mm and a 150 mm PVC pipe in Texas, and a 150 mm PVC pipe in Florida. The results of cost analysis indicated that HDD is more cost effective than open cut for the installation of the small diameter PVC pipelines, with an average of 39 percent in these case studies.

Ariaratnam et al. (2013) examined environmental impact, costs, and social impacts of four construction techniques: open cut, pilot tube micro-tunneling, horizontal directional drilling, and vacuum micro-tunneling technology, which are common methods in the installation of underground utility infrastructure. The paper contributed to developing an overall underground sustainability index rating (USIR) through case studies based on the aforementioned factors. An installation project in Portland, Oregon was used as a case study to demonstrate the application of USIR. The project consisted of 313 m of 400 mm PVC sewer line. The project costs were estimated, all cost factors related to this project were considered, and a subjective evaluation quantified social impacts. The results emphasized the inherent advantages of trenchless methods in these areas.

In another study, Ariaratnam et al. (2014) provided a discussion on trenchless technologies, especially pipe bursting trends, for replacement and renewal of underground systems. The study included results from a survey questionnaire examining 886 projects from 2007 to 2010 in Canada and the United States, and the results supported the advantages of trenchless technologies. Islam et al. (2014) assessed social costs in trenchless projects, comparing them to traditional trenching methods through five case histories in different countries, including the United States, Austria, Italy, and Belgium. They used the Social Cost Calculator (SCC) developed in the Trenchless Technology Center (TTC) at Louisiana Tech University, and the results showed that the social cost of trenchless alternatives are significantly lower than the open cut method, and trenchless methods reduce a project's associated social costs by a factor of 5 to 17.

Whitehead et al. (2015) studied various challenges in constructing the underground pipeline in a heavily-populated area through the Southern Delivery System (SDS) in Colorado. The study identified some challenges with potential disruption to neighbouring businesses, traffic control, safety, construction noise, vibration, and dust. Whitehead et al. found that trenchless technologies saved time and money in this project, and also facilitated a safer project with fewer social inconveniences.

As stated above, cost effectiveness of construction methods is an important factor in selecting the appropriate option for each project. Clear definition of all cost items would help the designer have an impressive economic evaluation of the project. Based on the above literature review, few similar research studies have been conducted in underground construction projects in Canada. Additionally, there are limited price evaluation studies available for the use of local contractors in Edmonton, Alberta. Traditional open cut methods are still prevalent in Canada for underground development. This study aims to present the benefits of using trenchless alternatives rather than traditional open cut methods from economic and social impact standpoints.

4.3. Underground Construction

Increasing demands to develop urban areas results in the construction of more infrastructure lines, including telecommunication, sewerage, water supply, and waste management. As many parts of these infrastructure developments are underground installations, there is a growing trend to use effective means of underground construction other than traditional open cut construction. The main concerns in finding alternatives are sustainability principles, such as environmental impact, cost, and social impacts (Ariaratnam 2013).

4.3.1. Traditional Open Cut

Open cut, or trenching, is the conventional method for construction, replacement, and renewal of underground utilities. This method includes trenching along the alignment of utility lines, supporting slope sides (the trench wall in most cases), placing the utility line, and finally backfilling and compacting the trench soil. For many years, these methods have been considered appropriate for the installation of underground infrastructure networks because there were no alternatives available other than direct trenching (Najafi 2004).

Open cut methods create high social costs to the general public, including traffic disruptions, pavement damage, dust, and construction noises. Moreover, environmental concerns, such as damage to trees, removing green areas, and high GHG emissions, are also part of the open cut disadvantages. Decision makers and social activists are focused on drawbacks associated with this traditional method, and are looking for effective alternatives to decrease or eliminate these disadvantages.

4.3.2. Trenchless Technologies

Trenchless technologies were established in the mid-1980s, and many developments have arisen since then. These developments include the availability of more powerful drilling and tunneling equipment, tracking tools, and pipe-ramming equipment, as well as better pipe materials and joints. Advancements in technology facilitate applying alternative means of installation, including trenchless techniques, or no-dig methods, which involve pipeline installation and renewal with minimum surface excavation. Therefore, these trenchless techniques have fewer impacts on surrounding areas.

