Comparative Study between Hydro and Air Excavation Technologies

by

Roshan Rijal

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Civil (Cross-Disciplinary)

Department of Civil and Environmental Engineering

University of Alberta

Abstract

Infrastructure development is in demand throughout the world. Rebuilding and redeveloping are happening in urban areas across the globe, whether for installation of underground pipes for sewer, gas, water supply or for deployment of telecommunications and electrical cables. Given the ever-increasing demand for construction work for underground utilities, the requirement for excavation is also increasing. Traditionally, hand tools or mechanical excavators were used for underground utilities construction. However, this type of tools and machinery can be unsafe in certain circumstances, i.e. excavation near existing utilities or excavation for existing electrical cables or excavation for existing telecommunication lines. Also, traditional mechanical excavation equipment produces a large amount of greenhouse gases, whereas alternative methods such as Suction excavation technology (SET) are more cost efficient, and have less social and environmental impacts. Innovations in technology in recent years have led to suction excavation (hydro and air excavation) for underground utilities projects. Hydro excavation uses water during excavation and produces a waste mixture of solids and liquid which is known as slurry. Strict government guidelines/regulations must be followed before disposing slurry or backfilling at legal dumping site. However, air excavation uses pressurized air for excavation and produces less negative impacts on the environment. The excavation industry and government regulatory bodies have yet to recognize the benefits of air excavation, since it is a new technology compared to hydro excavation. This research provides a comparison between traditional and suction excavation, as well as hydro and air excavation technologies to determine which excavation method is the best solution for underground utility projects. The factors considered include productivity rate, cost, safety considerations, and environmental impact, and the choice of excavation method under different conditions i.e. ground conditions, moisture content, and applicable temperature ranges is also considered.

The study began with determining the overall cost of excavation for daylighting an underground utility by the traditional open-cut excavation using hand tools, mechanical excavation, and suction excavation. In addition, a comparative study was conducted between traditional and suction excavation technology in terms of life-cycle costs from pre-construction to post-construction for underground utility projects, considering the social and environmental costs. Furthermore, the Analytical Hierarchy Process (AHP) was applied to determine the most cost-effective method of excavation among hydro and air excavation with respect to direct, indirect, environmental, and social costs for underground utility installation and rehabilitation projects in urban areas. Finally, an online pilot survey questionnaire was conducted to investigate hydro and air excavation technology in detail to gain a thorough understanding of the conditions under which it is appropriate to use air and hydro excavation technologies.

Considering the life-cycle costs for a typical urban underground utility project, suction excavation was found to be more cost effective than traditional excavation methods. Also, after conducting an AHP considering direct, indirect, social and environmental costs with their respective weights based on expert opinion, air excavation was found to be the most cost-effective method for excavation project in urban areas. Furthermore, based on the responses collected from an online pilot survey, the total savings in terms of cost and time from excavation to management of slurry or dry earth is greater for air excavation than hydro excavation. In addition, air excavation is considered to be environmentally friendly due to reduced emission of greenhouse gases, and lack of requirement for fresh water during excavation, reducing the requirement for regulated disposal of excavated material at a waste management facility. However, air excavation is not suitable for conducting excavation during extremely cold (winter) conditions.

Preface

The work in this thesis has been completed by Roshan Rijal. This thesis is completed and worked by Roshan Rijal. The online questionnaire survey which forms part of thesis, “Survey of Hydro and Air Excavation Technologies,” Pro00097011 (January 31, 2020) received research ethics approval from the University of Alberta Research Ethics Board.

Dedicated to

My mother Menuka and father Rameswor, for unconditional love and providing motivation to complete the challenging work in foreign land.

My entire family, for their love and care.

To my wife Shreya Sharma and daughter Shanvi

Acknowledgements

I would like to express my deepest appreciation to my supervisor Dr. Alireza Bayat for his continuous support and guidance throughout the entire research and the coursework.

I would also like to take an opportunity to acknowledge TELUS, the University of Alberta, the National Science and Engineering Research Council (NSERC), and the Consortium for Engineered Trenchless Technologies (CETT) for providing the funding and support in conducting the research. This thesis would not have been possible without the help and revisiting my paper from our Research Coordinator Lana Gutwin.

I am also grateful to the support provided from Mr. Colin Donoahue (Ox Equipment) for his kindness and helpful nature in sharing information related to this research.

I would like to take this opportunity to appreciate all the professors who directly or indirectly helped me during the coursework.

I would also like to extend deepest appreciation to all the people who were directly and indirectly involved in extending their support in completing my research work.

Last but not the least, I would like to thank to my family, friends for their indefinite support throughout my journey of master studies.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Infrastructure development is in demand throughout the world. In particular, the demand for underground construction for the placement of utilities is increasing, due to increasing population in urban areas. According to a report published by the United Nations on World Urbanization prospects, 68% of the world population will be concentrated in urban areas by the year 2050, compared to 55% in the year 2018 (United Nations , 2018). This increase in urban population has increased the need for brownfield installation of underground utilities, which has the associated drawbacks of limited working space and more traffic disruption. According to American Water Works Association (2001), by 2030, the cost of pipe replacement will be three and a half times more than the cost of replacement in 2011 due to pipe deterioration and studies conducted on 20 utilities found that rehabilitation and repair requires more than $6 billion in revenue in North America compared to current spending at 2011 over the next 30 years (2001). In addition to this, the demand for internet bandwidth has been increasing, and higher bandwidth is in demand for better homeland security, classrooms, e-learning, e-banking, job opportunities, and ultimately a better quality of life (Ferris, 2004). The need for high-transmission broadband is due to the rise of streaming media, YouTube, online video streaming sites, etc. In North America, Netflix itself contributes towards 30% of peak internet traffic (OECD, 2014). For fulfilling this ever-increasing demand for high-speed bandwidth and replacement of underground utilities (water, gas, and electrical pipelines), underground construction is inevitable. To meet the increasing demand for the construction of underground utilities, specifically in urban areas, suction excavation technology (SET) is widely used, which can further be divided into hydro excavation technology (HET) and air excavation technology (AET). In hydro excavation, highly pressurized water is used to liquefy soil, creating a slurry mixture which is then extracted using a powerful vacuum or suction system (The Badger Hydrovac, 2020). In air excavation, highly compressed air (rather than water) is used to loosen the soil, and the disturbed soil is sucked up using a vacuum system into a disposal tank.

The selection of the proper excavation technology for underground excavation can help to deliver projects with greater time and cost savings when completing underground utility installations. The excavation technologies to be implemented for the execution of an underground construction project should also consider environmental and social aspects of the project. From an environmental point of view, excavation technologies are projected to be the major carbon dioxide emissions (Perry & Grace, 2014). In general, hydro excavation technologies have a greater impact on the environment due to the execution of a given excavation project. The social impacts during execution of an underground utilities project, including public safety, public health, worker safety, and disturbance to the surrounding landscape, among others, also should be considered. This research focuses on comparing existing traditional and new excavation technologies, considering such factors as environmental and social impacts, and the time and cost required to complete excavation project for installing, restoring, redeploying the underground utilities in urban areas.

1.1 Background

Excavation is an important aspect of many different construction projects, and the choice of the appropriate excavation technology can impact the overall delivery of a project in terms of cost and schedule. Traditional excavation methods for the construction of underground utilities have been open-cut methods using mechanical tools and machinery. The traditional method of excavation involves the use of hand tools for digging; the shovel is one of the most used hand tools in traditional methods of excavation. Mechanical excavators are also used including tracked excavators, wheeled excavators, back-hoe excavators, bulldozers, dragline excavators, trenchers, and dozers. However, this type of excavator is not feasible for installation and rehabilitation of underground utilities, as excavation is conducted over larger areas instead of excavating a limited area of utility location for rehabilitation. In recent years, innovations in technology have led to suction excavation technology being feasible for underground utilities projects. Considering different suction excavation technologies, hydro excavation is well-established; however, air excavation has many advantages, including no production of liquid waste, and less environmental impact.

1.2 Research Objectives and Scope

The main objectives of this thesis are listed as following.

Objective 1: To determine the cost effectiveness by comparing the overall cost of excavation for an underground utility daylighting operation using traditional open-cut excavation (hand tools), mechanical excavation, and suction excavation.

Objective 2: To perform a life-cycle cost comparison of traditional and suction excavation for underground utility installation.

Objective 3: To collect and analyze expert opinions regarding direct, indirect, environmental, and social cost aspects involved due to excavation in urban areas for underground utilities project by hydro and air excavation technologies using AHP.

Objective 4: To make a statistical comparison between hydro excavation and air excavation technologies to determine the effectiveness and productivity of Air excavation to the Hydro excavation under different conditions, i.e. ground conditions, moisture content, and applicable temperature ranges using information collected from online pilot questionnaire survey.

1.3 Research Methodology

To meet the above objectives, first, a comprehensive literature review about suction excavation technology was conducted. In conducting the literature review, as these are relatively new technologies, there is not much in the literature yet, information is collected from online resources, including limited academic publications, industrial guidelines, and recommendations from various industry experts. A detailed cost estimate for daylighting underground utilities using different excavation technologies was performed using the online cost database software RS Means (RSMeans , 2020). Another objective of this thesis to compare two innovative excavation methods: Hydro excavation and Air excavation with respect to Direct, Indirect, Environmental and Social Cost impact during the excavation project in urban areas was achieved using AHP. An analytical hierarchy process as developed by (Saaty T. L.) was used in decision-making process that utilizes ratio scales in making a decision from paired comparisons among different alternatives and provides a comparison between considered options.

The suggestions to execute which technologies is the better method for the application on excavation for installation of underground utility is suggested with the help of survey responses collected from industry experts working in SET field. The pilot version of online survey questionnaire was prepared using Survey Monkey software, and survey was distributed among industry expert from the field of SET. The survey contains 20 questions and divided into 3 sections:

Section 1 provides a questionnaire about the HET and asks the survey respondent for the information on the productivity rates of hydro excavator on different soil conditions, temperature ranges, moisture conditions and ground conditions. Furthermore, it has question related to Solid waste management facility and the cost for the treatment of slurry and backfilling cost of dry soil. Section 2 provides the similar question as in Section 1 but with respect to AET. Sections 3 contains questions for general information related to the excavators and contractors.

1.4 Thesis Structure

The thesis consists of a total of six chapters. A description of each chapter is given below.

Chapter 1 includes a brief background related to excavation technologies used in the installation and rehabilitation of underground utilities. This chapter also gives an overview of the problems associated with each excavation technology and the objectives of the current research. In addition, the methodology used to achieve the objectives is described. An overview of the thesis and its structure is also given.

Chapter 2 Literature related to innovative technologies used for the excavation in urban areas for the installation of underground utilities are described, focuses on determining the overall cost of excavation for daylighting underground utility by traditional open-cut using hand excavation, mechanical excavation, and suction excavation. Advantages and disadvantages of traditional and suction excavation methods are mentioned, including the treatment methods for the hydro excavation slurry.

Chapter 3 gives a comparison between HET and AET with respect to the direct, indirect, environmental, and social costs for excavation in urban areas. A stepwise AHP procedure is applied to reach the goal of determining the most cost-effective method of excavation for installation and rehabilitation of underground utility projects in urban areas.

Chapter 4 includes an investigation of HET and AET to gain a thorough understanding of when it is appropriate to apply air and hydro excavation methods by using online survey responses. The survey targeted companies that were involved in the suction excavation industry. In addition, a hypothetical scenario was created to compare two excavation method: hydro and air excavation by using the survey results.

Chapter 5 includes a comprehensive life-cycle cost comparison that was developed for traditional excavation and suction excavation for the installation of underground utilities, including the applicability and classification of excavation tools, along with their advantages and disadvantages.

Chapter 6 includes a summary of the results and conclusions of previous chapters. It also includes suggestions for future research that can be performed related to the present work.

Chapter 2: Advantages and Disadvantages of Suction Excavation Technology Compared to Traditional Open-Cut Excavation using Hand Tools and Mechanical Excavators

2.1 Abstract

This paper focuses on recent developments in excavation technology and facilitates a comparison between traditional excavation – i.e. excavation using hand tools or mechanical excavators – and suction excavation (including air excavation and hydro excavation) to determine the most cost-efficient method of excavation for daylighting underground utilities. Previously, open-cut excavation methods were compared with available trenchless technologies to determine the cost, safety, environmental and traffic impacts of each method for underground utility projects. However, the cost estimate in this research considered only direct cost, overhead and profit in RS Means. The cost per cubic meter of performing the daylighting operation using suction excavation was determined to be 38% and 14% lower than excavation using hand tools and mechanical excavators, respectively. In addition, the current research provides information on the advantages and disadvantages of suction excavation in terms of cost, safety, environmental and traffic impacts.

Keywords: *Daylighting, suction excavator*

2.2 Introduction

Experts within North America's underground construction industry are currently facing the challenge of adapting to modern needs. Rebuilding and redevelopment efforts are more and more frequent in urban areas across the globe. Whether underground pipes that supply safe water to the public or underground telecommunications cables that provide internet services to households are considered and these underground utilities have been laid out at different times. These different utilities have varying life expectancies and are in the dawn of the replacement era (Association, 2001). Additional strain is placed on aging infrastructure as communities and commercial areas expand with increasing population. According to report published by United nations on World Urbanization prospects, 68 % of the world population will be concentrated in urban areas by year 2050 in compare to 55 % in year 2018 (United Nations , 2018). The increase in population has increased brownfield installation of underground utilities that has the associated drawbacks of limited working space and more traffic disruption.

Traditionally, open-cut methods were widely used for the utility installation (Neil & Samuel, 2008). However, open trench construction methods require more excavation than trenchless methods. The cost related to double handling soil and resurfacing the excavated area can be up to 70 % of total cost on an open cut project by using mechanical excavation equipment for excavation (Mohammad & Kyoung, 2004). The excavation of trenches for open-cut utility rehabilitation requires the removal of streets and sidewalks, causing an increase in the expense of repairs. One recent innovative in excavation technology that can help to reduce the impact caused by open-cut methods in excavation projects is performing excavation using suction excavation technology (SET). SET can be used to excavate soil to prepare the ground for underground facilities, reducing the cost and time to complete an excavation project.

SET, is a set of non-destructive excavation methods where excavation is accomplished by removing soil using suction pressure. SET can further be subdivided into HET and AET. HET utilizes pressurized water to break up the soil, whereas air excavation uses pressurized air for the same purpose. Both hydro and air excavation make use of a vacuum to suction the excavated material, and both can be conducted with limited open access. However, slurry is formed during the excavation process using hydro excavation, and this slurry is commonly referred to as hydrovac waste (Government of Alberta, 2018). The slurry produced during hydro excavation generally consists of about 60% liquid and 40% percent solids (Government of Alberta, 2018): it is neither soil nor water and requires appropriate disposal. Due to the reliability and accuracy of SET, the demand for suction excavation is increasing across many civil works. Despite the increasing demand for SET, a lack of proper guidelines, standards, and regulations currently exists in the suction excavation industry.

This paper provides a case study on the comparison between the cost of excavation for a daylighting operation performed using hand tools, mechanical excavation equipment, and suction excavation. In addition, a generalized overview of excavation technologies, including the different types of vacuum trucks currently available in the underground utility market is included. Guidelines for the vicinity of excavation to underground utilities are given, along with stepwise procedures on how to perform vacuum excavation. Finally, slurry management guidelines for hydro excavation waste and treatment methods for contaminated and non-contaminated slurry are summarized.

2.3 Objective

The paper is a comprehensive literature review on traditional, hydro and air excavation technology, highlighting the advantages and disadvantages of each method. Innovative excavation technologies for the installation and rehabilitation of underground utilities are explained in detail, including applications, challenges, and limitations, particularly related to the installation and rehabilitation of underground utilities. A secondary objective of this paper is to determine the cost effectiveness of various excavation methods by comparing the overall cost of excavation for daylighting underground utilities using traditional excavation using hand tools, mechanical excavation and suction excavation. Finally, treatment methods for the waste slurry generated by hydro excavation have been described.

2.4 Methodology

The information in this paper was collected from various sources, including academic publications, industrial guidelines, online resources and recommendations from various industry experts. A portion of the data was obtained from conducting interviews with contractors, manufacturers, and suppliers working in the area of SET (Yaehne, 2020).The online cost database software RS Means was used for the purpose of the detailed cost estimate.

2.5 General excavation information

2.5.1 Traditional open-cut excavation

Traditional open-cut excavation is the most common method used for underground utility construction due to its simplicity in excavating soil and laying underground utilities (Ariaratnam, 2008). However, the cost incurred for the excavation is much higher compared to other excavation methods. Traditional open-cut excavation consists of excavating a trench with a width of 0.3 to 2 m or more for the installation of underground utilities or laying conduits, pipes, electrical cables and telecommunication lines (CSMG, 2010). Open-cut excavation is an alternative for installing underground utilities in areas where there is adequate space for excavation of a trench, protection for utilities is not required, and restoration costs are low, among other factors (Alan Atalah, 2004). However, shoring is required when the excavation occurs in rocky layers or below the water table; resulting in an increase in the cost of excavation (Alan Atalah, 2004).

2.5.2 Suction Excavation

SET involves softening the soil using either pressurized water or air, combined with a vacuum system to remove soil and debris (Hydro vs Air Excavation - Which is best for your industry?, 2018). Suction excavation is also commonly known as vacuum or pneumatic excavation and can be further broken down into air excavation or hydro excavation (depending on whether air or water is used to soften the soil). Suction excavation is currently widely used within the trenchless industry, and has great versatility, with the additional advantage of being safer than hand digging and other excavation technologies. Suction excavators utilize powerful suction through a wide rounded pipe, normally up to 30 centimeters or so in diameter. Suction excavation minimizes the risk of damage to underground utilities compared to excavation using mechanical digging or backhoe or other mechanical excavation tools. Air excavation is also considered to be a sustainable practice in the construction industry since it uses pressurized air instead of water during excavation. Non-destructive digging practices are being promoted with the help of SET.

2.5.2.1 Challenges with Suction Excavation Technology

SET is a relatively new non-destructive installation technology for all parties, including utility providers, contractors, municipalities, and government. SET has not yet been fully investigated, and there is currently a lack of proper procedures, guidelines, and standards available. There is limited academic literature on the area of SET. According to the Government of Alberta (Government of Alberta), guidance documents for operating hydro excavation waste management facilities are still ongoing. Also, there are very few waste management facilities that allow the treatment of hydro excavation waste. Furthermore, gathering data regarding excavation technologies from contractors, manufacturers and utility providers can be challenging as there is a reluctance to share technical information.

2.5.3 Hydro Excavation

In hydro excavation, highly pressurized water is used to liquefy soil, creating a slurry mixture which is then extracted using a powerful vacuum or suction system (The Badger Hydrovac, 2020). The liquefied soil or debris is then transferred to the debris tank using air conveyance or vacuum. This method provides a non-destructive method of excavation and is broadly used for increased accuracy in the excavation of soil and the location of underground utilities (What is hydro excavation?, 2019). Hydro excavation units typically have two separate systems, a high-pressure water system, and a vacuum source. Two types of vacuum systems are available, a fan system or a positive displacement blower (What is hydro excavation?, 2019). Typically, the fan system can transfer a huge amount of air, resulting in faster excavations. On the other hand, the positive displacement blower can transfer air over longer distances. The waste slurry is moved to a debris tank attached to the hydrovac truck or transferred to a dumper for dumping at a legal dump site.

2.5.3.1 Historical Perspective of Hydro Excavation in Canada

The history of hydro excavation technique started in California, USA in the 1800s where miners used steam pump-pressurized water to excavate the ground surface (Aka hydrovacing , 2017). Hydro excavation was introduced in the Canadian oil and gas industry in 1970's and 80s (Jetnews, 2012). Canada has a combination of extremely cold weather conditions, including regions with permafrost, many petrochemical plants, and an extensive oil and gas industry, excavation contractors realized that using heated water to excavate was possible. The first hydro-excavation machine, the ExcaVactor, was built by Vactor in 1969 (Jetnews, 2012). At that point in time, the market was immature and the ExcaVactor was the only hydro excavator unit built. Modification of vacuum trucks and sewer cleaners for hydro excavation use was performed in the 1970s and 80s. (Jetnews, 2012). During the same time, to make remote locations accessible by hydro excavation units, the vacuum components were removed from trucks and mounted on vehicles that could be available in any location.