4.3.2.1. Auger Boring Method

Auger boring is a common trenchless method, which is efficient in the installation of underground utilities, such as water lines and gravity sewer pipes. Using guided boring machines with guidance systems provides accurate pipeline installation. This accuracy is achieved through the use of video monitor surveillance of an illuminated target via a theodolite guidance system. The process of using this method consists of three stages: installation of a pilot tube, installation of a reaming head and auger tube sections behind the pilot tubes, and finally, installation of the product pipe.

Similar to other construction methods, auger boring has benefits and drawbacks. In this method, there is a minimal ground surface settlement because the casing is installed as the bore excavation takes place. This method is also applicable in a variety of soil conditions, which makes it a more common and available technology. Conversley, there are some limitations to this method, including requiring large entrance and receiving pits, and needing various sizes of augers and cutting heads for different sizes of casing.

4.3.2.2. Horizontal Directional Drilling

Horizontal directional drilling (HDD) is a trenchless method that has a low impact on surrounding areas. In most cases, HDD is a two-stage process: drilling a pilot hole along the proposed design centerline, enlarging the pilot hole to the appropriate diameter for the product pipeline, and pulling the pipe back in the hole at the same time. For pipes with larger diameters, repeating the second stage may be required to have the desired size, and then the pullback operation is performed separately.

Engineers have many concerns about using HDD in their projects. The main concern associated with this method in water and sanitary sewer construction is the installation of the pipe to grade, which is essential for gravity flow systems. Nowadays, there are tracking electronics, which measure grade and help this method to be precise for grade work.

4.4. Research Methodology

Project costs are usually categorized into three groups: preconstruction, construction, and post-construction. Preconstruction costs include all costs associated with preparations before starting construction on the job site, such as studying existing conditions on the site, engineering and planning, land and permit acquisition, and any provision costs. The most significant cost category is construction costs. This category includes all direct, indirect, and social costs arising at the time of construction. The last category is post-construction costs, which are also called operation and maintenance costs, and include all costs related to activities for operating and maintaining the construction site, and also depreciation and loss of revenue costs.

This study focuses on construction costs (direct, indirect, and social) to show the difference between open cut and trenchless construction. Direct and indirect costs are measurable in dollar amounts; however, social impacts and their influences require qualitative comparison.

4.4.1. Construction Costs

4.4.1.1. Direct Cost

The direct costs of construction include all costs directly involved in the construction stage of projects, such as the cost of labour, materials, equipment, and subcontractors' expenses. In pipe installation projects, direct costs include pipe material, mobilization, detour roads, trenching and excavation, backfilling and compaction, and labour and machinery costs related to these activities. Cost factors are either major or minor in estimating the total construction costs, depending on the type and size of the project, and construction method.

4.4.1.2. Indirect Cost

The indirect costs, which are also called “cost of doing business,” include all head office and job overhead costs (such as taxes, temporary utilities, field supervision, traffic control, profit, contingency, and insurance costs) that are normally fixed and spread out over the entire project (Najafi 2004). Indirect costs are added as a percentage of the direct costs after detailed estimation of direct costs has been conducted. Based on the type, size, and duration of the construction project, indirect costs can be a percent of the direct cost, and this estimation requires remarkable knowledge about construction.

4.4.2. Social Impact

The most difficult component of the cost to quantify is social inconvenience cost. Social impact is subjective, and includes damages to the environment and disruption to surrounding areas and existing structures. Growth of public awareness about the quality of life and protecting the environment resulted in the necessity for more research to quantify social costs of different construction methods. Various modeling techniques have been developed by researchers based on the percentage of occurrence and level of impact for determining socials costs. To compare different installation methods, various possible social impacts in a specific project can be defined, and numerical weights can be assigned to each factor, finally evaluating the average weight of the factors in all alternatives to identify the best solution.

4.5. Case Study and Results Analysis

To assess the cost of construction in three different pipe installation methods, a case study on a project in Edmonton using traditional open cut construction is demonstrated and compared with two different trenchless alternatives.

4.5.1. Project Description

The project included installation of storm, sanitary, and water lines, as shown in Table 4-1, to develop an area for future residential community construction. All lines, including main and service lines, and connections, were installed with the traditional open cut method. Cost component data was obtained onsite by monitoring the open trench construction operation.

Table 4-1-Project specification: main lines, service lines

	Quantity		**Sum**
Main Line	Storm	460 m	1035 m
	Sanitary	250 m	
	Water	325 m	
	MH/CB*	18 EA	---
	FH**	3 EA	
Service Line	Storm	160 m	608 m
	Sanitary	208 m	
	Water	240 m	

**: MH: Manhole, CB: Catch Basin **FH: Fire Hydrant.*

In this project, the traditional open cut installation process started with the excavation of the entire alignment of the main line pipe to facilitate pipe placement, and continued by digging holes and pits required for manholes and catch basins. In some areas, especially near to main city lines, a hydro-vac excavator was needed to avoid damages to existing underground utilities. As the soil condition and trenching slope were suitable to support the trench walls, there was no need for shoring and supporting components to support the trench. The next steps were covering the trench with bedding material, placing and joining the pipes, embedment, and finally backfilling and compaction the soil (Figure 4-1).