In the 1990s, as the demand for hydro excavation machines was growing, several companies began manufacturing truck and trailer-mounted units in varying configurations (Aka hydrovacing , 2017). By 2000, hydro excavators was widely used in every sector where excavation is involved across Canada. Today, hydro excavation trucks come in many different configurations, with various dimensions, specifications and functions. These units are widely used by utility contractors for line locating, daylighting, utility hole cleaning, shoring for excavation, and piling, among other applications.

2.5.3.2 Overview of Hydro Excavation Procedure (Government of Alberta, 2018)

1. A locate request for identification of buried utilities prior to excavation is put through to an Authorized Utility Identifier: in Alberta, this agency is Alberta One Call.

2. Safety barricading should be placed around the excavation area before starting excavation.
3. Bonding mats should be used in the area where the operator stands while performing the excavation. The use of bonding mats helps to prevent operator injury while excavating near energized underground utilities due to the potential of damage to electrical cables and shorting to ground.
4. Highly pressurized water is used to break up dense soil in the excavation area using a rotating hydro excavation nozzle.
5. The slurry formed after the application of pressurized water to the excavation area is suctioned and stored in a slurry storage tank on the excavation unit.
6. The waste slurry stored in the slurry storage tank is transported to hydro excavation waste management facilities for the phase separation or treatment in case of contaminated slurry.
7. The treated slurry is transported off-site for proper disposal at an authorized disposal site or used as backfill in excavation site.

2.5.4 Air Excavation

In air excavation, highly compressed air (rather than water) is used to loosen the soil, and the disturbed soil is sucked up using a vacuum system into a disposal tank. Pressurized air is converted into excavating power; however, the pressurized air does not damage sensitive pipe coatings, underground utilities and even tree roots (Advantages of air-vacuum, 2019). The disturbed soil produced during air excavation is removed by a vacuum system, resulting in a clean work environment.

Air excavation can be used for line locating of underground utilities and daylighting operations, among other applications. Air excavation is the preferred method for rehabilitation and repair of underground electrical utility lines, since air is non-conductive in nature, in contrast to water. Air excavation has benefit of producing dry soil, which can be reused for backfilling. However, in some cases the disturbed soil could contain contaminants, such as when there are hazardous materials around the excavation site. The treatment of contaminated soil is necessary before landfilling or dumping at a legal dumping site. Non-contaminated soil removed by air excavation can either be used for backfilling at the excavation site or landfilling at a legal dumping site without any treatment (Air excavation, 2019).

2.5.5 Guidelines for Using Suction Excavation Equipment in the Vicinity of underground utilities (GTI, 2012)

The following procedures shall always be followed when excavating by suction excavation near the underground utilities within the tolerance zone:

1. The locates of underground utilities shall be obtained by an excavator using suction excavation equipment prior to the commencement of work.
2. Suction excavation equipment shall operate only by a competent and qualified worker.
3. The maximum water pressure to be used while using pressurized water wands with a straight dip nozzle during excavation for underground utilities in public roads or easements shall be 2500 psi for the depth of excavation up to 18 " inch. The maximum water pressure to be used while using pressurize water wands with a straight dip nozzle during excavation for underground utilities in public roads or easements shall be 1500 psi for the depth of excavation below 18".
4. The maximum water pressure to be used while using a spinning nozzle during excavation shall be 3000 psi. During the excavation, pressure gauge mounted on the excavation machine is used to monitor the pressure of the spinning tip nozzle.
5. The pressurized air or water wands shall never remain in stagnation during excavation. The air or water wands shall always never aim directly to underground facilities.
6. The distance between the end of the pressure wand nozzle and the underground facility/utility shall remain 8".
7. Only use the specifically designed suction excavation equipment and pressure wand nozzles for the excavation above buried gas lines.
8. At the point of excavation, the setup capable of stopping the excavation on demand shall be available, like Emergency Shut-off Setup device.
9. The maximum temperature and pressure of water during excavation shall never exceed 115-degree F and 2500 psi respectively.
10. During the excavation, while using suction excavation technology, if damage to underground utilities occurs the excavator shall contact the facility owner/operator.

2.5.6 Types of suction excavation truck

Suction excavation truck comes in varying dimension and sizes depending upon the number of compartments mounted in the truck. The truck consists of single to multi compartments for increasing the payload capacity of truck by transporting large volume of excavated soil from excavation site to proper disturbed soil management facilities. The types of suction excavation truck are briefly discussed below.

2.5.6.1 Straight Vac

Straight vac (SV) trucks are equipped with a compartment for storing debris, with a capacity ranging from three to eight cubic meters. SV trucks are designed for larger volume waste hauling and are able to accommodate hazardous waste. SVs are available as a single axle, double axle, tri-drive and trailer mounted units (Westech Vac Systems, 2020). SVs have a hydraulic lift for cleaning operations, hydraulic values to control the system by automation, remote control operation systems, storage lockers and van bodies.

2.5.6.2 Combination Vac

The combination vac (CV) has similar capabilities as the straight vac but without the heavy boom and associated hydraulics. CV is mostly used as a hazardous waste hauling truck. The sizes of combination vac trucks vary according to the manufacturers, but they are usually greater than straight-vac. CV are fitted out with high-pressure wash units that are capable of penetrating and breaking up the soil. Furthermore, combination vacs can also be applied for spill clean-ups, fluid transfers, mud tank cleaning, sewage hauling, and trenching.

2.5.6.3 Trailer Vac

Trailer vac (TV) units are a combination of straight vac and combination vac that maximize the payload and maximize hauling capacity. TV are available as a single axle, double axle, tri-drive and trailer mounted units (Westech Vac Systems, 2020). TV unit consists of hydraulic lift, hydraulic valves, remote control systems etc. TV are used for cement jobs, completion services, field spreading, pressure testing, waste transfers, sewage hauling etc.

2.5.7 Overview of Recent Machinery in Suction Excavation Technology

There have been advances in the equipment available for suction excavation, including hydro excavator equipped with a shaker deck for the separation of liquid and solid from slurry at excavation site (Vermeer, 2020), and air excavator employing twin fan technology that can produces over 24,000 CFM of suction power (Ox Equipment, 2020). In this section, a few examples of the latest available suction excavation equipment (both hydro and air excavation equipment) are listed and briefly described. Some excavator manufacturing companies manufacture both types of suction excavator (i.e hydro excavation and air excavation equipment) and other manufacturers produces only hydro excavation or air excavation equipment.

2.5.7.1 XR2 vacuum excavator

XR2 vacuum excavator has a water system with a maximum pressure of 206.8 bar mounted with four water tanks and a slurry storage tank. The maximum flow of pressurized water through water system is 37.9 L/min. Each water tank is having a capacity of 500 gallons, with a maximum water storage capacity of 2000 gallons and maximum slurry storage capacity of 1300 gallons (Vermeer, 2020). Furthermore, the boom can rotate around 260 degrees, and capacity with a maximum vacuum pressure of 18 inHg. XR2 vacuum excavator is equipped with a shaker deck that has the capability of separating liquids and solids to allow workers to remain at the jobsite for a longer time and helps to increase the overall productivity of jobs including a reduction in disposal expenses of slurry (Vermeer, 2020).The separated water from slurry is pumped into the fluid storage tanks for disposal (Vermeer, 2020).

2.5.7.2 MTS DINO Series

The MTS Dino suction excavator series contain container volume from 4.5 m^3 to 12 m^3. MTS DINO Suction excavator employs a twin fan system that produces over 24,000 CFM of suction power to collect the soil that was disturbed during excavation (Ox Equipment, 2020). MTS DINO series has an additional feature of side-tipping of container which allows for fast, efficient and easy dumping of sucked soil either directly on-site or into dumper, which allow the unit to stay on job site and assists in doubling the productivity (Ox Equipment, 2020). Furthermore, air compressor at pressure 116 psi is used for breaking down the soil during the excavation process.

2.5.7.3 Ramvac

Ramvac truck-mounted suction excavator has 3000 to 5400 CFM blowers with hose pipe of 6 inch and 8 inch diameter. The debris tanks are available from 2 m³ to 15 m³ capacity. The important feature of Ramvac vacuum excavator is the water heater of 800,000 BTU that allows heating of water for excavation on iced land (Ramvac by Sewer Equipment, 2020).The boom can reach up to 26 feets with a 320-degree working radius. Water system is including water tank of capacity from 500 gallons to 1300-gallons, with water flow capacity of 10 gpm from a 2500 psi pump (Ramvac by Sewer Equipment, 2020).

2.5.7.4 Ring-O Matic Hydro Excavation

Ring-O Matic vacuum excavator are available in vacuum trailers, vacuum trucks, and skid mount configurations (Ring-O-Matic, 2019). Ring-O-Matic are offered in a variety of sizes and available for both hydro excavation and air excavation. FT150vx is the smallest hydro excavator in series of ring-o-matic, with water system which can supply 3.5 GPM water at 3000 psi. Furthermore, water storage tank capacity is 90 gallon and with spoil tank capacity of 150-gallon (Ring-O-Matic, 2019). Ring-O-matic are equipped with air vacuum excavators that generates air pressure of 185 CFM at 150 psi (Ring-O-Matic, 2019).

2.5.7.5 Rival Hydrovac

The rival hydro-vac has a water tank capacity of 800 to 1200 gallons with 3 to 110 m³ tank. Rival hydrovac is easy to maneuver in urban areas where there is space restriction since it is shorter inlength, that is lower than the traditional hydro-vac units. (Rival Hydrovac, 2020) The vacuum system comprises from 2000 to 4000 CFM. The boiler has a capacity up to 480,000 BTU and can be used for excavation on negative temperature conditions (Rival Hydrovac, 2020).

2.5.7.6 Smartvac

Smartvac is the lightest single and tandem axle hydro-vac truck weighing 28,000 lbs when it is empty. Smartvac has debris capacity from 3 to 10 m³ with water storage capacity from 800 to 1100 gallons (SmartVac, 2020). The maximum pressurized water flow rate is 10 GPM, tuned to produce equivalent 3000 psi from water system. Smartvac uses artificial intelligence to operate the truck reducing the requirement of manpower to one operator during excavation operation. Smartvac produces noise levels of 84 dB during operation, which helps to minimize sound pollution during excavation.

2.5.7.7 Vac-con

Vac-con hydrovac units offer both truck and trailer-mounted models. Vac-con utilizes the combination of wet/dry truck-mounted machine with a 15 to 28-inHg vacuum system. Furthermore, vac-con are available from 3 to 15 m^3 debris tanks and 500 to 1300 gallons of water storage capacity (Vaccon, 2020).

2.5.7.8 Supervac

Supervac vacuum excavator has water system with maximum pressure of 6000 psi. Maximum flow of water system is 60 L/min and water tank is having capacity up to 1500 gallons and maximum slurry storage capacity up to 3600 gallons (SuperVac, 2020). Supervac truck series include hydro excavator, combination sewer cleaner, wet/dry vacuum truck and sanitary truck.

Table 2.1: Summary and comparison of different types of suction excavator

Company	Machinery Name	Vacuum System Air Flow Rate (m^3/hr)	Water System		Suction Hose Diameter range		Tanks		References
			Max pressure (psi)	Water heater (BTU)	(inch)	(mm)	Number of tanks	Tank capacity each (L)	
Vermeer	XR2 Vacuum excavator	5777	3000	22.9	6	152.4	4	1892.7	(Vermeer, 2020)
OX Equipment	MTS DINO 4.5	40776	N/A	N/A	10	254	1	3440	(Ox Equipment, 2020)
Ramvac	HX-15	7475.64	2500	400,000	8	203.2	1	4921	(Ramvac by Sewer Equipment, 2020)
Ring-O Matic hydro excavation	850 vx	1019	1500	N/A	6	152.4	1	1893	(Ring-O-Matic, 2019)
Rival Hydrovac	T10	6796	2850	480,000	8	203.2	1	4542	(Rival Hydrovac, 2020)
Smartvac	Tandem Axle	5436	3000	420,000	8	203.2	1	4163	(SmartVac, 2020)
Vac-Con	XX-cavator	11893	4000	410,000	8	203.2	1	3406	(Vaccon, 2020)
Supervac	Atlas	6456	4000	700,000	6	152.4	1	6813	(SuperVac, 2020)

2.6 Case Study Description

It is important for utility owners and project managers to understand the costs associated with daylighting underground utilities. In this case study, a typical daylighting scenario has been developed for a location in Edmonton, AB. The costs of the daylighting operation have been compared for each excavation method considered: (1) open-cut method using hand excavation, (2) open-cut method using mechanical excavation, and (3) suction excavation. This analysis focuses on the environmental impacts, safety considerations, traffic impacts, disruption to commercial business and the total cost associated with each excavation method. The cost analysis is limited to the daylighting operation and backfilling the trench, followed by suitable compaction. The data for the detailed cost estimate is based on Robert Snow Means (RSMeans , 2020).

To compare the cost per unit excavation for daylighting using hand excavation, mechanical excavation, and suction excavation, the following assumptions have been made.

- The size of trench required for the daylighting operation is 1.4 m by 1 m by 30 m. The cross section of the trench is shown in Figure 2.1.
- The location of the trench is in Millwood, Edmonton, Alberta, Canada.
- The soil for the daylighting location is assumed to be common earth, and the water table rises when the excavation is performed.
- The size of underground utility pipe considered is 0.4 m in diameter.
- The hourly rate of labour includes overhead, profit and workers' compensation insurance of 13%, 10% and 9.8% respectively.
- The trench will be safeguarded against the loose earth falling into the trench by using a shoring system.
- In this research, the detailed cost estimates are conceptual estimates, therefore, the costs given by contractors may differ depending upon the specific conditions, hourly labor rates, incentives, profit margins, and overhead, among others.

- The cost estimation for this case study includes direct cost, overhead and profit.

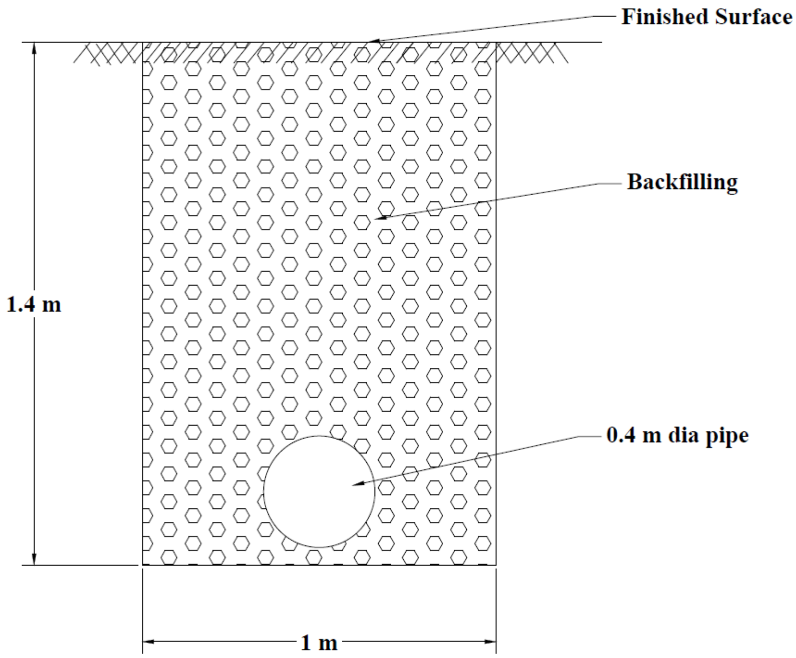


Figure 2.1: Cross-section of trench for daylighting scenario (fig not in scale)

The estimation of total direct costs is carried out using data from (RSMeans , 2020). Table 2.2 shows the information related to one of the activities required to determine the detailed direct cost of the daylighting activity. Also, table 2.3 provides the information related to the detail cost to the activity mentioned in table 2.2. The excavation production rate for the suction excavator is taken from the (GTI) industry.

Table 2.2: RS means data for Open cut Item *(RSMeans , 2020)*

Line Number	312316.13
Description	Common earth with no sheeting or dewatering included, excavating trench 4' to 6 ' deep, ½ C.Y. excavator
Crew	B11M
Daily Output	200
Labour-Hours	0.08
Unit	B.C.Y[1]
Total	$1023.20
Total O & P	$1440.44

Table 2.3: Crew Information for typical excavation activity described in table 2.2 from RS means *(RSMeans , 2020)*

Crew No.	**Bare Costs**		**Inclusive O&P**		**Cost per Labour-Hour**	
B-11M	**Hr.**	**Daily**	**Hr.**	**Daily**	**Bare Costs**	**Incl. O & P[2]**
1 Equipment operator. (med.)	$56.75	$454	$84.85	$678.80	$49.42	$74.05
1 Laborer	$42.10	$336.80	$63.25	$506		
1 Backhoe Loader, 48 H. P		$232.40		$255.64	$14.53	$15.98
16 L.H., Daily Totals		$1023.20		$1440.44	$63.95	$90.03

[1] Bank cubic yards
[2] Overhead and profit

2.7 Detailed cost estimate, discussion, and results

2.7.1 Cost of daylighting underground utilities by mechanical excavator

Table 2.4 shows the detailed cost estimate for carrying out excavation for a trench of 1.4 m by 1 m by 30 m for a daylighting operation using a mechanical excavator. For simplicity, the open cut estimate for daylighting operation using a mechanical excavator was based on a typical section as shown in figure 2.1. The first activity of excavating trench is performed with the help of ½ cubic yard excavator and crew includes 1 equipment operator and 1 labour. The water table arises when the excavation reaches the depth of 1 m, and dewatering trench is completed with the help of 2-inch diaphragm pump and 1 equipment operator. Shoring the trench with the provision of timber for safeguarding against loose earth falling into the trench is followed by excavating the bottom level of trench with the help of hand excavation tools for safeguarding the utility. The rehabilitation of utilities is completed followed by backfilling excavated soil. Finally, surfacing of the ground is performed after compacting the backfilled area of trench. The manual excavation at the bottom of trench is the dominant cost factor among all other activities. . The cost associated with each of the activities for the daylighting operation using mechanical excavation is given in Table 2.4. The analysis indicates that the total cost for the 42 m^3 excavation is $7113, which works out to $170 per cubic meter.

Table 2.4: Detailed cost estimate for daylighting by mechanical excavator *(RSMeans , 2020)*

S.N	Activity	Volume	Unit	Daily Output	Crew	Hourly Cost (Inclusive O & P)[3]	Total Cost ($)
1	Common earth with no sheeting or dewatering included, excavating trench 4' to 6' deep, 1/2 C.Y. excavator						
	1 Equipment operator					84.85	108
	1 Laborer	31.92	B.C.Y[4]	200	B11M	63.25	81
	1 Backhoe Loader, 80 H. P					255.64	326
2	Pumping 8 hr. attended 2 hrs. per day, including 20 L.F. of suction hose and 100 L.F discharge hose - 2" diaphragm pump used for 8 hours						
	1 Equipment operator					84.85	679
	.5 Laborer					63.25	253
	1 Diaphragm Water pump, 2 "						95
	1-20' Suction hose, 2 "	1	Day		B10H		4
	2- 50' Discharge Hoses, 2"						8.8
3	Shoring with timber, no salvage allowance (4.592'×98.4 '× 1")						
	1 Labor foreman					66.25	218
	4 Laborers	0.9		2.2	B51	63.25	831
	1 truck driver					70.8	566.4

[3] Overhead and profit
[4] Bank cubic yards

	1 Flatbed truck, gas, 1.5 ton		M.B.F[5]				215.76
4	Backfill by hand, no compaction, light soil	40	L.C.Y[6]	14	1 Clab[7]	63.25	1442.1
5	Compaction -rammer tamper 6" to 11", 4 lifts, 2 passes	32	E.C.Y[8]	31	1 Clab		
	1 Building Laborer					63.25	248
	1 Rammer/Tamper, Gas, 8 "						51.15
6	Bottom level of height 0.4374 yard is excavted by manual hand tool to safeguard the utility	16	B.C.Y	4	1 Clab	63.25	1985
	Excavating trench, By hand with pick and shovel 2' to 6 ' deep						
	1 Building Laborer						
Total Cost (Direct cost, Overhead & Profit)							**7113**

[5] Thousand board feet
[6] Loose cubic yards
[7] Common labour
[8] Embankments cubic yards

2.7.2 Cost of daylighting underground utilities by hand tools

Table 2.5 shows a detailed cost estimate for 1.4 m by 1 m by 30 m daylighting operation using hand tools. For simplicity, the open cut estimate for daylighting operation using hand tools in this work was based on a typical section as shown in figure 2.1. The first activity of excavating trench is performed by hand using pick and shovel by 1 labour. The water table arises when the excavation reaches the depth of 1 m, and dewatering trench is completed with the help of 2-inch diaphragm pump and 1 equipment operator. Shoring the trench with the provision of timber for safeguarding against loose earth falling into the trench is followed by excavating the bottom level of trench with the help of hand excavation tools for safeguarding the utility. Once the rehabilitation of utility is completed, trench is backfilled with the excavated soil on site. Finally, surfacing of the ground is performed after compacting the backfilled area of trench. The excavating trench by manual hand tools is the dominant cost factor among all other activities. The cost associated with each of the activities for the daylighting operation is given in Table 2.5. The analysis indicates that the total cost for the excavation of 42 m^3 is \$8660, which is \$206 per cubic meter.

Table 2.5: Detailed cost estimate for daylighting operation carried out using hand tools *(RSMeans , 2020)*

SN	Activities	Volume	Unit	Daily Output	Crew	Hourly Cost (Inclusive O & P)	Total Cost ($)
1	Excavating trench, By hand with pick and shovel 2' to 6' deep	31.92	B.C. Y	4	1 Clab	63.25	4048
	1 Building Laborer						
2	Pumping 8 hr. attended 2 hrs. per day, including 20 L.F. of suction hose and 100 L.F discharge hose - 2" diaphragm pump used for 8 hours	1	Day		B10H		
	1 Equipment operator					84.85	679
	.5 Laborer					63.25	253
	1 Diaphragm Water pump, 2 "						95
	1-20' Suction hose, 2 "						4
	2-50' Discharge Hoses, 2"						9
3	Shoring with timber, no salvage allowance (4.592'× 98.4 '× 1")	0.90	M.B. F	2.2	B51		
	1 Labor foreman					66.25	218
	4 Laborers					63.25	831
	1 truck driver					70.8	566
	1 Flatbed truck, gas, 1.5 ton						216
4	Backfill by hand, no compaction, light soil	39.9	L.C. Y	14	1 Clab	63.25	1442
5	Compaction -rammer tamper 6" to 11", 4 lifts, 2 passes	31.92	E.C. Y	65	1 Clab		
	1 Building Laborer					63.25	248
	1 Rammer/Tamper, Gas, 8"						51
	Total Cost (includes direct costs, overhead & profit)						**8660**

2.7.3 Cost of daylighting underground utilities by suction excavation

Table 2.6 shows the detail cost estimate for 1.4×1×30 m daylighting operation by suction excavator (air excavator).For simplicity in this research, the open-cut estimate by suction excavator was based on a typical section as shown in figure 2.1. The first activity of excavating trench is performed using suction excavation (air excavation) with the help of 1 equipment operator and 1 labour. The water table arises when the excavation reaches the depth of 1 m, and dewatering trench is completed with suction pump equipped in air excavator truck. Therefore, the need of renting the diaphragm pump for dewatering is not required while performing daylighting operation with air excavator. Shoring the trench with the provision of timber for safeguarding against loose earth falling into the trench is followed by backfilling the trench when the rehabilitation of utilities is completed. Then final surfacing of the ground is performed after compacting the backfilled area of trench. The excavating trench and dewatering the trench by air excavator is the dominant cost factor among all other activities. The cost associated with each of the activities for daylighting operation is showed in table 2.6. It indicates that the total cost for 42 cubic meter of excavation is $ 6232, which is $ 149 per cubic meter.

Table 2.6: Detail cost estimate for daylighting operation by suction excavator *(RSMeans , 2020)*

S.N	Activities	Volume	Unit	Daily Output	Crew	Hourly Cost (Inclusive O & P)	Total Cost ($)
1	Excavating trench by suction excavator & dumping the backfill material at the site for later backfilling with dewatering the trench (MTS Dino Series)	31.92	B.C.Y	33.44	1 operator & 1 labor	350	2660
	1 Machine operator and 1 Labor						
2	Shoring with timber, no salvage allowance (4.592'×98.4 '×1")	0.90	M.B. F	2.2	B51	66.25	218
	1 Labor foreman						
	4 Laborers					63.25	831
	1 truck driver					71	566.4
	1 Flatbed truck, gas, 1.5 ton						216
3	Backfill by hand, no compaction, light soil	39.9	L.C. Y	14	1 Clab	63.25	1442.1
4	Compaction -rammer tamper 6" to 11", 4 lifts, 2 passes	31.92	E.C. Y	65	1 Clab	63.25	248
	1 Building Laborer						
	1 Rammer/Tamper, Gas, 8 "						51.15
Total Cost (Direct cost, overhead & profit)							**6232**

2.7.4 Comparisons and Analysis

2.7.4.1 Comparison of cost

Table 2.4, 2.5 and 2.6 represents the detail cost (direct cost, overhead and profit) estimated for a daylighting operation involving the excavation of 42 m^3 using mechanical excavators, hand tools and suction excavator. The chart illustrates that the cost of performing the daylighting operation by suction excavator is 38% less compared to excavation using hand tools and 14% less compared to mechanical excavation.

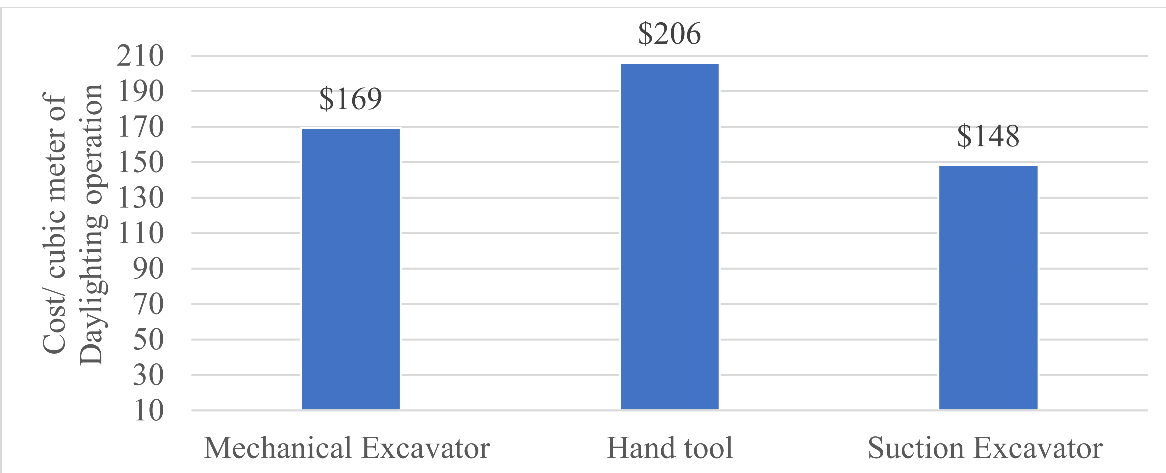


Figure 2.2: Total cost per cubic meters of excavation for mechanical, suction excavator and hand tool.

2.7.4.2 Safety during Construction

Traditionally, the triple constraints of any civil construction projects are considered to be cost, time and quality. However, a lack of safety in construction works indirectly results in time and cost increases for construction activities and the overall project (Enshassi, Factors Affecting Safety on Construction Projects, 2003). Since civil works present serious hazards to the worker, occupational health and safety has evolved as an additional constraint on construction projects.

Suction excavation uses less manpower during operation and requires one worker to hold the hose pipe and one operator. Additionally, excavation using hand tools requires more manpower and excavation using mechanical excavators requires the equal number of manpower as in the case of suction excavation. The human effort for suction excavation and mechanical excavation is much less compared to excavation by hand tools.

Even after following the safety guidelines and ensuring every worker wears personal protective equipment, excavation using hand tools still carries the possibility of hazards or accidents due to involvement of more human factor during the excavation. Hence, suction excavation is safer than excavation by hand tools.

2.7.4.3 Environmental Impacts

Excavation using hand tools or mechanical excavators generates a large amount of dust which reduces air quality in the surrounding areas and decreases the aesthetic aspects of the environment. During suction excavation by air, any dust created during excavation from the pressurized air is removed using a suction hose, resulting in less dust in the environment.

2.7.4.4 Traffic Impacts

Daylighting operations performed with a mechanical excavator require a large area and safety barricades. However, a suction excavator can be stationed some distance from the work site where the pressure and suction hoses are used for breaking up and removing the disturbed soil. Thus, suction excavation can be used in urban areas where there are space restrictions and produce less traffic disruption.

2.8 Advantages of Suction Excavation over Traditional Excavation

The use of suction excavation provides benefits over hand excavation and mechanical excavation. The need to expose and identify underground services on construction sites by hand dig creates a situation where damage to underground utilities can occur and result in cost overruns for a project. A detailed comparison of the advantages of suction excavation with hand excavation and mechanical is included in Table 2.7.

Table 2.7: Summary of comparison between traditional open-cut and suction excavation

Comparative advantages	Traditional open-cut excavation and Mechanical excavation	Suction Excavation	
			Application
Cost	Major	Minor	For daylighting underground utilities
Speed	Minor	Major	Rehabilitation for underground utilities
Traffic Impacts	Major	Minor	

Business and Commercial Impacts	Major	Minor	For deployment of telecommunication lines using slot trenching or micro-trenching
Environmental Impacts	Minor	Major	Can be used for excavation in urban areas where there are space restrictions
Traffic congestion	Major	Minor	and help in reducing traffic congestion
Sound pollution	Minor	Major	
Time	Major	Minor	Combination of pressurized air and heated water makes use in cold weather conditions

2.9 Disadvantages of hydro excavation compare to air excavation technology

Suction excavation technology includes both air excavation (breaking apart soil with air) and hydro excavation (breaking apart soil with water), and in this section the disadvantages of hydro excavation in compare to air excavation is summarized. The main disadvantages of hydro excavation compared to air excavation technology is the formation of waste slurry from the process. An overview of considerations related to the slurry produced by hydro excavation, as well as available treatment technologies, is included in this section.

2.9.1 Hydro excavation Slurry

A slurry is formed during the excavation process using hydro excavation, and this slurry is commonly referred to as hydro excavation waste (Government of Alberta, 2018). The slurry produced during hydro excavation generally consists of about 60% liquid and 40% percent solids: it is neither soil nor water and requires appropriate disposal.

The soil at the excavation site may be contaminated. If it is, the contaminants are present in the waste slurry produced during hydro excavation. Any contaminated slurry which is part of the excavated material requires special attention in terms of management, storage and disposal according to existing legislation (Government of Alberta, 2018). Before excavation, an assessment is conducted in order to determine any contamination onsite prior to hydro excavation. This assists with planning for any treatment for the slurry generated during the hydro excavation and identification of disposal options if contamination is detected (Government of Alberta, 2018). The screening of soil includes screening for hydrocarbons, *E. coli*, pesticides, heavy metals (eg. lead, mercury etc.), polychlorinated biphenyls, polycyclic aromatic hydrocarbons, pH and salinity (Government of Alberta, 2018). The most employed site screening methods for contamination are listed below:

- **Geophysical assessments**
- **Soil gas surveys**
- **Screening groundwater and soil samples**
- **Portable gas chromatography**
- **Field atomic absorption spectroscopy**
- **Field X-ray fluorescence spectroscopy**

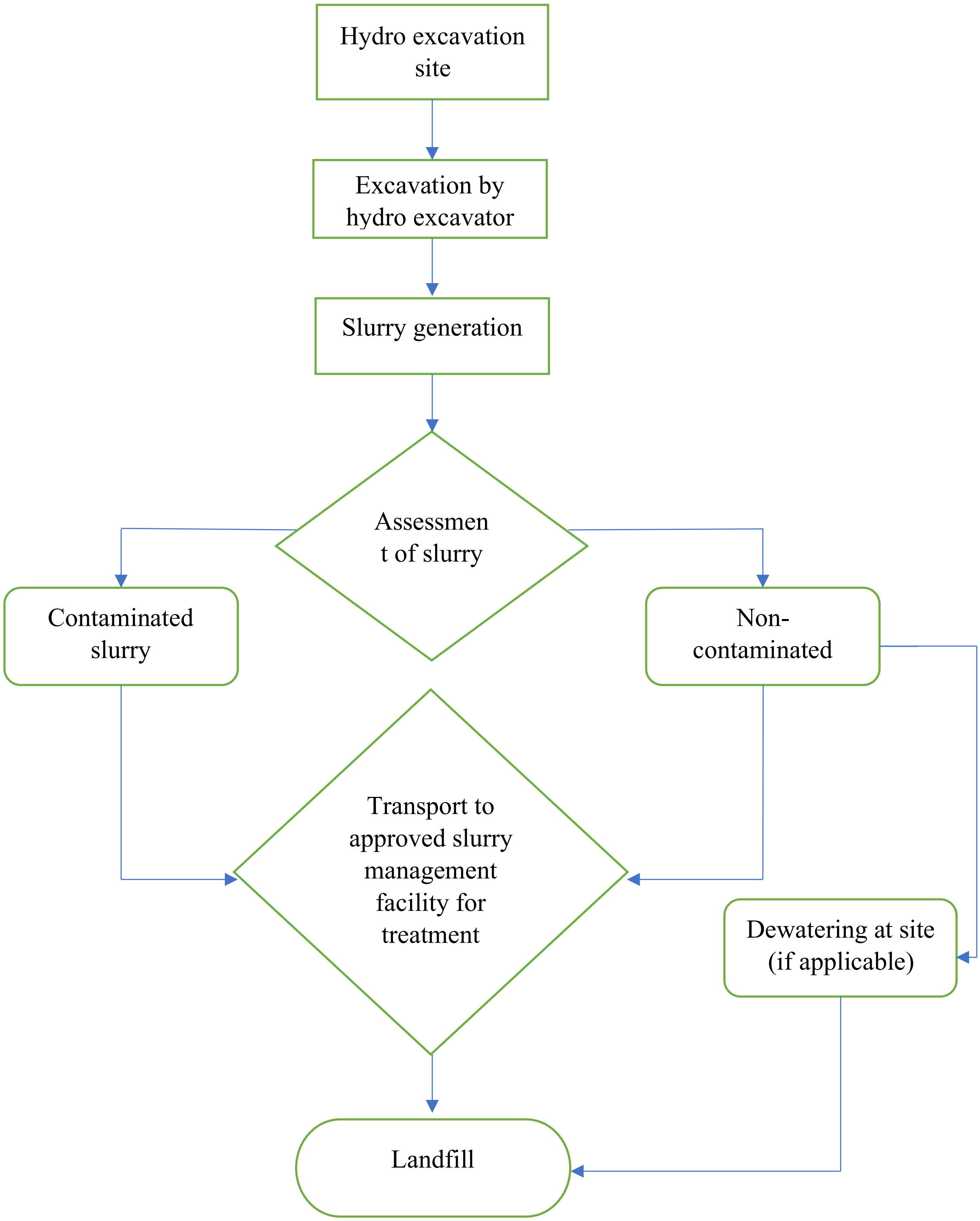


Figure 2.3: Hydro excavation slurry management process

Hydro excavation waste is also too thick to be dumped into sewers (Berkenbosch, 2018). The slurry mixtures produced by hydro excavation do not have a beneficial use in agricultural land applications, since slurry is a mixture of water and clay, which is not good for agriculture. The application of slurry mixture on topsoil results in the degradation of the topsoil. Therefore, even non-contaminated slurry must be treated at an authorized waste management facility. Figure 2.3 provides the stepwise procedure for the management of hydro excavation slurry.

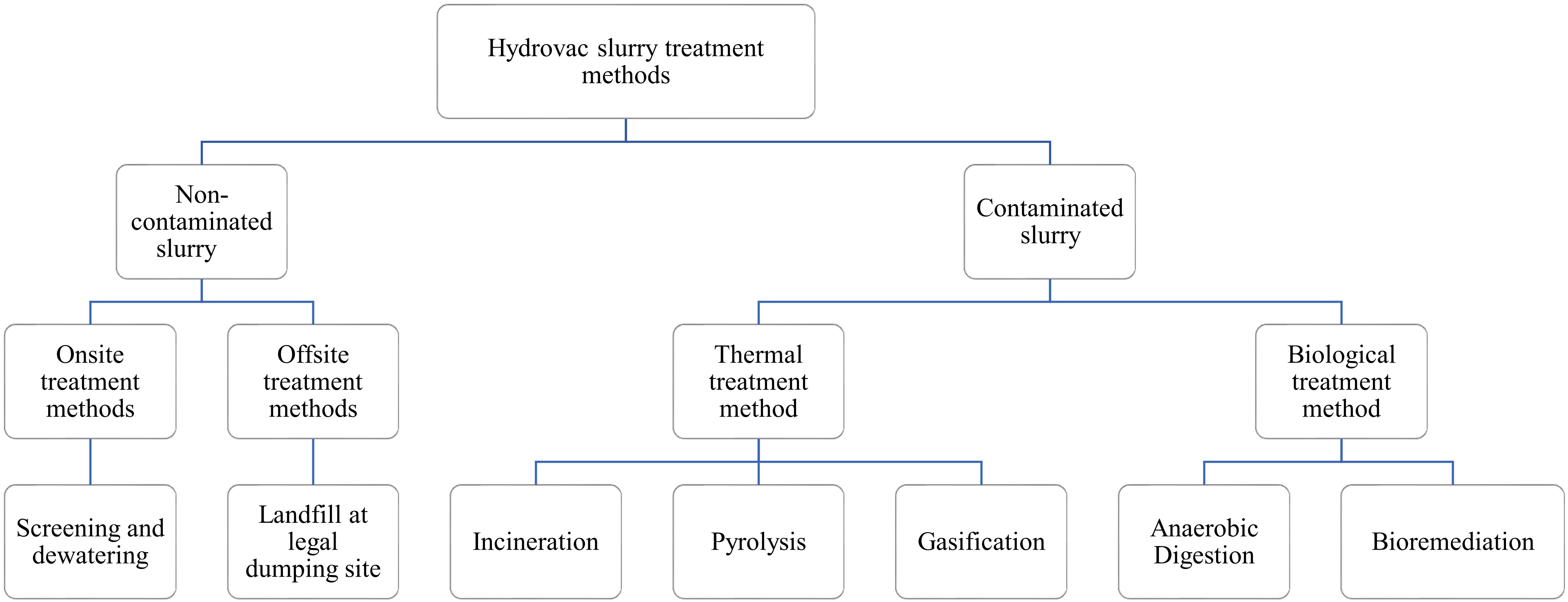


Figure 2.4: Treatment methods for non-contaminated and contaminated hydrovac waste

2.10 Treatment Methods for hydro excavation slurry

Treatment methods such as phase separation and dewatering are used for the treatment of non-contaminated hydro excavation slurry waste at excavation site. Phase separation is the process of generating two distinct phases from a homogenous mixture. Hydro excavation slurry containing a mixture of oil and water is separated with the help of phase separation. Dewatering is the process of draining the water from mixture of soil and water. Contaminated hydro excavation slurry, which may contain different heavy metals, hydrocarbons, oils, gasoline, solvents or waste with any characteristics such as toxicity, flammability, corrosivity or reactivity requires treatment before landfill disposal. Promising treatment technologies for contaminated and non-contaminated hydro excavation slurry is thermal, (incineration, pyrolysis, and gasification), biological and landfill treatment methods. Figure 2.4 lists the different types of treatment methods available for the treatment of contaminated and non-contaminated hydro excavation slurry.

2.10.1 Onsite treatment methods

The slurry waste generated by hydro excavation activities can be treated mechanically on-site using centrifugal force. Some hydro excavators are mounted with decker where the phase separation of the waste slurry can be done. In other cases, the hydro excavation site can be facilitated with a containment unit where the slurry is fed into the tank and gravity is used for the phase separation. This allows the hydro excavator to remain on site for a longer time compare to hydro excavator without decker, increasing the productivity of hydro excavation.

2.10.2 Off-site treatment methods

Off-site treatment of hydro excavation waste involves logistics problems for hydro excavation contractors, utility providers, municipalities, and governments. The cost of treatment depends upon the distance of the waste management facility from the excavation site. Since most waste management facilities are located far from the city, transportation of waste from the excavation site to the waste management facility takes time and also contributes to traffic congestion. Legal landfill sites are often located miles away from the excavation site, which makes landfilling of hydro excavation slurry treated onsite time-consuming and costly. The principles used for the treatment of slurry offsite are dewatering, decanting, settling tanks, chemical treatment to remove solids, among others.