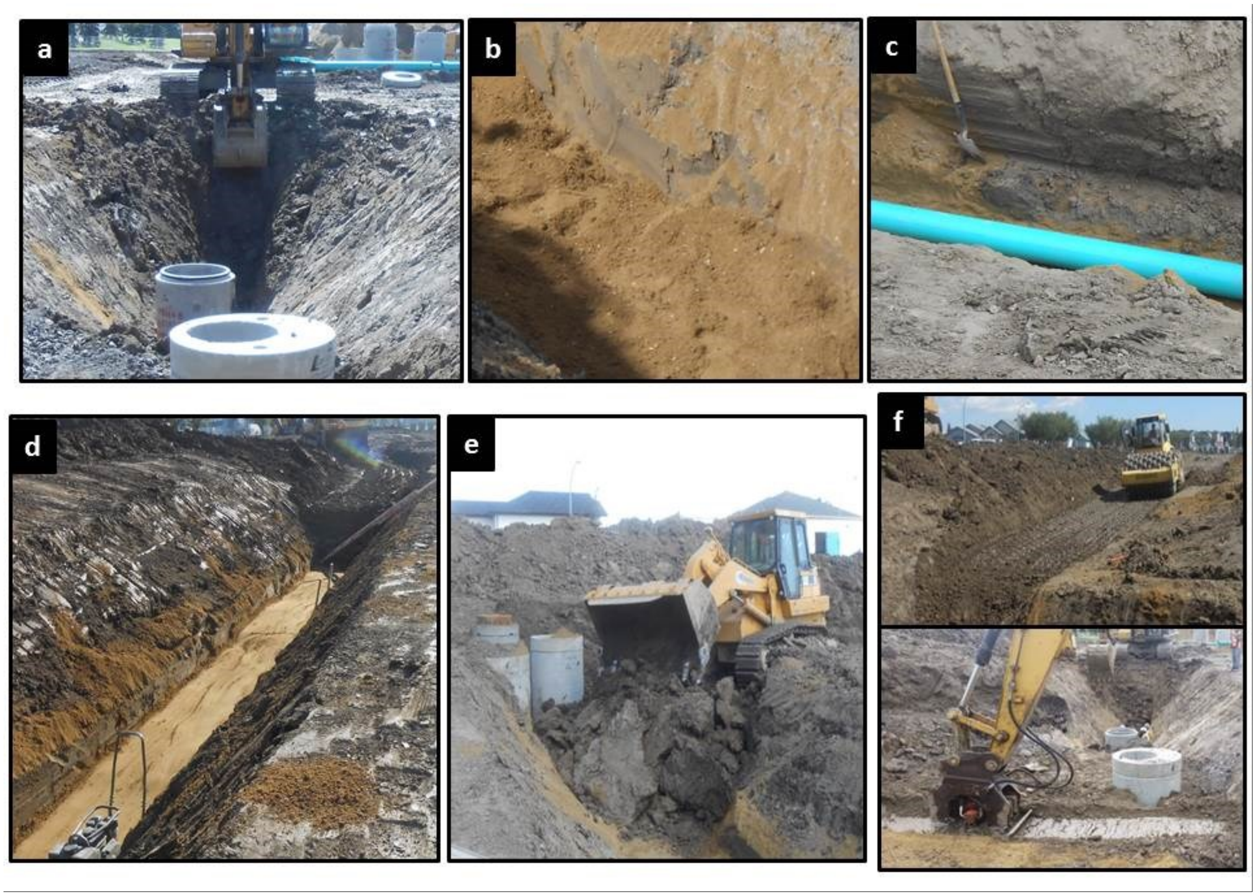

Figure 4-1-Main line installation by open cut: a) excavation, b) bedding, c) pipe installation, d) embedment, e) back fill, f) compaction

In the corners of the lines, or connection points, where the designers placed manholes and catch basins, the same installation procedure has been used (Figure 4-2). After completion of the main line, manholes, catch basins, and fire hydrant installations, the contractor continued the project by installing the service lines and connections. The service line installation process started with the excavation of connection points, which were marked during the main line installation. For the storm and sanitary lines, the connections were available and installed before; however, for the water line, the pipe layers cut the main line pipe using specific cutting and piercings tool at joints, and attached the service PVC pipes to them.

Figure 4-2-Main line installation by open cut: a) man hole & catch basin, b) fire hydrant

The actual material usage, labour, and equipment operating times were recorded for calculating the cost of the project. Work package details, machinery, and labour information are shown in Tables 4-2 and 4-3. As time is one of the most significant components of the project, and any delays in construction may cause undesirable over costs, it is necessary to record working time and any shut downs during the project. The time table of the project, including active and shutdown days, is reported in Table 4-4. The project crew was working 142 hours on a regular base, and 55 hours of overtime in this project.

Table 4-2- Work package details

Work Package		Quantity	Material
Main Line	Storm	460 m	PVC pipe 250–300 mm
	Sanitary	250 m	PVC pipe 200 mm
	Water	325 m	PVC pipe 200 mm
	MH/CB	18 EA	Concrete 900/600 mm
Connection	Storm	160 m	PVC pipe 150 mm
	Sanitary	208 m	PVC pipe 150 mm
	Water	240 m	PVC pipe 50 mm

Table 4-3- Machinery and labour information for open trench project

Machinery		Labour	
Sheepsfoot Roller, 240HP	1	Foreman	1
CAT 963C crawler loader	1	Pipe Layer	1
CAT 450D HYD, Excavator	1	Pipe Layer Helper	1
CAT 336 DL HYD, Excavator	1	Top man	1
CAT 320DL HYD, Excavator	1	Machine Operator	4
CAT 930H Wheel Loader	1	Packer	1
Gas Plate Tamper	1	Labourer	2

Jumping Rammer	1	

Table 4-4- Time table of the open trench project

8 August– 7 September 2016	**Date**	**Hours**	**Date**	**Hours**	**Date**	**Hours**
	8 Aug	8.50	17 Aug	11.00	28 Aug	0.00
	9 Aug	0.00	18 Aug	11.00	29 Aug	11.50
	10 Aug	11.50	19 Aug	11.00	30 Aug	9.50
	11 Aug	10.00	20 Aug	0.00	31 Aug	9.00
	12 Aug	11.00	21–23Aug	0.00	1 Sept	10.00
	13 Aug	8.00	24 Aug	10.50	2 Sept	9.00
	14 Aug	0.00	25 Aug	0.00	3–5 Sept	0.00
	15 Aug	11.00	26 Aug	10.50	6 Sept	9.00
	16 Aug	11.00	27 Aug	8.00	7 Sept	6.00
	Active days			Shut down days		
	Calendar	Weekday	Weekend	Rainy day	Weekend	Holiday
Day	31	18	2	4	6	1
Percentage	*	58%	6%	13%	19%	3%