2.10.2.1 Screening and dewatering

The management of hydro excavation waste can be done using a vibrating platform for screening and dewatering the slurry. Fine sand and grit can be recovered from slurry using the dewatering and screening. The recovered material is then ready to be disposed of as an inert waste in a landfill: up to 40-50 % of the recovered material is sand and diverted from landfills (CDEnviro, 2020). The remaining weight of material is dewatered to reduce the overall weight of material to be disposed off at legal dumping site.

2.10.2.2 Settling Tanks

Another technique to manage the hydro excavation slurry is using settling or a sedimentary tank, where slurry is fed into a settling tank and fine particles present in slurry settle to the bottom of the tank (CDEnviro, 2020). The clean water present after settling of fine particles overflows from the tank and is pumped back for re-use in hydro excavation process.

2.10.2.3 Chemical treatments

The fine silt and clay present in the hydro excavation slurry which could not be settled in the settlement tank can be treated with the help of chemical treatment (CDEnviro, 2020). The multi-stage chemical dosing is performed that results in high water quality with ultra-low residual solids from slurry.

2.10.3 Thermal Treatment Method

Incineration is the process of waste devastation in a furnace at high temperatures, between 750 and 1100 °C (Alperen, 2016). Another process is co-incineration process, in which sewer sludge or hazardous liquid waste such as hydro excavation slurry is incinerated with the use of a fuel such as coal or sawdust at a higher temperature from 750 to 1400 °C (US Patent No. US4753181A, 1987). Incineration involves three processes, which are incineration, energy recovery and air pollution (Alperen, 2016). Air pollutants including SO_x, CO_x and NO_x are formed during the incineration process.

Pyrolysis is the process of treating waste at high temperatures in the absence of oxygen, and can be divided into conventional pyrolysis (277-630 °C), fast pyrolysis (600-1000 °C), and flash pyrolysis (780-1030 °C) (Alperen, 2016). This method is used for the treatment of contaminated hydro excavation waste, and produces air pollutants including H_2, CH_4, CO, CO_2 and N_2 (Biogreen , 2020).

A third thermal method used in the management of hydro excavation slurry is gasification. Gasification is the process of converting waste into CO_2, CO and H_2O by treating waste at high temperatures without combustion (Alperen, 2016).

2.10.4 Biological Treatment Methods

Hydro excavation slurry containing organic matter can be treated by biochemical methods which can be divided into two subgroups, anaerobic digestion and composting (Khanjan, 2013). Hydro excavation slurry waste contains a large concentration of solid particles and upon phase separation of solids from the slurry, the liquid content of slurry can be transported to the biochemical treatment facility for processing to make suitable for re-use. Anaerobic digestion is a biological treatment method where microorganisms break down biodegradable material in the absence of oxygen at almost 65°C (Alperen, 2016). The residual formed remaining after anaerobic digestion of hydro excavation slurry waste can be composted or directly applied to agricultural lands.

Another biological treatment method for hydro excavation slurry waste is composting for the solid particles. Composting is the biological decomposition of biodegradable waste in the presence of oxygen (Khanjan, 2013).The decomposed organic solids from the slurry waste is converted into a rich soil called compost (Khanjan, 2013).

2.10.5 Landfill

After treating contaminated hydro excavation slurry waste by thermal or biological treatment method, the residue of the waste can be landfilled at legal landfilling site.

2.10.6 Bioremediation

Bioremediation is the process of treating contaminants in the soil using microorganisms, plants, or microbes (Gouma, Fragoeiro, Bastos, & Magan, 2014). Dumping sites for hydro excavation slurry containing contaminants can be treated using microorganisms or by adding a rich culture of microorganisms. Bioremediation is a natural process enhancing the balance in natural ecosystems (Gouma, Fragoeiro, Bastos, & Magan, 2014). However, the bioremediation process is limited to waste containing organic compounds that are biodegradable and cannot be used to treat hazardous waste. Contaminated solids separated from hydro excavation slurry can be treated with bioremediation process.

2.11 Conclusion

This paper focused on collecting information related to SET, challenges with SET, historical perspective of hydro excavation in Canada, among others. The different types of hydro and air excavators that are available in the market, along with their different technical specifications and production capacities are compared and summarized. Also, using detailed estimates, a cost comparison between excavation for daylighting underground utilities using mechanical excavator, hand tool and suction excavator indicates that the excavation by suction excavator is cheaper than hand tools and mechanical excavator by 38% and 14%, respectively. Furthermore, the treatment methods for the slurry produced during hydro excavation process is briefly summarized.

Chapter 3: Application of AHP for a Decision Support System for Hydro and Air Excavation

3.1 Abstract

This paper describes a multi-criteria-decision making analysis using the Analytical Hierarchy Process (AHP) to determine the best alternative between hydro and air excavation for the installation of underground utilities in urban areas. AHP has been extensively used to analyze complex problems and facilitate decision-making, which is important for the success of construction operations. This research takes into account environmental, social, and indirect costs involved in excavation for the installation of underground utilities, in addition to direct costs. AHP was conducted based on the judgements of experts within industry. The judgements values are synthesized in the hierarchy structure to make a comparison. The analysis results indicated that air excavation had a priority value of 53%, compared to 47% for hydro excavation, leading to the conclusion that air excavation is preferable to hydro excavation for installation of underground utilities in urban areas. However, the analysis conducted has limitations, since the expert judgements to perform AHP that the comparison is based on are somewhat arbitrary and may differ from person to person.

3.2 Introduction

Underground utilities are the infrastructure that includes pipes and cables for the transportation and transmission of water, gas electricity, telecommunications, and fiber optics data from source to the recipients. The world population is increasingly migrating to urban areas. The world population is expected to increase by 10% in 2030 and 26% in 2050 (United Nations , 2019).With increasing population, the need for utilities is also rising in urban areas. Almost every aspect of life depends on the reliable operation of underground utilities, including telecommunications, natural gas transportation, water transmission and distribution systems, sewer systems, and electricity distribution, among others. Increasing demand for new installation of underground utilities results in more construction of underground utilities in urban areas. Furthermore, demand for underground utility construction and rehabilitation is also increasing due to many utilities that are reaching the end of their service life (Association, Reinvesting in Drinking Water Infrastructure, 2001). Any installation or rehabilitation of underground utilities requires some form of excavation.

Previously, installation of underground utilities involved hand digging or mechanical excavation using hand tools or mechanical excavators, including backhoes or similar excavation equipment (Jetnews, 2012). The use of hand tools and mechanical excavation causes numerous reports of accidents, including accidents involving injuries, every year. According to research conducted considering utility strikes data from nine organizations in the United Kingdom, accounting for more than 3348 incidents, the use of hand tools results in a large amount of damage to buried infrastructure during rehabilitation, closely followed by mechanical excavators (Metje, Ahmad, & Crossland, 2015). Utility strikes in underground utility construction result in schedule delays and increased costs to complete underground utility project. This risk of accidents during construction and/or rehabilitation work on underground utilities can be mitigated by using techniques such as suction excavation rather than traditional excavation methods. Suction excavation utilizes either high-pressure air (air excavation) or water (hydro excavation) to loosen the soil, followed by removal of the excavated material by suction. The first hydro excavation machine built was the "ExcaVactor" in 1969 (Jetnews, 2012), and main disadvantage of hydro excavation method is the production of slurry (60% liquid and 40% solids) during excavation, which requires proper treatment at slurry management facility before landfilling at legal dumping site (Government of Alberta, 2018). In contrast, air excavation does not produce slurry during excavation, however, the benefit of this newest technology has not yet been fully recognized by the underground utility industry.

This paper focuses on developing a comparison between hydro excavation and air excavation with respect to the different factors, including cost, and environmental and social aspects to facilitate decisions regarding the choice of excavation method for underground utility installation and/or rehabilitation. The comparison has been performed using the AHP. AHP is a multi-criteria technique that assists decision making by choosing among several alternatives with different objectives and criteria (Albers & Nijkamp, 1989). In particular, AHP has gained significant attention in solving construction-related decision-making problems (Cheng, Tsai, & Sutan, 2009).

A case study in Edmonton (Canada) was analyzed to give validity to the proposed method of comparison. The structure for this research was carried out from the similar kind of study conducted for comparison between microtunneling and trench excavation (Bottero & Peila, 2005). The study was supported by results obtained from interviews carried out with subject matter experts (contractors, manufacturers, suppliers, and consultant) working in suction excavation to determine their opinions.

3.3 Objective

The main objective of this paper is to collect and analyze expert opinions regarding direct, indirect, environmental, and social cost aspects involved due to excavation in urban areas for underground utilities project by hydro and air excavation technologies. The result of analysis should help decision maker to select appropriate excavation technology for application in underground utility construction project. Also, another objective is to determine most cost-effective method of excavation among hydro excavation and air excavation for installation and rehabilitation of underground utility projects in urban areas.

3.4 Methodology

To fulfill the objectives, stepwise AHP is applied to organize different criteria and sub-criteria related to the direct, indirect, social and environmental aspects of excavation for an underground utility construction project in urban areas using a hierarchical network diagram. To conduct and analyze AHP, a pairwise comparison matrix is formed after conducting interviews with experts in the field of excavation technology and the expert judgements and opinions are converted to weightage criteria using Saaty's fundamental scale
(Gregory, 2020; Donoahue, 2020; Yaehne, 2020).

3.5 Suction Excavation Methods

Two excavation methods are compared in this study, hydro excavation and air excavation. Both hydro and air excavation are forms of suction excavation and are described in detail below.

3.5.1 Hydro Excavation

Hydro excavation units have two separate systems, a high-pressure water system, and a vacuum source. In hydro excavation, highly pressurized water is used to liquefy soil, creating a slurry mixture which is then extracted using a powerful vacuum system (The Badger Hydrovac, 2020) The liquefied soil or debris is then transferred to a debris tank using air conveyance or vacuum. This method provides a non-destructive method of excavation compare to conventional open-cut method, and is broadly used for increased accuracy in the excavation of soil and for identifying the location of underground utilities since excavation can be done for the particular ground just above where the utilities lies.

Two types of vacuum systems are available for hydro excavation units. The vacuum can be generated using a fan system or a positive displacement blower (What is hydro excavation?, 2019) Typically, the fan system can transfer a huge amount of air, resulting in faster excavations. However, the positive displacement blower system is able to transfer air over longer distances and its application can be used for the excavation in urban areas where there is limitation of space for halting the excavator and excavator can be parked remotely.

HET combines pressurized water with an air vacuum: high-pressure water is used to cut the soil and break it up, and a vacuum then is used to remove the liquefied soil from the excavation area. The waste slurry is moved to a debris tank attached to the hydrovac truck or transferred to another dumper for dumping at a legal dump site.

In addition to excavation in civil works, hydro excavators can be used for transporting and transferring product for pipeline operators, cleaning, and removal of hazardous and non- hazardous waste for commercial and industrial operators, as well providing removal of septic waste for commercial and residential industries. Hydro excavators also can be used to transport waste to an environmental waste management facility.

3.5.2 Air excavation

In air excavation, highly compressed air (rather than water) is used to loosen the soil, and the disturbed soil is sucked up using a vacuum system into a disposal tank. The dry disturbed soil produced during air excavation is sucked by vacuum system, resulting in clean work environment. Pressurized air is converted into excavating power; however, pressurized air does not damage sensitive pipe coatings, underground utilities and even tree roots (Advantages of Air-vacuum, 2019). Air excavation can be used for line locating of underground utilities, and daylighting underground pipelines, among other applications. Air excavation is the preferred method for rehabilitation and repair of underground electrical utility lines, since air is non-conductive in nature, in contrast to water. Air excavation has benefit of producing the dry disturbed soil during excavation which can be reused for backfilling the holes, or excavation site. During the excavation dry disturbed soil could be mixed with the contamination like hazardous materials around the excavation site. The treatment of contaminated disturbed soil is necessary before landfilling or dumping at legal dump site. The non-contaminated disturbed soil can either be used for backfilling at excavation site or landfilling at legal dumping site without any treatment (Air excavation, 2019)

3.6 The Analytic Hierarchy Process

AHP is a multi-criteria decision-making process that utilizes ratio scales in making a series of paired comparisons among different alternatives and provides a comparison between considered options (Saaty T. L., 2000). AHP has been used as a stand-alone tool or integrated with other tools in complex decision-making problems in the construction industry in the area of risk management and sustainable construction (Amos, et al., 2019). AHP is based on the bifurcation of the problem incorporating subjective assessments and objective in a hierarchical form (Saaty T. L., 2000).The goal is used to derive hierarchical structure that divide into criteria, sub criteria and the alternatives. (Thomas & Luis, 2012). The factors that are related to the sub criteria are developed and place in the hierarchical structure for the comparison between two alternatives.

AHP is a rational analysis for problem solving where information about the problem is known, to generate a framework of relations and influences (Thomas & Luis, 2012). The analysis provides the decision maker a means to organize thoughts and judgements to make a productive decision. AHP begins with the pairwise comparison of two or more criteria, sub criteria, and alternatives utilizing qualitative judgements and thoughts from subject matter experts and advances to generate the ranking of the elements in the hierarchy (Saaty T. L., 2000). AHP can also be used to generate a preference list of the available alternatives.

AHP is a descriptive process that allows social, economic, political, environmental, and cultural factors to be integrated, and on this basis an optimum choice is obtained which incorporates both qualitative and quantitative variables (Saaty T. L., 1980). AHP can be applied in determining the list of priorities, selection of best policy, risks assessment and planning, optimal allocation of resources, optimal costs, opportunities and benefits, and conflict resolution, among others (Saaty T. L., 1980). The entire process of pairwise comparison between a pair of criteria, sub criteria and alternatives has two parts, (1) dominance, i.e. which of the factors has more influence than the other? intensity, i.e. how much more? (Saaty T. L., 2000).

The analysis in this paper is based on three fundamental principles (Saaty T. L., 2000; Bottero & Peila, 2005):

- Develop a hierarchical representation of the problem
- Perform pairwise comparisons to establish matrixes in forming priority vector in hierarchical structure

- Determine weightings by combining local priorities to determine the final priority vector, synthesizing expert judgements.

The first step of developing a hierarchical representation of the problem or goal consists of subdividing the problem into criteria, sub criteria and alternatives in a network structure (Thomas & Luis, 2012). The subdivision of the goal in the network structure is carried out from top to bottom, starting from the goal to the final alternatives (Saaty T. L., 1980).

The second step of the AHP consists of using Saaty's fundamental nine-point scale shown in Table 3.1 (Saaty & Vargas, 2012) to make a pairwise comparison between two alternatives derived for the comparison. The scale is assigned by subject matter experts using their judgement, experience, and knowledge of the field, in this case, hydro and air excavation. A weight is assigned for pairwise comparison matrix among all the elements in the hierarchical structure (Saaty T. L., 1980).

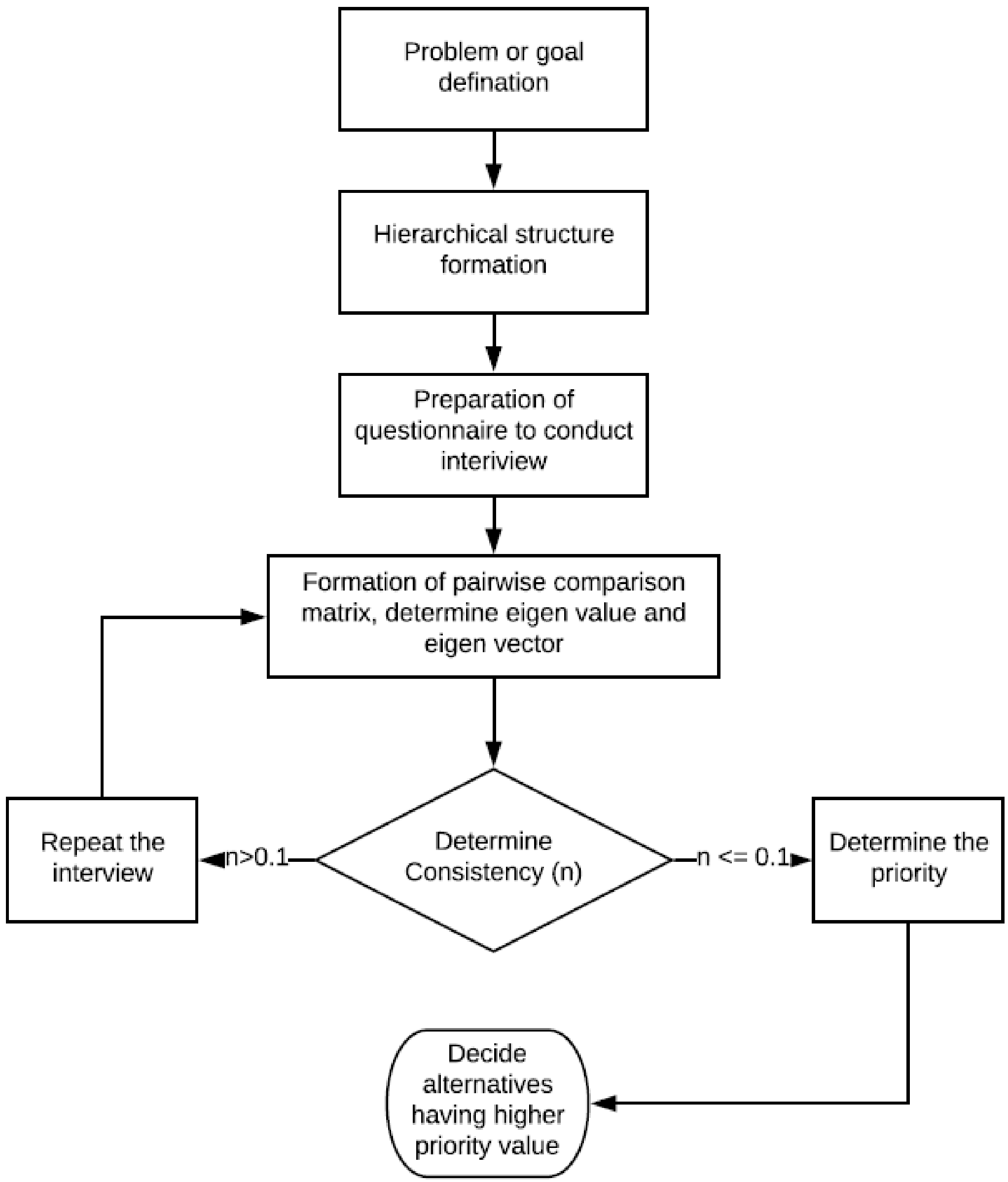


Figure 3.1
Stepwise procedure for the application of AHP in comparison between two excavation method *(Saaty T. L., 2000)*

Table 3.1: Saaty's Fundamental Scale "Reprinted from" *(Saaty & Vargas, 2012)*

Scale	Definition	Explanation
1	Equal Importance	Two activities are equally preferable to each other
2	Weak	Expert judgements slightly prefer one activity over another
3	Moderate importance	
4	Moderate plus	Expert judgements strongly prefer one activity over another
5	Strong importance	
6	Strong plus	Expert judgements very strongly prefer one activity over another
7	Very strong or demonstrated importance	
8	Very, very strong	Expert judgements prefer one activity over another with higher value of importance
9	Extreme importance	

The judgements related to the weight to be applied to each factor established for each level of the hierarchical network form pair matrixes (Saaty T. L., 2000). The number of comparisons is a combination of the number of elements in the hierarchical structure at each level. Suppose j is the number of criteria at a certain level in network diagram and i is the number of alternatives. The matrix **A** is formed with j rows and i columns connecting criteria to the goal (Thomas & Luis, 2012). If one criteria is judged to be six times more influential than another criteria, the other is 1/6 times as important as the first (Saaty T. L., 2000). Also, the principal diagonal elements of matrix **A**, p, are always equal to one because the criteria is compared with itself and thus has equal importance, where p is the diagonal elements of matrix **A** (Saaty T. L., 2000)**.** The pairwise comparison matrix is indicated in Figure. 3.2.