The direct cost of construction for each part of the work package is calculated based on actual material usage, labour, and equipment operating times. The unit cost of labour, material, and machinery were obtained from Alberta Government resources and local providers. The total cost of each work package includes labour, material, and machinery costs, which are calculated and compared to the total cost of the project. The total cost column shows the percentage of each work package's total cost compared to the project's total cost (Table 4-5). Table 4-5 also shows the percentage of different cost categories, including labour, material, and machinery costs in each work package and in the total cost of the project.

Table 4-5- Direct cost percentages of open trench project based on daily progress and Alberta costs

Work Package		**Duration (Hours)**	**Quantity**	**Labour cost**	**Material cost**	**Machinery cost**	**Total cost**
Main Line	Storm	62	460 m	32.10%	35.50%	32.40%	27.34%
	Sanitary	37	250 m	28.34%	43.07%	28.60%	16.68%
	Water	38	325 m	23.93%	51.91%	24.16%	22.57%
	MH/CB	14	18 EA	17.87%	64.09%	18.03%	10.58%
	FH	5	3 EA	22.20%	55.38%	22.41%	3.04%
Connection	Storm	12	160 m	26.68%	39.77%	33.56%	4.87%
	Sanitary	14	208 m	24.93%	43.72%	31.35%	6.08%
	Water	12	240 m	14.71%	66.79%	18.50%	8.84%
Total		197		26%	48%	27%	100%

Using work package details and unit cost provided by the RS Means data base, the costs associated with each part of the package, consisting of labour, machinery, and materials, were estimated and compared with authurs's estimation based on actual monitored project. Table 6 shows the cost comparison of the case study project estimation based on local sources and the RS Means data base. The table also includes the comparison with three bidders' total cost estimations to perform this project, which have been obtained from bid packages submitted by local contractors. The comparison of the estimation with local bidders verifies the accuracy of the estimation.

Table 4-6- Open trench cost comparison based on case study estimation, RS Means and bid

	Estimation	**RS Means**	**Bidder 1**	**Bidder 2**	**Bidder 3**
Total Project Cost	1	1.0282	1.0221	1.0262	1.3484

4.5.2. Alternative Trenchless Methods

Comparing open trench in this project with trenchless techniques requires cost estimation comparisons using similar projects that were performed with these alternatives. Two alternatives combining the different construction options are proposed for analysis. The two project alternatives are the installation of sewer lines, including storm and sanitary pipelines using horizontal auger boring, and the installation of a main water line using HDD.

In this study, local contractors were consulted to provide cost and productivity estimations. One estimation for each method from local contractors and the RS Means data base have been used to estimate the auger boring and HDD costs for this project.

4.5.2.1. Alternative 1: Auger Boring Method in the Installation of Sewer Lines

Auger boring is accurate for on-line and on-grade installation, and this method is recommended for storm and sanitary sewer lines because of its accuracy in slope installation (Martin et al. 2011).

Based on the local contractor's estimation, the daily progress of auger boring in the installation of underground lines is about 25 m. The machinery and labour information are illustrated in Tables 4-7.

Table 4-7- Machinery and labour quantity for auger boring

Machinery		**Labour**	
Guided Boring Machine	1	Labourer	4
Power Pack	1	Forman/Operator	1
Guidance System	1	Oiler	1
Pilot Tube	1	Welder	1
PRH Kit	1		
Augers and Casings	1		
Lube Pump	1		

4.5.2.2. Alternative 2: Horizontal Directional Drilling in Installation of Water Lines

HDD accuracy in pipe installation is more useful in the installation of pressurized pipe lines, such as water lines. However, there are some techniques to improve the HDD monitoring system. Professional contractors in HDD had some success in accurate installation (Ariaratnam 2013). The required equipment and labour list are illustrated in Table 4-8. Local contractors estimated that the daily progress of HDD in the installation of underground lines would be about 100 m for this project and pipe size.

Table 4-8- Machinery and labor quantity for HDD

Machinery		**Labour**	
Dump Truck	1	Labourer	2
Flatbed Trailer	1	Equipment operator	2
Horizontal Dir. Drill	1		
Mud Trailer	1		
Pickup Truck	1		
Loader, Skid Steer	1		

4.5.3. Cost Comparison Between Open Cut and Trenchless Methods

The comparison of costs, including capital and social costs, among open cut, auger boring, and HDD in pipeline construction, such as water, storm, and sanitary line installations, is discussed. As the service line installation used open trench, the comparison just includes the main line installation. The comparison is based on the estimated amount calculated in this study, considering local available labour, material, and machinery.

As discussed above, in this case study, all main lines were installed with the open trench method. The process was the same for all lines, except for laying and swinging the pipes, which needed more time for pipes that required slopes to function. Consequently, the cost is different between graded lines and water lines because of different installation productivity rates and materials.

The results showed that, direct installation cost of storm and sanitary lines using auger boring is about 3.15 times of open cut installation. The installation cost of water lines using HDD is about

1.53 times of cost in open trench installation of them. There are three main source of construction cost difference between traditional open cut and trenchless alternatives; the main difference is expensive equipment and machineries in trenchless methods comparing to open cut. On the other hand, because of automated installation process in trenchless methods, these methods would have considerably lower labour cost compared to open cut. The type of materials including pipe, manholes, and catch basins remain the same in both categories of pipeline installation, so there in no noticeable difference in this source of cost.

Based on the author's observations in this project, there were lots of interruptions, or even whole day shut downs due to raining. Although summer is construction season in Alberta, the weather created lots of delays in the schedule, which was about 13 percent of the total time of the project, and forced the contractor to work overtime each day and on weekends to make it up. However, it would have been possible to continue the pipe line installation during rainy days if trenchless techniques were used. Aditionally, the overtime and other unpredictable costs related to delays because of weather conditions would be less if trenchless methods were used.

Indirect costs are inherently dependent on the project's duration as the costs increase the longer a project takes (Najafi and Kim 2004). As discussed above, trenchless methods are more productive and are less sensitive to weather conditions, and the duration of completing underground installation projects are less than open cut. Therefore, indirect costs, such as head and field offices, field supervisions, and temporary utilities, are consequently minor in trenchless methods.

Social costs are specific to each project. Studying social costs in this project may differ from projects in complex urban areas, since this project was in an undeveloped green neighbourhood. The location of the project was in a residential community, with no or very low traffic, so the only disruption to vehicle traffic was the time of equipment transportation to the construction site. As there were no roads or paved area on job site, damage to existing pavement was not a concern. The only damaged road in this project was the area of connection to the main city lines out of the fenced area.

As this case study was in a new development area, factors such as loss of ground vegetation, public safety, dust, noise pollution, and waste material were applicable to this research. The social costs of all installation alternatives were compared in mentioned categories. In this installation project, the nearest structures to the project were an assured distance from construction, and were safe from any damages and settlement caused by open trenching. However, noise, vibration, and air pollution from heavy construction in the open trench method, especially during excavation and back filling, were the main social inconveniences in this project, which affected the area during construction.

4.6. Conclusions

Cost is an essential element when considering sustainable development of underground infrastructure. Considering social and economic aspects of a project are main concerns in sustainable urban constructions. Project owners and decision makers look for economical methods for underground installation and renewal of underground utility pipes. Advancements in technology and improvements in trenchless construction options result in remarkable competition with traditional methods, and no-dig methods are now more productive and society friendly than open cut utility construction.

Comparing open trench methods in this project with trenchless techniques required cost estimations from similar projects performed with trenchless methods. The actual material usage, labour, and equipment operating times from the open trench case study were recorded for calculating the cost of the project. The information, including cost and productivity from local contractors and the RS Means data base, was used to estimate auger boring and HDD costs for this project.