Judgement values are obtained after conducting the pairwise comparison between two elements. The relative priority vector resulting from a pairwise comparison matrix is obtained by solving (Saaty & Vargas, 2012) .

$$\sum_{j=1}^{n} A\,ij\,Wj = \lambda\max Wi \qquad [3.1.1]$$

where, $\mathbf{A}_{ij} = 1/\mathbf{A}_{ji}$, $\mathbf{A}_{ij} \cdot A_{ji} = 1$, and $\mathbf{A}_{ij} > 0$, i.e., $\mathbf{A}_{ij}$ is a reciprocal matrix and i and j are equal to 1,2,3…

N	1	2	3	…	m
1	1	$\mathbf{A}_{12}$	$\mathbf{A}_{13}$	…	$\mathbf{A}_{1m}$
2	$1/\mathbf{A}_{12}$	1	$\mathbf{A}_{23}$	…	$\mathbf{A}_{2m}$
3	$1/\mathbf{A}_{13}$	$1/\mathbf{A}_{23}$	1	….	$\mathbf{A}_{3m}$
…	…	…	…	1	…
n	$1/\mathbf{A}_{1m}$	$1/\mathbf{A}_{2m}$	$1/\mathbf{A}_{3m}$	$1/\mathbf{A}_{\dots m}$	1

Figure 3.2: Pairwise comparison matrix for AHP

λ_{max} is the principal eigenvalue of pairwise matrix **A**. The vector W is the normalized eigenvector of the matrix **A** and is used to determine criteria priorities with respect to the goal (Saaty & Vargas, 2012).

Inconsistencies can arise during the pairwise comparisons in the individual values of matrix **A**, i.e., $\mathbf{A}_1$ may be more important than $\mathbf{A}_2$ and $\mathbf{A}_2$ to $\mathbf{A}_3$, but $\mathbf{A}_3$ may be more important than $\mathbf{A}_1$ (Bottero & Peila, 2005). In such a case, inconsistency in the values informed by expert judgements can be determined, as it is known that the principal eigenvalue of the pairwise matrix is equal to the size of comparison matrix, i.e. $\lambda_{max} = n$, where n is equal to the size of the comparison matrix (Saaty T. L., 2000). Thus, the consistency index or degree of consistency index (CI) can be determined by following formula derived by Saaty, as shown in Equation [3.1.2].

$$CI = \frac{\lambda\ \max - n}{n-1} \qquad [3.1.2]$$

After determining the CI, Saaty proposes that CI be compared to Random Index (RI). Saaty has derived the RI for matrixes of up to 11×11 elements with a sample size of 500 (Saaty T. L., 2000). Thus, the consistency ratio (CR) for determining the consistency of input judgements can be defined as:

$$CR = CI/RI \qquad [3.1.3]$$

Table 3.2: Average Random Consistency Index (RI) *(Thomas & Luis, 2012)*

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	.52	.89	1.11	1.25	1.35	1.40	1.45	1.49

The AHP involves determining the consistency of the entire hierarchy. The consistency ratio is obtained by determining the ratio of CI to RI, using the appropriate RI from Table 3.2 where n is the size of matrix. If the value of CR is greater than 0.1, the level of inconsistency is not acceptable, and a revision of the subjective judgement must be done. If the value of CR is less than or equal to 0.1, the inconsistency is acceptable. A value of CR of less than 0.1 implies that the discrepancy in the judgement is small compared to the actual values of the eigenvector entries (Thomas & Luis, 2001).

The last step in AHP consists of aggregating the priority vector of different levels to obtain the final vector for determination of the alternatives. Thus, the final priorities at the level of the alternatives are obtained by summing the eigenvalues for all levels in reaching the initial goal (Thomas & Luis, 2012).

3.7 Example of Application of the Analytic Hierarchy Process

The application of AHP considered in research conducted by Ramanathan (Ramanathan, 2001) and (Mohammed, 2001; Bottero & Peila, 2005) is discussed to provide an example of AHP as applied to a construction problem. The decision problem used in this example involves selection of the best delivery method for a small to larger construction project. The topmost level is the goal: the goal is described with different criteria to be considered by the decision maker in selecting the best delivery method for the project. The criteria included in this example of selection of the best project delivery method are project characteristics, owner needs and owner preferences. The criteria could be further subdivided with sub criteria; however, in this example, sub criteria are eliminated in the interest of the simplicity of analysis. The simple hierarchy network diagram developed for this example is shown in Figure 3.3, and includes the goal, criteria and alternatives, which are Design-Bid-Build, Design-Build and Construction Management.

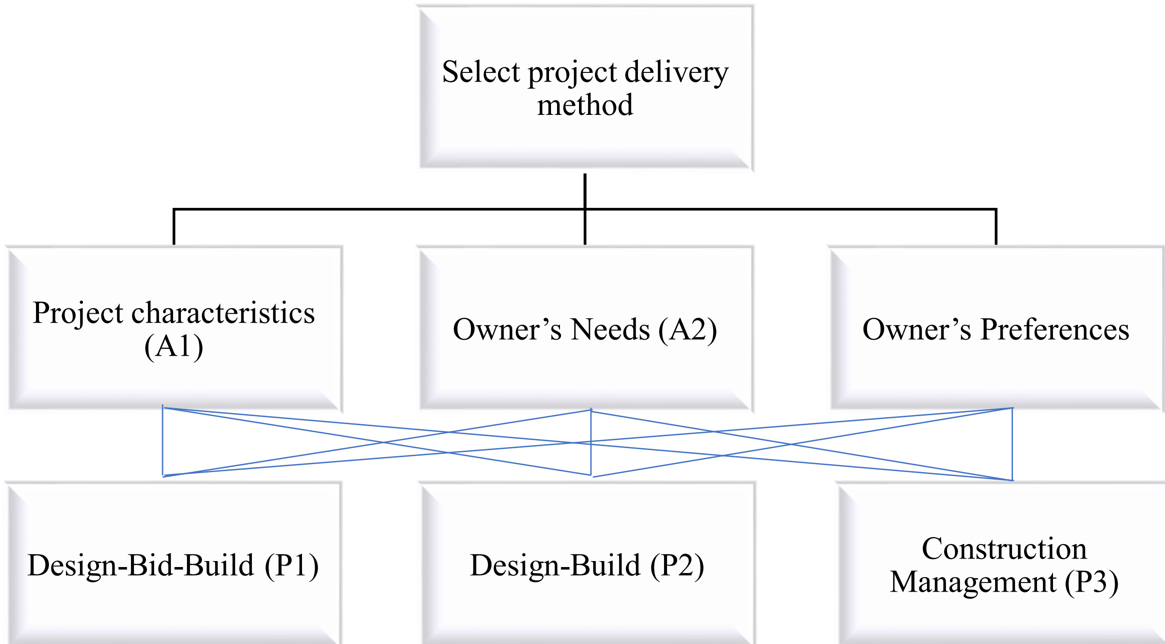


Figure 3.3: Example of a hierarchy network diagram for AHP used in selecting a project delivery method for a small construction project

After the development of a hierarchical diagram specific to the decision under consideration, AHP consists of performing pairwise comparisons between the different criteria and eventually between the criteria and alternatives (Thomas & Luis, 2012). The comparison between two criteria $\mathbf{A}_1$ and $\mathbf{A}_2$ with reference to goal consists of asking questions to experts in the subject area such as "Which of the criteria $\mathbf{A}_1$ and $\mathbf{A}_2$ is more preferred when making a decision in selection of project delivery method, and how much more?" The judgments and qualitative opinion are translated into numerical weights using the scale developed by Saaty included as Table 3.1 (Thomas & Luis, 2012).

For this particular example, the values determined from judgements made by subject matter experts for comparison of the criteria with respect to the overall goal are included in Table 3.3. It can be seen that based on this, the owner needs are more influential than other criteria in achieving the overall goal. Table 3.4 to 3.6 includes the comparison between three project delivery methods with respect to the criteria considered. In Table 3.4, while considering the criteria Project

Characteristics in making the comparison, Construction Management is the preferred delivery method compared to Design-Bid-Build and Design-Bid.

The final vector in aggregating and synthesizing the values from (Tables 3.3 to 3.6) is included in Table 3.7. This was one analysis done for one circumstance using one set of criteria, it is evident that Design-Bid is the preferred method for delivery of construction projects.

Table 3.3: Comparison of criteria with respect to overall goal

Overall goal	Project Characteristics	Owner Needs	Owner Preferences	Local Priorities
Project Characteristics	1	½	3	0.29
Owner Needs	2	1	7	0.61
Owner Preferences	1/3	1/7	1	0.092

λ_{max}=3.004, CI = 0.0018, CR = 0.00324

Table 3.4: Comparison of alternatives with respect to criteria Project Characteristics

Project Characteristics	Design-Bid-Build	Design-Build	Construction Management	Local Priorities
Design-Bid-Build	1	2	½	0.31
Design-Build	½	1	½	0.19
Construction Management	2	2	1	0.49

λ_{max}=3.006, CI = 0.003035, CR = 0.0523

Table 3.5: Comparison of alternatives with respect to criteria Owners Need

Owner's Need	Design-Bid-Build	Design-Build	Construction Management	Local Priorities
Design-Bid-Build	1	1/5	1/4	0.09
Design-Build	5	1	2	0.56
Construction Management	4	½	1	0.33

λ_{max}=3.03, CI = 0.016, CR = 0.02806

Table 3.6: Comparison of alternatives with respect to criteria Owners Preferences

Owners Preferences	Design-Bid-Build	Design-Build	Construction Management	Local Priorities
Design-Bid-Build	1	1/7	½	0.10
Design-Build	7	1	2	0.62
Construction Management	2	½	1	0.26

Table 3.7: Final priorities for three project delivery methods

Construction Management	Final Priorities
Design-Bid-Build	0.10
Design-Build	0.45
Construction Management	0.43

3.8 Use of the Analytical Hierarchy Process for Comparison of Hydro and Air Excavation

AHP was used to compare hydro and air excavation for the installation of underground utilities in an urban setting in Canada. The analysis was carried out after performing interviews with experts working in the field of SET, including contractors, suppliers, manufacturers and consultants. This scenario includes installation of telecommunication, electrical, oil and gas, sewer, or fibre optic lines or rehabilitation of similar utilities, among others. The first step in performing AHP consists of defining the goal or objective of the analysis (Saaty & Vargas, 2012): in this case, the goal is a cost-effective method of excavation for installation and rehabilitation of underground utility projects. The criteria include social, economic and environmental factors. A hierarchical network diagram including criteria, sub criteria and alternatives for this decision is included in Figure 3.4.

For the purpose of the analysis, the costs associated with hydro or air excavation for utility installation/rehabilitation have been categorized as follows:

- Direct construction costs
- Indirect construction costs

- Social costs
- Environmental costs

The summation of these costs gives the total cost incurred in performing excavation works for an underground utility project. The questionnaire includes questions such as out of the two excavation methods, which has the least impact on environmental, social and economic areas while performing excavation for the installation of an underground utility project? The complete set of questions are included in Appendix A. The pairwise comparison sets for each level of the hierarchy are illustrated in Table 3.10. The interview responses collected were taken into account for making the comparison between two excavation methods using AHP.

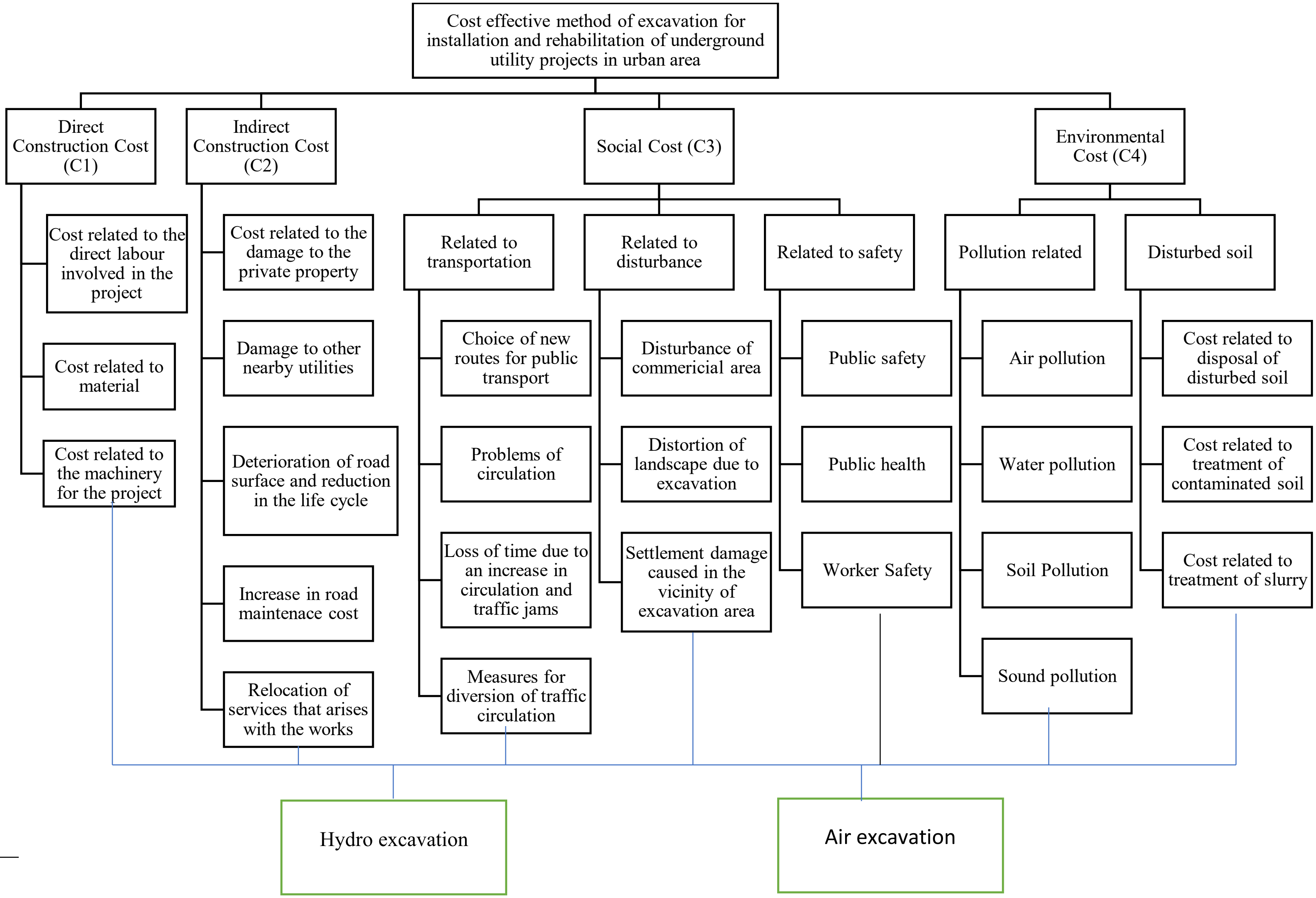


Figure 3.4:Hierarchical diagram including criteria, sub-criteria, and alternatives for AHP model for comparison of hydro excavation and air excavation to install underground utilities in an urban area.

3.9 Analysis of General Criteria for AHP

3.9.1 Direct Construction Costs

Direct construction costs include costs and expenses which are directly associated with the installation of underground utilities, i.e., costs incurred on wages, materials, and machinery, among others. With reference to hydro and air excavation, the direct costs are higher for air excavation than hydro excavation, since the hourly rental cost of an air excavator is higher than a hydro excavator by $100 per hour. In addition to the direct construction costs considered, sub criteria are analyzed using opinions from experts to determine the most important sub criteria for the direct construction costs with respect to Table 3.8. The cost related to the machinery for the project is considered the most important among the sub criteria of direct costs for the excavation, with a priority of 66%.

Table 3.8: Pairwise comparison for the sub-criteria of direct construction costs for hydro and air excavation

Direct construction cost	Cost related to direct labor involved in project	Cost related to material	Cost related to the machinery for the project	Local Priorities
Cost related to direct labor involved in project	1	2.62	0.30	0.24
Cost related to material	0.38	1	0.17	0.10
Cost related to the machinery for the project	3.3	5.8	1	0.66

3.9.2 Developing Sub-criteria for Indirect Construction Costs

Indirect construction costs are the expenses that contribute indirectly towards the total project cost. The sub criteria for the indirect construction costs for this model were developed by considering similar types of previous studies through a literature review (Bottero & Peila, 2005). The costs listed below were considered under indirect construction costs in this analysis.

- Costs related to damage to private property

- Costs related to damage to nearby infrastructures
- Costs related to deterioration of the road surface and reduction in service life of roadway
- Costs related to increased road maintenance
- Costs incurred due to relocation of services that arise from the excavation work

It is important to understand the way in which the sub-criteria in the category of indirect construction are compared and to determine the importance of each factor relative to the others. For this purpose, a pairwise comparison matrix is developed which needs to be completed based on information obtained by conducting interviews with subject matter experts. Table 3.9 shows the pairwise comparisons among the sub-criteria of indirect construction costs and the priority list obtained after calculating the principal eigenvector from the pairwise matrix. The analysis shows that the indirect costs incurred due to relocation of services arising from excavation work is more important than the other factors. In case of both hydro excavation and air excavation, the impact of relocating the services that interfere with the excavation work is equal. However, damage to nearby infrastructure (underground utility services) during excavation is higher for hydro excavation than air excavation, since the pressure of water in hydro excavation is in the range of 500 to 3000 psi is higher than the air which is in the range of 100 to 200 psi.

Table 3.9: Pairwise comparison matrix and priorities with respect to indirect construction costs

Indirect construction cost	Cost related to damage to the private property	Cost related to damage to nearby infrastructures	Cost related to deterioration of road surface and reduction in the life cycle	Cost related to increase in road maintenance	Cost incurred by relocation of services that arises with the works	Local Priorities
Costs related to damage to private property	1	0.69	0.46	0.38	0.25	0.08
Costs related to damage to nearby infrastructure	1.4	1	0.34	0.5	0.36	0.10
Costs related to deterioration of road surface and reduction in service life	2.15	2.88	1	1	0.72	0.23
Costs related to increased road maintenance	2.59	2	1	1	0.51	0.21
Costs incurred due to relocation of services due to excavation works	3.97	2.75	1.38	1.95	1	0.34

3.9.3 Developing Sub criteria for Social Costs

Social costs are the overall impact of a construction activity on the welfare of society; these are external costs that are not included in the construction bit and are external costs of the construction project *(Robert, 1997)*. The sub-criteria related to social costs for factors related to transportation around the excavation site have been considered based on previous studies that are applicable to this case *(Maddison, et al., 1995; Bottero & Peila, 2005)*. The social construction costs are further divided into three groups; related to transportation, related to disturbance and related to safety. The provision of new routes for public transport, problems of circulation, loss of time due to increase in circulation and traffic jams and measures for diversion of traffic circulation due to excavation is similar and cause same level of problems for both hydro and air excavation. Also, disturbance of commercial area, distortion of landscape due to excavation and settlement damage of utilities caused in the vicinity of excavation area is also similar in hydro and air excavation.

Table 3.10: Pairwise comparison sets for goal, criteria, sub-criteria & alternatives

Name of criteria group	**With respect to**	**List of criteria compared**	**Number of pairwise comparison sets**	**Sample pairwise comparison question**
Goal (1)	Criteria (4)	Direct construction costs Indirect construction costs Social costs Environmental costs	6	Which criteria has more importance related to underground utility project in reaching the goal?
Criteria (1)	Alternatives (2)	Hydro excavation Air excavation	1	Which method would contribute less direct construction cost for excavation?
Criteria (1)	Sub criteria (3)	Public safety Public health Worker safety	3	Which is more important in terms of social costs?

Table 3.11: Pairwise comparison matrix and priorities of sub-criteria under social cost

Social cost	Public Safety	Public Health	Workers Safety	Local Priorities
Public safety	1	0.29	0.18	0.09
Public health	3.41	1	0.38	0.28
Worker safety	5.51	2.62	1	0.62

If these sub-criteria are considered, both hydro excavation and air excavation contribute in an equal manner to the societal impacts of excavation. However, additional factors such as impact to public health, public safety and worker safety also should be considered., Hydro excavation contributes to a less safe environment for workers compared to air excavation. This is since air is nonconductive in nature and thus gives a safer environment for workers while excavating around underground electrical lines. Also, according to expert opinion in the analysis with reference with table 3.11, worker safety is considered to take precedence over public safety and public health.

3.9.4 Environmental Costs

The environmental costs of construction are defined as the loss value of natural resources in output and consumption due to the use of natural resources and the impact value of pollution generated due to construction activities (United States Environmental Protection Agency, 1995). In this case, air, soil, water and sound (noise and vibration) pollution are considered (Bottero & Peila, 2005). In order to further improve the analysis, costs related to disposal, treatment of contaminated soil and slurry (mixture of soil and water) are compared using AHP. Based on this analysis, it was found that the costs related to the treatment of contaminated soil and/or slurry are more than the costs related to the disposal of disturbed soil. The results are included in Table 3.12. The air excavation does not produce slurry during the excavation, as a result the cost of management of disturbed soil is minimum in air excavation. However, hydro excavation produces mixture of solid and liquid during excavation that requires proper treatment before making it suitable to dump at legal dumping site. According to pairwise comparison for sub criteria of Environmental cost, the cost related to treatment of slurry is higher than the costs related to disposal of dry disturbed soil. With respect to sub criteria air pollution, the air excavation produces fine soil particles around the environment during excavation as a result, air excavation is considered to produce more air pollution than hydro excavation. However, with reference to soil and water hydro excavation has more environmental impact than air excavation. Therefore, air excavation is more preferable than the hydro excavation.

Table 3.12: Pairwise comparison matrix and priorities for sub criteria under environmental costs

Environmental Cost	Cost related to disposal of disturbed soil	Cost related to treatment of contaminated soil	Cost related to treatment of slurry	Local Priorities
Cost related to disposal of disturbed soil	1	0.19	0.20	0.09
Cost related to treatment of contaminated soil	5.12	1	1.81	0.54
Cost related to treatment of slurry	4.76	0.55	1	0.36

3.10 Comparison of Hydro Excavation and Air Excavation

The fundamental goal of this research is to determine the most cost-effective method of suction excavation for the installation of underground utilities in urban areas. Both tangible and intangible factors are taken into consideration for the analysis and the goal, criteria, and sub-criteria that are relevant to the decision-making process are systematically structured through the development of a hierarchy. Previously, pairwise comparisons between the sub criteria and their respective priorities have been determined to reflect the importance of each factor relative to the others. In order to determine the importance of the criteria for reaching the overall goal, pairwise comparisons, along with assigning weights for each criteria on the basis of expert judgements using Saaty's fundamental scale (Thomas & Luis, 2012), are necessary. Table 3.13 provides the pairwise comparison matrix along with the respective weights for the general criteria. It can be observed that some of the factors that are not usually considered in the total cost of a construction project have high weights in this case. Direct construction costs and social and environmental costs were considered very important in this comparison. Using Saaty's fundamental scale for feedback from experts can give results that are somewhat arbitrary, yet these results are extremely important for selecting the appropriate alternatives. The rating using Saaty's scale could differ from person to person according to their point of view. The priority list for the criteria are the outcomes of the pairwise comparison matrix followed by the calculation of the eigenvector and subsequent normalization, as shown in Table 3.13.

Table 3.13: Pairwise comparisons for the criteria at the second level of the hierarchy network diagram with respect to the goal

Overall Goal	**Direct costs**	**Indirect costs**	**Social costs**	**Environmental costs**	**Local priorities**
Direct costs	1	3.1	2.5	1.58	0.41
Indirect costs	0.32	1	0.38	0.33	0.10
Social costs	0.39	2.62	1	0.79	0.20
Environmental costs	0.62	3.3	1.25	1	0.27

From Table 3.13 the weight for direct cost, indirect costs, social costs and environmental costs are in the order of 41%, 10%, 20% and 27%, respectively. Tables 3.14 through 3.17 show the pairwise comparison matrix along with local priorities for the criteria and alternatives. The AHP analysis is performed to determine the final priorities, and the result is shown in Table 3.18.

After analyzing and synthesizing the priority vector from goal to alternatives, air excavation was determined to have a result of 53% while hydro excavation has 47%. If indirect construction costs, social costs, and environmental costs are considered in the analysis, air excavation is preferable to hydro excavation. However, when the analysis is performed with a higher weight assigned to direct costs, hydro excavation is preferable. The comparison of final alternatives with respect to the criteria in graphical form is shown in Figure 3.5.

Table 3.14: Pairwise comparison matrix for direct costs and alternatives

Direct Costs	**Hydro excavation**	**Air excavation**	**Local Priorities**
Hydro excavation	1	4	0.8
Air excavation	0.25	1	0.2

Table 3.15: Pairwise comparison matrix for indirect costs and alternatives

Indirect costs	Hydro Excavation	Air Excavation	Local Priorities
Hydro Excavation	1	0.3	0.23
Air Excavation	3.3	1	0.76

Table 3.16: Pairwise comparison matrix for social costs and alternatives

Social costs	Hydro Excavation	Air Excavation	Local Priorities
Hydro Excavation	1	0.38	0.27
Air Excavation	2.62	1	0.72

Table 3.17: Pairwise comparison matrix for environmental costs and alternatives

Environmental costs	Hydro excavation	Air excavation	Local Priorities
Hydro Excavation	1	0.32	0.24
Air Excavation	3.10	1	0.75

Table 3.18: Final priorities of the two excavation methods

Alternatives	Overall Priorities
Hydro excavation	0.47
Air excavation	0.53

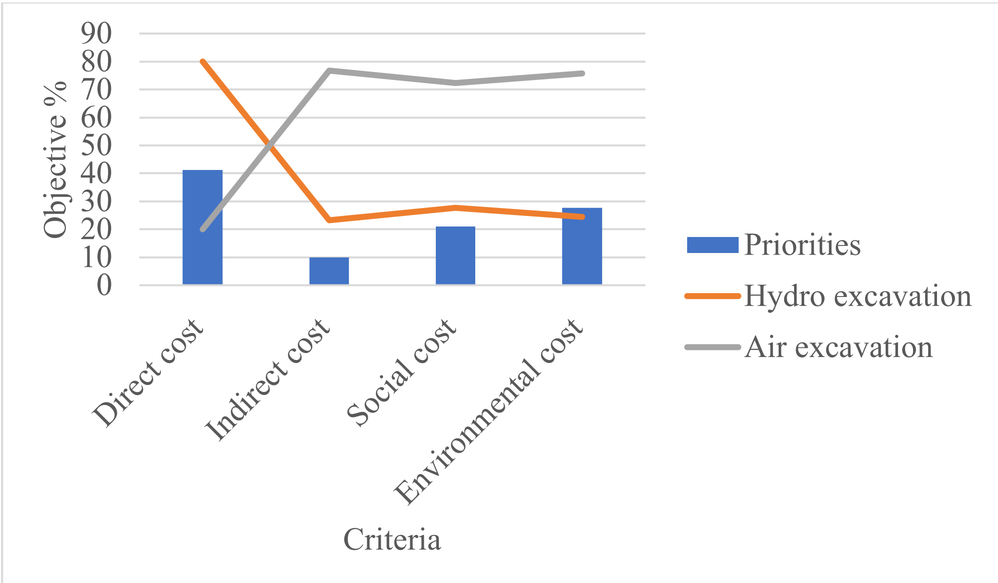
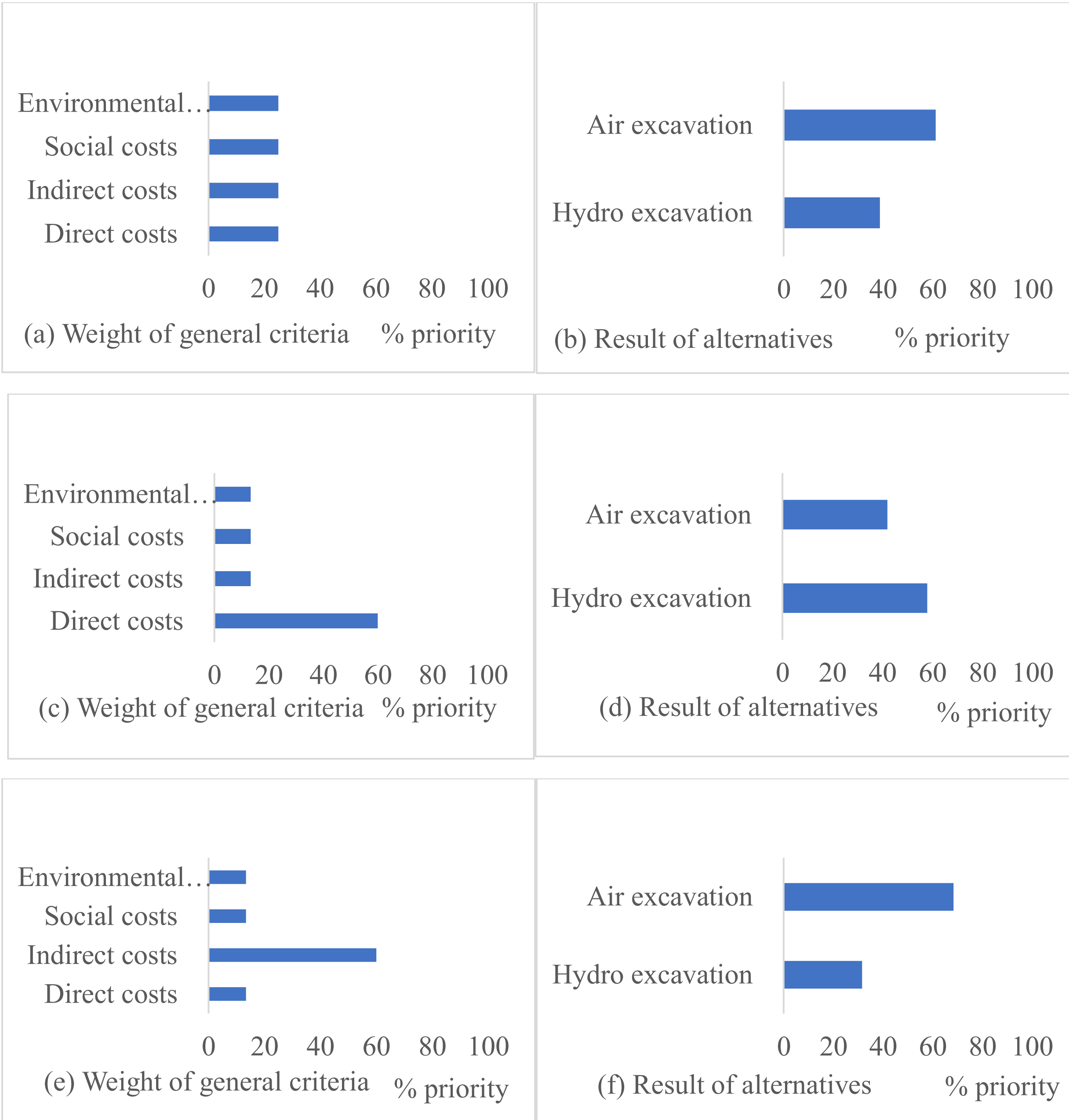


Figure 3.5:Performance graph showing the comparison of criteria with respect to alternatives

3.11 Sensitivity Analysis

As for any AHP, the results obtained for application of AHP to the comparison of air and hydro excavation for underground utility installations in urban settings is dependent on the hierarchy created for the analysis as well as the relative judgements made for the various criteria of the goal, considering many factors that are directly or indirectly related to the project. A change in the judgement value assigned to a criterion in the hierarchy may result in a change in the outcome. Thus, a sensitivity analysis has been done on these results. To perform the sensitivity analysis, five different scenarios were analyzed. First, AHP was done with all criteria (direct, indirect, social and environmental costs) given the same weight. Eventually, the weight of each criteria (60%) was changed, keeping the other criteria constant. The weight of each criteria could be from anywhere between 0% to 100%, but in this analysis the weight of 60 % is considered. The results of the sensitivity analysis are shown in Figure 3.6 (a-j). With respect to the analysis, it is concluded that if the decision maker gives maximum importance to the direct costs, hydro excavation is better. However, in all other cases, when the indirect, social and environmental costs associated with the excavation project are considered, results indicate that air excavation is the best solution.


Environmental…
Social costs
Indirect costs
Direct costs
0 20 40 60 80 100
(a) Weight of general criteria
% priority
Air excavation
Hydro excavation
0 20 40 60 80 100
(b) Result of alternatives
% priority
Environmental…
Social costs
Indirect costs
Direct costs
0 20 40 60 80 100
(c) Weight of general criteria
% priority
Air excavation
Hydro excavation
0 20 40 60 80 100
(d) Result of alternatives
% priority
Environmental…
Social costs
Indirect costs
Direct costs
0 20 40 60 80 100
(e) Weight of general criteria
% priority
Air excavation
Hydro excavation
0 20 40 60 80 100
(f) Result of alternatives
% priority

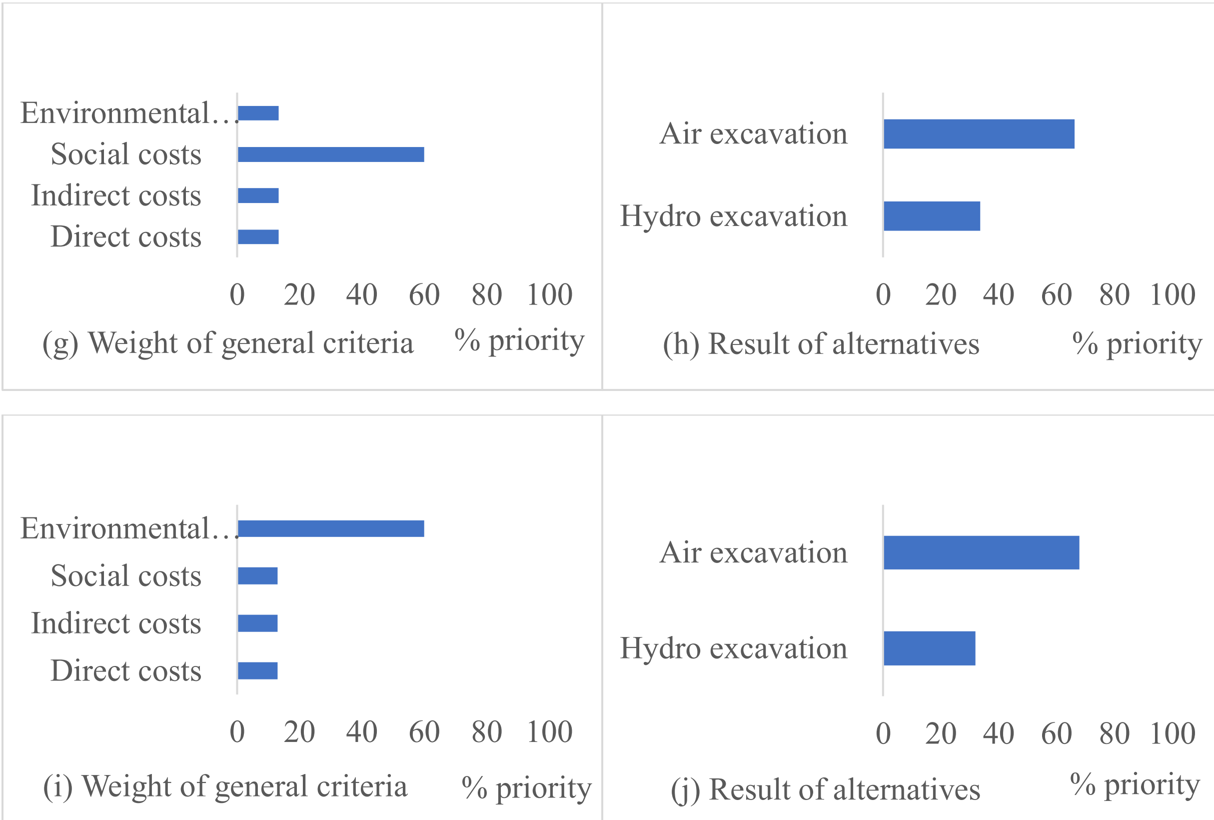


Figure 3.6 (a-j): Sensitivity analysis results for criteria and alternatives.

3.12 Conclusion

The expert opinion regarding different cost aspects involved due to excavation in urban areas for underground utilities project by hydro and air excavation technologies has been analyzed. The criteria's related to direct, indirect, environmental and social cost involved in underground utility project are structured in the hierarchy. The criteria related to each of the cost aspects has been further subdivided into sub criteria that helps decision maker to understand different cost factors involved in the underground utility construction project.

The use of hydro excavation technology for deployment of underground utilities may represent significant environmental and social disadvantages including additional increased construction costs. The comparison of hydro excavation and air excavation that was done in this analysis concludes that when indirect, social and environmental cost is considered with respective weights, air excavation is the cost-effective method for excavation project in urban areas. Air excavation is better options due to absence of slurry during the excavation that is a sustainable practice and results into reduction of negative impact towards the environment while excavating for underground utility project. The results of the analysis also suggest that AHP helps to structure the problems and integrate the criteria considering their relative importance, otherwise it would never be considered in the analysis.

Chapter 4: Comparative Study Between Hydro vs Air Excavation Technology by Using Online Survey Results

4.1 Abstract

Generally, the conventional methods for installation of underground utilities have been open-cut methods using mechanical tools and machinery. However, the development of suction excavation in the underground utility industry has resulted in numerous advantages, including a safer working environment for laborers. Although hydro and air excavation are increasingly used, not much previous information exists in literature and also it is important to have solid understanding of when this excavation tools are best applied. The main goal of the research is to make a comparison between hydro and air excavation technologies by analyzing the results obtained from an online pilot survey questionnaire conducted regarding HET and AET under given soil and temperature conditions. According to the survey responses and corresponding analysis, air excavation is cost effective and time efficient in compare to hydro excavation.

4.2 Introduction

Excavation is an important aspect of many different underground utilities' construction projects, and the choice of the appropriate excavation technology; traditional vs suction excavation can impact the overall delivery of a project in terms of cost and schedule. Traditional excavation employs hand tools for digging; the shovel is one of the most used hand tools in traditional excavation. Furthermore, advancements in mechanical units for excavation has made it easier for civil contractors to perform excavation works. However, this type of machinery produces large amount of greenhouse gases and may be unsafe for underground utility excavation in certain circumstances, i.e. excavation near existing utilities or excavation for electrical cables or excavation for telecommunication lines. In other hand, suction excavation uses pressurized water or air to soften the soil and a vacuum system to remove the loosened soil and debris (Hydro vs Air Excavation - Which is best for your industry?, 2018) Under SET, two other excavation technologies come, hydro and air excavation technologies. The contractors working in the suction excavation industry, previously working as electrical contractor has gradually moved into underground utility company after finding the potential and strong market demand for SET (Ken, 2018). According to (Ken) in the year 2017, the daylighting to expose underground utilities for the facilitating inspection around underground utilities calculated for about $ 1 million of $ 20 million of gross sale.

Hydro-excavation was used in the Canadian oil and gas industry in 1970s and 80s after modifying vacuum trucks and sewer cleaners (Jetnews, 2012). Since Canada has extremely cold winter weather conditions, permafrost, petrochemical plants, oil and gas industries, and underground utilities construction industries realized that heating the water to melt the frozen ground to excavate in cold weather conditions can be possible with hydro excavation. The first hydro-excavation machine, the "ExcaVactor," was built by Vactor in 1969. (Jetnews, 2012). At that time, the underground utility industry was immature and the ExcaVactor was the only hydro excavator unit of its type built. At about the same time, to make it possible to access remote locations, vacuum components were removed from the trucks and mounted on vehicles that could handle rougher terrain.

The demand for hydro excavation grew during the 1990s, and at that time several companies began manufacturing truck and trailer-mounted hydro excavation units in varying configurations (Jetnews, 2012). By 2000, hydro excavation became popular excavation technology in industry project where excavation is required and was slowly moving into the United States.

Today, hydro excavation trucks come in a wide variety of different dimension, specifications and with different functional requirements. However, hydro excavation process generates a mixture of liquid and solid which is known as slurry waste and slurry waste requires treatment before it can be disposed at a legal dumping site (Government of Alberta, 2018). The slurry can be contaminated or non-contaminated, depending on the type of hazardous and nonhazardous material mixed during excavation. As provincial and federal regulation related to disposal of waste increases and waste management facility option decreases, project owners are faced with large amount of money for handling and treating the slurry waste. The environmental impact of hydro excavation due to consumption of water during excavation has been subjected to increased scrutiny as this process is unsustainable practice. Therefore, one alternative that can reduce the impact caused by traditional and hydro excavation could be air excavation.

Air excavation uses pressurized air for excavation and produces less negative impact on the environment. After completion of air excavation, dry soil is produced and generally can be used as backfill or be disposed at a legal dumping site without treatment, unlike hydro excavation. Since air excavation is a new technology compared to hydro excavation, market acceptance slowly started from late 1990s, and the excavation industry has not yet recognized the benefit of excavation by air (Nate, 2018). The hourly rental cost of air excavation is higher than hydro excavation, and usually production rate of air excavation is lower than hydro excavation due to the reduced capacity of air excavation, and these are reasons that the excavation industry is yet to accept air for excavation. However, in recent years, due to advancements in technology, different air excavation units with enlarged capacity are available in the market. Therefore, this survey provides a comparison between hydro and air excavation. The results of the survey can help to determine which excavation is a better solution considering excavation under different conditions.