The results showed that, compared to other trenchless techniques, HDD is less expensive and more productive for pipeline installations. The installation cost using HDD for water lines with same slope in whole length is about 1.53 times of open cut. On the other hand, the unit cost of installation by auger boring is more expensive compared to open cut (3.15) and even HDD (2.05); however, considering the accuracy, productivity, and constructability of trenchless methods in all weather conditions, especially in cold areas such as Alberta, makes trenchless technologies beneficial alternatives to open cut.

Studying social costs in this project were different in some aspects from projects in complex urban areas since this project was in an undeveloped green neighbourhood. Noise, vibration, and air pollution were the main social inconveniences from heavy construction in the open trench method, especially during the time of excavation and back filling. These social costs would decrease significantly in trenchless alternatives because of less construction time and less equipment working on the ground.

5. Summary, Conclusions, and Recommendations

5.1. Summary

With the expansion of population in urban areas, development of new residential and commercial areas is essential to meet the needs of this ever-expanding population. Urban water and wastewater systems are fundamental infrastructures in this development, and are very important for high quality of life and strong urban economy.

Development of infrastructures in new residential and commercial areas is associated with different challenges these days. Environmental adaptability, cost effectiveness, safety, social conveniences during construction and seasonal constructability changes are some of these challenges, which should be considered in selecting of construction methods.

This research studied different challenges associated with underground construction of lifelines in new residential land development. The study demonstrated environmental impacts, construction costs, social inconveniences, and seasonal constructability comparisons between the traditional open cut and trenchless methods (auger boring and horizontal directional drilling (HDD) in two case studies, which consisted of three main lines: water, sanitary, and storm in Edmonton, Alberta.).

5.2. Conclusions

This thesis compared different underground installation methods in new residential land development in two case studies in Edmonton, Alberta based on values of indices used to evaluate environmental and social impacts, construction cost, and seasonal constructability of each method. The results revealed that:

- The GHG emissions generated from open cut in this project were significantly higher compared to that of the estimated trenchless alternatives. The total estimated amount of GHG emissions released into the environment was significantly reduced by 70 to 99 percent in auger boring, and by 90 to 99 percent in HDD, when estimated and compared to open cut.
- Quotations for trenchless installation methods from local contractor in Edmonton, Alberta shows that, compared to open trench, trenchless techniques are more expensive for pipeline installations in new urban area in Edmonton. The results of this study shows that, direct installation cost of storm and sanitary lines using auger boring is about 3.15 times the open cut installation. And the installation cost of water lines using HDD is about 1.53 times the cost in open trench installation of them.
- Studying the constructability of trenchless methods in in cold areas such as Alberta, shows that trenchless technologies are considerable alternatives to open cut. Interruptions in open cut installation case studies by extreme weather conditions as rain would have less impact on installation implementing trenchless technologies.
- As this project was in new residential development area, noise, vibration, and air pollution were the main social inconveniences from heavy construction in the open trench method, especially during excavation and back filling. The results indicated that these social costs would decrease significantly in trenchless alternatives because of less estimated construction time and less equipment working on the ground.

5.3. Limitation and Recommendations

Traditional open cut methods are still prevalent in Canada for underground development in new residential land development. Therefore, there is few information available for application of trenchless method in underground pipeline installation in new urban areas development. In the current study, the author compares trenchless alternatives based on one estimation and quotation from local contractor in Edmonton, Alberta for each trenchless method. Also, the construction costs of open cut installation in the case study project have been estimated based on local labour, material and machinery available in Edmonton, Alberta. This research presented the differences of using trenchless alternatives rather than traditional open cut methods from environmental, economic, social impacts and seasonal constructability standpoints. Further case studies in underground construction in new urban residential development using trenchless techniques is essential for accurate comparing the substitution of traditional open cut method with trenchless methods.

Accuracy in pipe installation, especially in on-grade pipelines as sewer lines, is very important to ensure they function correctly. Providing accurate tracking systems in trenchless methods is a substantial requirement to using trenchless techniques in underground construction. Further studies in accurate tracking systems would be beneficial as it would allow economical trenchless methods to be used for sewer lines installation.

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