This survey focuses on collecting information related to production rate, hourly rental cost, cost of treatment of contaminated and non-contaminated slurry, and transportation cost for moving the excavator to and from the excavation site, as well as other information related to hydro excavation and air excavation under different conditions, i.e ground conditions, moisture content, and applicable temperature ranges. The results of survey are useful for people within the construction industry, i.e. contractors, owners, etc., for selecting the best excavation technology for a particular project and contributing less negative impacts on the environment, as well as providing greater saving of time and cost on excavation projects.

4.3 Objective and Scope

The primary objective of this survey is to investigate excavation methods in detail to gain a thorough understanding of under what conditions it is appropriate to apply HET and AET. The secondary objectives of this research are divided into:

- To provide an overview of relatively new excavation methods, in particular to identify cost-effective, environmentally friendly, and innovative excavation methods.
- To make a statistical comparison between hydro excavation and air excavation technologies to determine the effectiveness and productivity of Air excavation to the Hydro excavation.
- To provide a scenario that helps project contractors, owners and consultant to select the most environmentally friendly, cost-effective method for excavation under given conditions based on survey results.

4.4 Methodology

To meet the objectives stated above, an online survey was created for distribution to contractors, equipment manufacturers, suppliers and owners in the field of suction excavation. The questions included in the survey relate to the productivity of air and hydro excavation, logistics of suction excavation and the associated disposal costs under given conditions. Further information is given in sections, a list of contractors, manufactures, suppliers and owners related to the field of suction excavation was developed using information from website. The survey questions were reviewed by an experienced contractor in air and hydro excavation.

4.5 Questionnaire Survey

An online survey tool (Survey Monkey) was used as a tool to distribute and collect data for the survey questionnaire. The survey contained 20 questions and divided into three sections. Section 1 includes questions about HET and asks for information on the productivity rates of hydro excavation under different soils, moisture conditions and ground conditions, as well as temperature. It also has questions related to the accessibility of waste management facilities for disposal of hydro excavation solids and the cost of treatment of the waste slurry and backfill material costs. Section 2 includes similar questions as those included in Section 1, but with respect to AET. Sections 3 contains questions related to general information about the excavators and contractors. The respondents were given an option to answer all sections and when respondents wanted only one section to be answered, the options of skipping the other sections was available. The survey information and questionnaire are provided in Appendix B.

4.6 Participation in the Survey

The survey was available to respondents through the online survey platform Survey Monkey from March 1 to June 30, 2020. Survey Monkey software was used to administer the survey and collect the responses. Invitations to participate in the survey were sent to contractors involved in hydro excavation and air excavation across North America. Potential respondents were identified through web searches and trade magazines, interviews with contractors, etc. A total of ten respondents submitted responses to the survey. It should be noted that not all participants answered every question in the survey, and that participants who responded to section 2 on AET did not respond for HET. The analysis is performed using the responses from three participants who responded to all questions in survey.

4.7 Hydro excavation and Air excavation information

4.7.1 Hydro excavation

Hydro excavation units have two separate systems, a high-pressure water system, and a vacuum source. In hydro excavation, highly pressurized water is used to liquefy soil, creating a slurry mixture which is then extracted using a powerful vacuum system (The Badger Hydrovac, 2020) The liquefied soil or debris is then transferred to a debris tank using air conveyance or vacuum. This method provides a non-destructive method of excavation compare to conventional open-cut method, and is broadly used for increased accuracy in the excavation of soil and for identifying location of underground utilities since excavation can be done for the particular ground just above where the utilities lies.

Two types of vacuum systems are available for hydro excavation units. The vacuum can be generated using a fan system or a positive displacement blower (What is hydro excavation?, 2019). Typically, the fan system can transfer a huge amount of air, resulting in faster excavations. However, the positive displacement blower system is able to transfer air over longer distances and its application can be used for the excavation in urban areas where there is limitation of space for halting the excavator and excavator can be parked remotely.

HET combines pressurized water with an air vacuum: high-pressure water is used to cut the soil and break it up, and a vacuum then is used to remove the liquefied soil from the excavation area. The waste slurry is moved to a debris tank attached to the hydrovac truck or transferred to another dumper for dumping at a legal dump site.

In addition to excavation in civil works, hydro excavators can be used for transporting and transferring product for pipeline operators, cleaning, and removal of hazardous and non- hazardous waste for commercial and industrial operators, as well providing removal of septic waste for commercial and residential industries. Hydro excavators also can be used to transport waste to an environmental waste management facility.

The demand of hydro excavation is increasing in Canada. The distribution of hydro excavation contractors among provinces in Canada is presented in Figure 4.1. As Alberta is the hub for the oil and gas industry, it is not surprising that it has the maximum number of hydro excavation contractors among all the provinces in Canada.

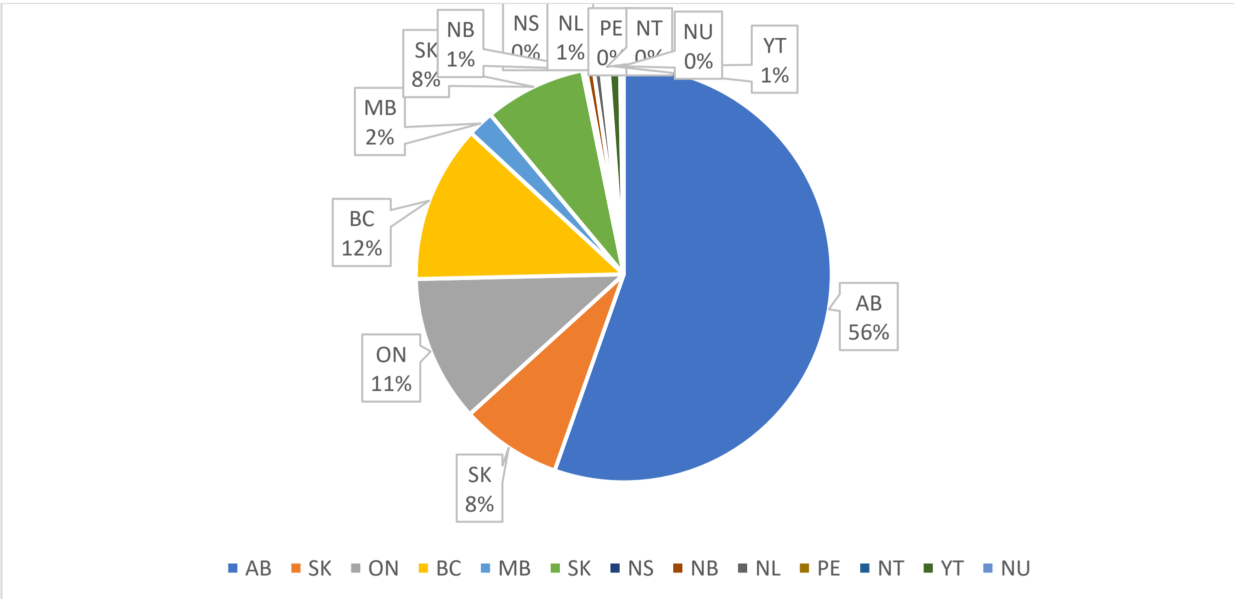


Figure 4.1[9]:Distribution of hydro excavation facility providers in Canada showing percentage of facilities located in each province

4.7.2 Air-excavation

In air excavation, highly compressed air (rather than water) is used to loosen the soil, and the disturbed soil is sucked up using a vacuum system into a disposal tank. The dry disturbed soil produced during air excavation is sucked by vacuum system, resulting in clean work environment. Pressurized air is converted into excavating power; however, pressurized air does not damage sensitive pipe coatings, underground utilities and even tree roots (Advantages of Air-vacuum, 2019).

Air excavation can be used for line locating of underground utilities, and daylighting underground pipelines, among other applications. Air excavation is the preferred method for rehabilitation and repair of underground electrical utility lines, since air is non-conductive in nature, in contrast to water. Air excavation has benefit of producing the dry disturbed soil during excavation which can be reused for backfilling the holes, or excavation site. During the excavation, dry disturbed soil could be mixed with the contamination like hazardous materials around the excavation site. The treatment of contaminated disturbed soil is necessary before landfilling or dumping at legal dump

[9] Retrieved from www.yellowpages.ca

site. The non-contaminated disturbed soil can either be used for backfilling at excavation site or landfilling at legal dumping site without any treatment (Air excavation, 2019).

4.8 Field Investigation for determining the production rate of Hydro vs Air excavation

A field investigation was carried out for determining the production rate of two different excavators in identical conditions. The case study was conducted by Ox Equipment (2019) and a MTS Dino Series air excavator and an industry standard hydro excavator performed the excavation work to dig a 1.2 × 1.2 × 0.91 m pit. In the first trial, the air excavator had a hourly production rate of 3.5 cubic meter, and the hydro excavator completed the excavation at hourly production rate of 1.9 cubic meter. The particle size distribution of the excavated soil was 41.1%, 33.8%, 20.2%, and 4.8% for gravel, sand, silt, and clay, respectively. In the second trial, the air excavator had an hourly production rate of 5.8 cubic meters and hydro excavator completed the excavation with an hourly production rate of 3.4 cubic meter. In addition, the particle size distribution for the excavated soil was 0%, 3%, 33%, and 64% gravel, sand, silt, and clay, respectively. The study demonstrated that the air excavator was more productive compared to the hydro excavator for these conditions. In addition, the rate of excavation was found to be higher when the soil contains a higher concentration of fine-grained particles and lower when the soil has a higher concentration of coarse-grained particles.

4.9 Comparison factors between hydro vs air excavation

A comparison between Hydro excavation and Air excavation for the excavation are performed with respect to productivity, number of manpower requirement, safety consideration, capacity of excavators, waste management considerations with respect to location (urban or rural), carbon emissions, proximity of waste management facility, among others. The cost factors that are responsible in performing the comparison between Hydro and Air excavation are mainly divided as: onsite cost factors, transportation cost for complete cycle of operation and management cost/disposal cost of disturbed soil.

4.9.1 Productivity

In general, productivity is defined as ratio of output to unit of input as machinery, manpower, material, among others. Productivity plays an important role in underground utility construction, including excavation. The productivity factor can help to form the estimate, plan of activities and work schedule for the given underground utility project. For the activity excavation, an increase in productivity tends to lower time for workers and machinery on site resulting in lower construction cost to the project. The productivity of excavators on site are affected by various factors: type of soil, moisture content in soil, temperature of ground (cold region), power, vacuum system of excavator, among others. Therefore, determining the productivity value is challenging task. It could also take recording of many operations to determine the actual productivity value of hydro and air excavation on site.

The factors that influences the productivity of machinery are mentioned below:

4.9.2 Type of soil

The rate of soil excavation depends on soil type for both hydro excavation and air excavation. The classification of soil types is carried out by American Association of State Highway and Transportation Officials (AASTRO) and Unified Soil Classification System (USCS). The USCS classify the soil with respect to texture and grain size of a soil, with a coarse-grained soil being a soil with 50% retained on or above a 0.0075 mm sieve, and fine-grained soils being soils where 50% or more passes through a 0.0075 mm sieve (American Society of Civil Engineers, 2000). In this survey, the productivity of excavators with respect to the USCS classification clay, silt, sand and gravel are determined. In general, the productivity rate of excavation is higher while performing the excavation on fine grained soil and comparatively lower when the excavation is performed on coarse grained soil. The tensile strength of the soil depends upon the bonding forces acted between the soil grains, and strength varies with saturation of soil (Ning, Tae-Hyung, Stein, & William, 2009), and this will also affect the excavation. To classify the soil, a sieve analysis has to be performed; however, this research is based on onsite production rates of excavators and contractors performing the excavation typically classify the soil using a visual inspection. Thus, for the purpose of this work, four types of ground conditions will be considered in the analysis, silt, clay, sand and gravel.

4.9.3 Temperature of ground

Earthwork operations are more difficult in the cold season, since air temperature, wind velocity and relative humidity govern the efficiency and comfort of workers while performing excavation (Lovell, 1968). The performance of machinery is also lower as the air temperature decreases. The effect of low temperature limits the use of machinery that would normally perform operations in normal weather conditions. In addition, due to freezing of the ground during winter, traditional or conventional excavation is not very efficient. Therefore, questions are related to effect of the temperature of the ground on the production rate of excavators for different types of soil is included in the survey.

4.9.4 Moisture content of ground

The shear strength of the soil is the principal factor in the excavation properties of the soil. The shear strength of soil is related to the moisture content, and generally the resistance of frozen soil to excavation is higher than that of thawed soil (Eranti & Lee, 1986). According to Heiner (1972) the shear strength of soil increases with decreasing temperature and increasing moisture content for silty sandy moraine. Therefore, for fine grained soil, the increase in moisture content result in an increase of the shear strength, and vice versa for coarse grained soil. Hence, the relative excavation resistance is also higher in the case of silt and clay soils, with their higher moisture content. On the other hand, in the case of sand and gravel, excavation resistance is lower, as when sand and gravel have a lower moisture content.

4.9.5 Density of Soil

The soil is classified as dense and loose with respect to density in the survey. Dense soil include fine sands, coarse gravel, very hard silt, and clay, whereas loose soils include fine to coarse sand, stiff clays, and silts. Soils that are dense tend to be compacted and difficult to excavate, whereas loose soils are less compacted, and the rate of excavation is higher.

4.9.6 Excavator's vacuum and power system

This section includes a general overview of technical specifications of the available suction excavator in the industry. Vacuum trucks come with different capacities for water and debris storage, ranging from 1 cubic meter to 6 cubic meters. According to their size and function, suction excavators are available as straight, combination and trailer vac units. There are varieties of excavator that comes with different number of tanks, for instance, XR2 Vermeer excavator has 4 number of water tanks that can be used for storing the water and the slurry (Vermeer, 2020).

The machinery in suction excavation industry comes with varying water and suction power, ranges from 1000 – 3000 psi and 1000 – 24000 CFM respectively. The diameters of air lances and water nozzles vary in size from 4 to 10 inches. The water and vacuum system of excavator plays an important role for delivering fast and productive operation during excavation. The higher the amount of maximum pressure generating capacity of excavator, the higher is the production rate of excavation under given conditions with respect to types of soil, moisture content, temperature of ground, among others.

4.10 Comparison for Hydro and Air excavation based on Survey Results

4.10.1 Productivity

The responses to this section of questionnaire provide information on the production rate of hydro excavation and air excavation under given conditions. According to survey responses, the average production rate of industry standard hydro excavators for excavation in sand and gravel is 2.5 m^3 per hour. For an air excavator with a twin fan technology system excavating sand and gravel, the reported rate is 3.5 m^3 per hour. Similarly, the production rate of hydro excavator and air excavator for excavation of ground with a particle distribution similar to that of silt and clay is 3 and 4 m^3 per hour, respectively. The temperature of ground at which the excavator can perform the excavation work ranges from negative -20°C to 40°C for hydro excavation in sand and gravel and -10°C to 40°C in silt and clay. Table 4.1 provides a summary of survey responses related to the production rate of hydro excavation and air excavation.

Table 4.1: Summary of survey responses related to the production rate of hydro excavation and air excavation

Type of excavation	Sand & Gravel (m^3/hr)	Silt & Clay (m^3/hr)	Working temperature range (°C)
Hydro excavation	2.5	3	-20 to +40
Air excavation	3.5	4	-10 to +40

4.10.2 Effect of moisture content in the production rate

The survey included questions regarding two types of ground conditions, dry and wet. For both types of excavation, hydro and air, the effect of moisture content in the ground is the same. The summary of survey responses related to the type of ground conditions with respect to moisture content in the production rate for hydro excavation and air excavation is presented in Table 4.2. For dry ground conditions, the productivity rates for silt and clay were reported to have an increase in production rate of 10% with respect to the production rates reported in Table 4.1. Similarly, for excavation of silt and clay in wet ground conditions, the production rate of excavation was reported to decrease by 10 % with respect to production rate provided in Table 4.1. Furthermore, in case of sand and gravel the production rate for dry and wet state of ground has 10 % decrease and increase with respect to the rate provided in Table 4.1, respectively. From the responses obtained, it can be concluded that the moisture content of the ground affects the production rate of the excavator.

Table 4.2: Summary of survey responses related to the type of ground conditions with respect to moisture content in the production rate for hydro excavation and air excavation

Type of excavation	Type of soil	Ground conditions	Effect of ground conditions in production rate in compare to rate provided in table 1 (%)
Hydro excavation	Sand & gravel	Wet	10
	Silt & clay		-10
	Sand & gravel	Dry	-10
	Silt & clay		10
Air excavation	Sand & gravel	Wet	10
	Silt & clay		-10
	Sand & gravel	Dry	-10
	Silt & clay		10

4.10.3 Effect of density of soil in production rate

The survey included questions regarding two types of ground conditions with respect to density, dense and loose. For both types of excavation, hydro and air, the effect of density of the ground is the same. For loose ground conditions, the productivity rates for silt and clay were reported to have an increase in production rate of 10% with respect to the production rates reported in Table 4.1. Similarly, for excavation of silt and clay in loose ground conditions, the production rate of excavation was reported to increase by 10% with respect to production rate provided in Table 4.1. Furthermore, in case of sand and gravel the production rate for dense and loose state of ground has 10 % decrease and increase with respect to the rate provided in Table 4.1, respectively. Table 4.3 provides the summary of survey responses related to the type of ground conditions with respect to density in the production rate for hydro excavation and air excavation. From the responses obtained, it can be concluded that the density of the ground affects the production rate of the excavator.

Table 4.3: Summary of survey responses related to the type of ground conditions with respect to density in the production rate for hydro excavation and air excavation

Type of excavation	Type of soil	Ground conditions	Effect of type of ground conditions in production rate in compare to rate provided in table 1 (%)
Hydro excavation	Sand & gravel	Dense	-10
	Silt & clay		-10
	Sand & gravel	Loose	10
	Silt & clay		10
Air excavation	Sand & gravel	Dense	-10
	Silt & clay		-10
	Sand & gravel	Loose	10
	Silt & clay		10

4.10.4 Cost of Suction Excavation

The cost for an excavation operation is the sum of direct, indirect, social and environment costs related to the excavation activity. In the survey question related to cost involved for the excavation, the disposal cost of the excavated material has been included. For suction excavation projects three main cost factors are primarily involved:

1. Cost incurred during excavation onsite,
2. Cost related to logistics, and
3. Cost related to handling of excavated material.

4.10.5 Cost incurred during excavation onsite

The factors that determine onsite excavation costs are the production rate of the excavator and the hourly rental cost of excavators. Survey responses were obtained for the hourly production rate of the excavator under given conditions and hourly rental rate for the excavator. Hydro excavation and air excavation units were reported to have average hourly rental rates of $250 and $350 in urban areas, respectively. Also, industry standard hydro excavation and air excavation units were reported to have average hourly rental rates of $350 and $450 in rural areas, respectively. It should be noted that the cost of transporting the slurry waste from excavation site to the slurry waste management facility (for hydro excavation) and the cost of transporting the excavated earth from the excavation to a legal dumping site (for air excavation) is not included in the hourly rental cost. The cost of labor involved during the excavation onsite is also not included in hourly rental cost of excavator. The total number of manpower involved during excavation is same for air and hydro excavation.

4.10.6 Cost related to logistics

Logistics costs include the cost of getting the excavator to and from the excavation site, the costs due to the distance between the disposal management facility and the excavation site, and traffic congestion due to excavation. In this case, the survey classified the hourly rental cost of excavators with respect to the location of the excavation, whether in an urban area or a rural area. The survey responses signify that the hourly rental cost of excavator in a rural area is greater by $100/hour for renting either an air excavation or a hydro excavation unit. The increase in hourly rental rate of the excavator by $100/hour includes the logistics cost of getting to and from the excavation site. The longer distance travelled by the excavation unit to reach the rural areas is covered by the additional cost of $100/hour. Table 4.4 provides the summary of survey responses related to the hourly rental cost for hydro excavation and air excavation. The higher the offsite time spent in management or disposal of excavated material, the less the excavator remains on site, resulting in less production time per day.

Table 4.4: Summary of survey responses related to hourly rental cost for hydro excavation and air excavation

Type of excavation	Hourly rental cost of excavator ($/hr)	
	Urban areas	Rural areas
Hydro excavation	250	350
Air excavation	350	450

4.10.7 Cost related to handling of excavated material

This part of the questionnaire focuses on costs incurred due to the management of excavated materials. Generally, hydro excavation uses pressurized water to break up the ground and a slurry is formed during the excavation process: this slurry is commonly called hydrovac waste (Government of Alberta, 2018). The slurry is composed of 60% liquid and 40% solid material and requires special treatment in order to either landfill the material or use it as backfill in accordance with provincial guidelines and legislations.

According to the survey results, the transportation cost per unit distance per unit slurry waste from the excavation site to the waste management facility ranges from $10-20/km/m^3$ for hydro excavation. Also, the cost treatment of non-contaminated and contaminated slurry waste was responded to be $100/m^3$ and $350/m^3$ respectively. In comparison, air excavation does not produce slurry during excavation; instead, the excavation process results in dry loose earth material that can be backfilled on site or taken to landfill without any treatment, provided that the soil is not contaminated with any hazardous materials. Table 4.6

Table 4.5: Summary of survey related to rate of treatment of slurry for hydro excavation waste

	Rate of treatment of slurry ($/m^3)	
Type of excavation	Contaminated Slurry	Non-contaminated slurry
Hydro excavation	350	100

Table 4.6: Summary of survey responses collected for hydro and air excavation

Description	Unit	Hydro excavation	Air excavation
Unit System	Metric		
Manpower required	Number	3	2
Sand & Gravel (excavation rate)	m^3/hr	2-3	3-4
Working temperature range	°C	-20 to 40	-10 to 40
Effect of density on excavation rate with respect to rate for normal conditions	%	+/-10	+/-10
Effect of moisture content in the ground with respect to rate for normal conditions	%	+/-10	+/-10
Silt & Clay (excavation rate)	m^3/hr	2-3	3-4
Temperature ranges		-20 to 40	-10 to 40
Effect of density on excavation rate with respect to rate for normal conditions	%	+/-10	+/-10
Effect of moisture content in the ground with respect to rate for normal conditions	%	+/-10	+/-10
Water consumption during excavation	Liters/m^3	1000-2000 (Sand & Gravel) 1000-2000 (Silt & Clay)	0
Hourly rental rate	\$/hr	200-300 (Urban area) 300-400 (Rural area)	300-400 (Urban area) 400-500 (Rural area)
Transportation cost of slurry	(\$/m^3/km)	10-20	0-20
Treatment of slurry waste	\$/m^3	200-250 (Non contaminated) 350-400 (Contaminated)	0

4.11 Formation of Scenarios using Survey Results and Discussion

An analysis and comparison between hydro excavation and air excavation for any specific completed job is difficult, as excavation at two different job sites is not identical. There are multiple variables involved in any excavation, including location of the site, ground conditions, weather, and productivity, among others. In order to make a comparison, two scenarios were developed with different conditions, and information from the survey responses was used in the analysis of the factors to be considered for each excavation.

4.11.1 Scenario 1

HET and AET are under consideration for the excavation of soil containing a high concentration of silt and clay. For the comparison between hydro excavation and air excavation, assumptions are made. The total material to be removed by excavation is assumed as 100 m^3. The ground conditions was assumed to be of type with higher concentration of silt and clay, moisture content of ground be dry, compactness of soil be dense, location of site was less than or equal to 50 kms away from the excavator station, and weather condition of the surrounding be assumed as warm. The type of contamination for the slurry after hydro excavation was assumed to be non-contaminated. The detailed information regarding the job site and related conditions are listed in Table 4.6. A detail calculation and comparison of cost of excavation of soil with high concentration of silt/clay using hydro and air excavator is shown in Table 4.7. From the survey responses, the rate of hourly excavation was considered 3 m^3/hr and 4 m^3/hr for industry standard hydro excavation and air excavation while performing excavation for silt and clay. The water tank capacity of industry standard hydro excavation ranges from 1 m^3 to 4 m^3 and debris tank capacity from 2 m^3 to 8 m^3 respectively. In this comparison, the size of hydro excavation water and debris tank were considered 4 m^3 and 8 m^3, respectively. The size of air excavation tank ranges from 2 m^3 to 12 m^3. For the comparison, air excavation truck capacity of 4 m^3 was considered. The hourly rental cost of hydro excavator and air excavator was considered from survey responses, i.e $250/hr and $350/hr, respectively.

Table 4.7: Scenario 1: Excavation of soil with high concentration of silt/clay

Job Scenario	1
Total material to be removed (m^3)	100
Type of soil	Silt and clay
Moisture content of ground	Dry
Weather conditions	Warm
Compactness of soil	Dense
Location of site	Urban area
Contamination/no contamination	Non-contaminated
No. of trucks	1
Truck water tank capacity (m^3)	4
Debris tank capacity (m^3)	8
Air excavator truck capacity (m^3)	4

Table 4.8: Calculation and comparison of cost of excavation of soil with high concentration of silt/clay using hydro and air excavator

Description	Hydro Excavation	Air Excavation
Hourly excavation rate (m^3/hr)	3	4
Hourly rental cost ($/hr) (b)	250	350
Water consumption (m^3)	100	-
Disposal cost of excavated material ($/$m^3$)	100	-
Total slurry (m^3)	200	-
Water fill time per truck (hr)	0.25	-
Travel to site (hr)	1	1
Halt time on site (hr)	33.33	25
Travel to disposal/dumping site (hr)	1	1
Disposal time/dumping time(hr)	0.25	0.16
Travel time back to site (hr)	1	1
Total number of cycles	25	25
Total cycle time (hr)	121	104
Site excavation cost ($)	8333	8750
Transportation cost ($)	21875	27650
Slurry management cost ($)	20000	-
Total cost ($)	50208	36400
Cost/cubic meter ($/$m^3$)	503	364

According to survey responses, water consumption during the hydro excavation was reported as 1 m^3 per m^3 of excavation for silt/clay and in this scenario total amount of slurry produced was equal to 200 m^3. In urban areas, the minimum travel speed for vehicle is 50 km/hr, with reference to the same travel speed, the excavator requires 1 hour to reach the excavation site from excavation station. The hydro excavator further requires time to fill the truck with water, assuming a discharge of 8 m^3/hr at water fill station, the hydro excavation requires 0.25 hr for filling of water tank. In addition to that, the excavating time for hydro excavation at excavation site was equal to 33.33 hrs at an excavation rate of 3 m^3/hr for the total of 100 m^3 of this job. The slurry produced during the hydro excavation is required to be disposed at a legal slurry management facility, for which the hydro excavator requires a total of 2.25 hours, including disposal time and travel to and from the slurry management facility. The cost per unit excavation for hydro excavation and air excavation in this analysis was \$503/m³ and \$364/m³, respectively. The total cycle time for the job by hydro excavation was reported to be 121 hours.

Air excavation requires similar types of activities, except that there is no water consumption during excavation, and no requirement for managing the excavated material, since non-contaminated disturbed soil can be dumped without any treatment at a legal dumping site or can be used as backfill at the excavation site itself. Due to these factors, the total cycle time for air excavation was reported to be 104 hours. This reduction in total cycle time for air excavation and no additional cost for treatment of disturbed soil results in a total cost saving of \$13,808 and total time savings of 17 hours when performing the excavation by air. The air excavator can dump and backfill the disturbed soil, whereas the hydro excavator requires travel to the slurry management facility to dump and treat the hydro excavation slurry. Table 4.8 shows the total savings in cost and time due to performing excavation by air excavator.

Table 4.9: Total savings in cost and time due to performing excavation by air excavator

	Air excavator Saving	
	Savings	Savings %
Total cost savings (\$)	13808	27%
Total time savings (hr)	16.83	14 %

Table 4.10: Percentage comparison of different costs between hydro excavator and air excavator

	Hydro Excavation	**Air Excavation**
Site excavation costs	16 %	24 %
Transportation costs	43 %	75 %
Slurry management costs	39 %	0 %

The transportation and slurry management costs contribute 43% and 39% of the total costs in the hydro excavation. Table 4.9 provides the percentage comparison of different costs between hydro and air excavator. The slurry management cost is not applicable to air excavation and this results in a time saving of 17 hours due to the excavator remaining on site and no requirement to travel back and forth to a waste management facility.

4.11.2 Scenario 2

In this scenario, hydro excavation and air excavation technologies are considered for the excavation of soil containing a higher concentration of sand and gravel (i.e. coarse-grained soil). Detailed information regarding the job site and conditions are listed in Table 4.10.

For the comparison between hydro excavation and air excavation, the following assumptions were made. The total material to be removed by excavation is assumed as 100 m^3. The ground conditions was assumed to be of type with higher concentration of sand and gravel, moisture content of ground was wet, compactness of soil was dense, and the location of site was assumed to be equal to or less than 50 km from the excavator station, and weather condition of the surroundings was assumed to be warm. The type of contamination for the slurry after hydro excavation was assumed to be non-contaminated. Detailed information regarding the job site and related conditions is listed in Table 4.10. The detailed calculation and comparison of cost of excavation of soil with high concentration of sand/gravel using hydro and air excavator is shown in Table 4.11. From the survey responses, the rate of hourly excavation was considered to be 2.5 m^3/hr and 3.5 m^3/hr for industry standard hydro excavation and air excavation while performing excavation for sand and gravel. The water tank capacity of industry standard hydro excavation ranges from 1 m^3 to 4 m^3 and debris tank capacities range from 2 m^3 to 8 m^3, respectively. In this comparison, the size of hydro excavation water and debris tank were considered to be 4 m^3 and 8 m^3, respectively. The size of air excavation tanks ranges from 2 m^3 to 12 m^3. For the comparison, an air excavation truck capacity of 4 m^3 was considered. The hourly rental cost of hydro excavator and air excavator was considered from survey responses, i.e. $250/hr and $350/hr, respectively.

Table 4.11: Excavation of soil with high concentration of sand/gravel

Job Scenario	2
Total material to be removed (m^3)	100
Type of soil	Sand and gravel
Moisture content of ground	Wet
Weather conditions	Warm
Compactness of soil	Dense
Location of site (<50 kms)	Urban area
Contamination/no contamination	Non-contaminated
No. of trucks	1
Truck water tank capacity (m^3)	4
Debris tank capacity (m^3)	8

Air excavator truck capacity (m^3)	4

Table 4.12: Calculation and comparison of cost of excavation of soil with high concentration of sand/gravel using hydro and air excavator

Description	Hydro Excavator	Air excavator
Hourly excavation rate (m³/hr)	2.5	3.5
Hourly rental cost ($)	250	350
Water Consumption (m³)	150	-
Disposal cost ($/m3)	100	-
Total slurry (m³)	250	-
Equipment loading water fill time per truck (hr) (a) at discharge of 8 m³/hr	0.25	-
Travel to site	1	1
Halt time on site (hr)	40	29
Travel to disposal/dumping site (hr)	1	1
Disposal time/dumping time(hr)	0.25	0.16
Travel time back to site	1	1
Total number of cycles	32	25
Total cycle time (hr)	152	117
Site excavation cost ($)	10000	10150
Transportation cost ($)	28000	32074
Slurry management cost ($)	25000	-
Total cost ($)	63000	42224
Cost/cubic meter ($/m³)	630	423

According to survey responses, water consumption during the hydro excavation was reported as 1.5 m³ per m³ of excavation for sand/gravel, and in this scenario, the total amount of slurry produced was equal to 250 m³. In urban areas, the minimum travel speed for a vehicle is 50 km/hr, with reference to the same travel speed, the excavator requires 1 hour to reach the excavation site from the excavation station. The hydro excavator further requires time to fill the truck with water, and assuming a discharge of 8 m³/hr at water fill station, hydro excavation requires 0.25 hr for filling of water tank. In addition to that, the excavating time for hydro excavation at excavation site was equal to 40 hr at an excavation rate of 2.5 m³/hr for the total of 100 m³ of job. The slurry produced during the hydro excavation is required to be disposed of at a legal slurry management facility, for which the hydro excavator requires total of 2.25 hr, including disposal time and travel to and from the slurry management facility. The cost per unit excavation for hydro excavation and air excavation in this analysis was \$630/m³ and \$ 423/m³, respectively. The total cycle time for the job by hydro excavation was reported to be 152 hours. Similarly, the air excavation requires similar types of activities except there is no water consumption during excavation, and no requirement for managing the excavated material, since non-contaminated disturbed soil can be dumped without any treatment at a legal dumping site or can be backfilled at the excavation site itself. Due to this, the total cycle time for air excavation was reported to be 117 hours. This reduction in total cycle time for air excavation and no additional cost for treatment of disturbed soil has resulted in a total cost saving of \$20,776 and total time savings of 35 hours for performing the excavation by air. The air excavator can dump and backfill the disturbed soil whereas hydro excavator requires travelling to the slurry management facility to dump and treat the hydro excavation slurry.

Table 4.13: Total fuel savings per cubic meter of excavation for Scenario 2

Description	Hydro excavator	Air excavator
Cycle times		
Travel to site (hr)	1	1
Halt time on site (digging) (hr)	40	29
Travel to disposal/dumping site (hr)	1	1
Disposal time/dumping time (hr)	0.25	0.16
Travel time back to site (hr)	1	1
Total number of cycles (hr)	32	25
Total cycle time (hr)	152	117
Fuel Consumption Ltr/hr		
Driving	40	40
Digging	40	40
Cubic meters dug	100	100
Total fuel	6080	4680
Liters of fuel used/m³ Dug and dump	60.8	46.80
Fuel Savings from excavation by Air excavation per m³	14	
Fuel saving for equivalent volume of excavation (ltr)	1400	

Fuel cost saving for equivalent volume of excavation, fuel at rate of $1/liter ($)	1400

Table 12 provides a comparison between fuel consumption for air and hydro excavation. For the analysis, the total time required for the completion of 100 m³ excavation was considered from Scenario 2 presented above. For both hydro excavation and air excavation, the hourly consumption of fuel was 40 L/hr. However, the total cycle time for completing the 100 m³ of excavation was higher by 35 hours when the excavation was conducted by hydro excavation. The extra 35 hours of working hydro excavation on excavation site resulted in 1400 L of extra fuel consumption, which results in a total cost saving of $1400 at rate of $1/L of fuel. This analysis shows that the air excavation is fuel efficient and produces carbon emissions compared to hydro excavation for a given volume of excavation.

4.12 Conclusion

This paper presents a comparative study of the costs of hydro and air excavation for performing excavation under specified conditions in four different scenarios. The calculations are based on questionnaire responses from contractors and manufacturers working with suction excavation technology. The analysis and conclusions are based on three responses from pilot survey conducted.

The excavation rate for an air excavator is reported to be higher than for a hydro excavator, however, the hourly rental cost of air excavator is greater than hydro excavator by $100/hr. With respect to the responses collected, two scenarios are analyzed and the total savings in cost and time from excavation to management of slurry or dry earth is greater in air excavation than hydro excavation.

The excavated soil obtained from air excavation can be retained and used for backfilling on site, provided that the soil is not contaminated. This allows the air excavation unit to remain onsite for longer duration for excavation, resulting in time and cost savings on the excavation project.

In addition, excavation by air is considered environmentally friendly due to the reduced emission of greenhouse gases, and lack of requirement for fresh water during excavation. Since water is not used, the requirement for regulated disposal management facility is reduced.

The results of this survey and analysis can help utility providers, government agencies, and contractors to realize the benefits of air excavation and to apply air excavation in the rehabilitation and installation of utilities for underground utility projects. However, the drawbacks of air excavation are unsuitability for conducting the excavation for frozen ground condition and slower excavation rate for very dense soil.

Chapter 5: Overview of Traditional and Suction Excavation Tools and Machinery and Life-Cycle Cost Comparison

5.1 Abstract

The conventional method for construction of underground utilities has been open-cut methods using mechanical tools and machinery. Innovations in technology in recent years have led to suction excavation being feasible for underground utilities projects. However, local municipalities and government agencies have been slow to recognize the cost benefits of suction excavation compared to traditional excavation. This is due to lower construction costs at the beginning of the project for traditional construction methods. Thus, a comparison of the life-cycle costs of traditional excavation and suction excavation is needed to expose the real costs for both methods. This study focuses on the investigation of the cost of construction of underground utilities using suction excavation in urban areas and provides a cost comparison with traditional excavation methods. The paper includes a breakdown of pre-construction and post-construction costs, including social and environmental costs, for both methods. In addition, an overview of currently available excavation tools and machinery is provided.

Keywords: Suction excavation, traditional excavation

5.2 Introduction

Infrastructure development is in demand throughout the world. The total annual revenue in Canada for building permits was 8.3 billion for October 2019 (Statistics Canada, 2019). Given the ever-increasing demand for construction work, the requirement for excavation is also increasing. Excavation is necessary in the execution of any civil works and in mining industry (Nuh Bilgin, 2014). Excavation involves two processes: digging the ground and disposing of at legal dumping site or backfilling the disturbed soil mass at the same excavation site (Tatiya, 2005). Traditional excavation (TE) employs hand tools for digging; the shovel is one of the most used hand tools in TE, but spades, hoes, trowels, rakes, pickaxes, and mattocks are also used. Furthermore, advancements in mechanical units for excavation has made it easier for civil contractors to perform excavation works. Mechanical excavators used in the construction industry include tracked excavators, wheeled excavators, back-hoe excavators, bulldozers, dragline excavators, trenchers, and dozers. However, this type of machinery produces large amounts of greenhouse gases, and other methods can be used that have less environmental impacts.

The latest innovation in excavation is suction excavation technology (SET). SET uses pressurized water or air to soften the soil and a vacuum system to remove the loosened soil and debris (Hydro VS Air Excavation - Which is best for your industry?, 2018). Many drawbacks of using mechanical excavators or TE in excavation are reduced by SET. Safety, health and environment factors are often not addressed in excavation works (Enshassi, Factors affecting safety on Construction Projects, 2004). TE involves the manual handling of excavated material, resulting in strains and muscle soreness for workers in the excavation industry. In addition, TE methods can be unsafe for underground utility excavation in certain circumstances, i.e. excavation near existing utilities or excavation for electrical cables or excavation for telecommunication lines. In contrast, SET is safe for excavation of underground utilities. The applications of SET are not only in excavation; SET can also be used for piling holes, line-locating, daylighting, shoring, manhole cleaning, and excavation of underground utilities in wet conditions.

This paper involves a comparative study between traditional excavation and suction excavation in terms of life-cycle costs from pre-construction to post-construction, including social and environmental costs. Various aspects associated with excavation in urban areas for pipelines or utilities, including safety considerations, accessibility, availability, sustainability, productivity and cost, are compared for SET and other types of excavation (including TE and mechanical excavation).

5.3 Objective

The objective of this paper is to develop a comprehensive life-cycle cost comparison for traditional excavation and suction excavation, including the applicability and classification of excavation tools, along with their advantages and disadvantages.

5.4 Methodology

This paper presents key excavation technologies and compares them in terms of various factors, including applicability, sustainability, occupational health and safety, among others. The comparison is made in terms of cost associated with construction, from the beginning of a project to completion. Information was collected from multiple sources, including academic publications, online resources, website and industry standards and regulations. Interviews were also conducted with contractors and manufacturers to gain detailed information based on their experience, and some of the information presented in this paper comes from these interviews. It should be noted that the academic literature provides detailed and comprehensive information on the SET however, the academic literature on this topic is relatively scarce.

5.5 Importance of Construction Excavation

Any civil works start with excavation, which is the process of removing earth or rocks using traditional or mechanical excavation (Inc, 2019). Factors to consider while choosing the type of excavation and excavators to be used depends on soil type, depth of cut, water content of soil, rock content, changes due to weather or climate, among others (Canada, 2019). Excavation work is involved in many aspects of construction, including digging trenches, piling holes, tunnel, mining, and underground works. The foundation of a structure can be laid only after completion of excavation work. Whether it is construction of buildings, roads, bridges, dams, culverts, laying electric cables, or laying conduits for fibre in telecommunication industry, excavation is required.

5.6 Excavations and their classification

Excavation usually involves two operations: removing the earth or rock and its disposal. In the modern construction industry, the types of excavation can be classified based on purpose, locale and function and utilities (Tatiya, 2005). In terms of purpose, excavation can be classified as surface excavations and subsurface or underground excavations. Furthermore, surface excavation can be divided into excavation for transportation, waterways, storage, buildings and mining. Subsurface excavation can be further divided into excavation for transportation/conveyance, storage and plants, protection openings, underground mining, among others.

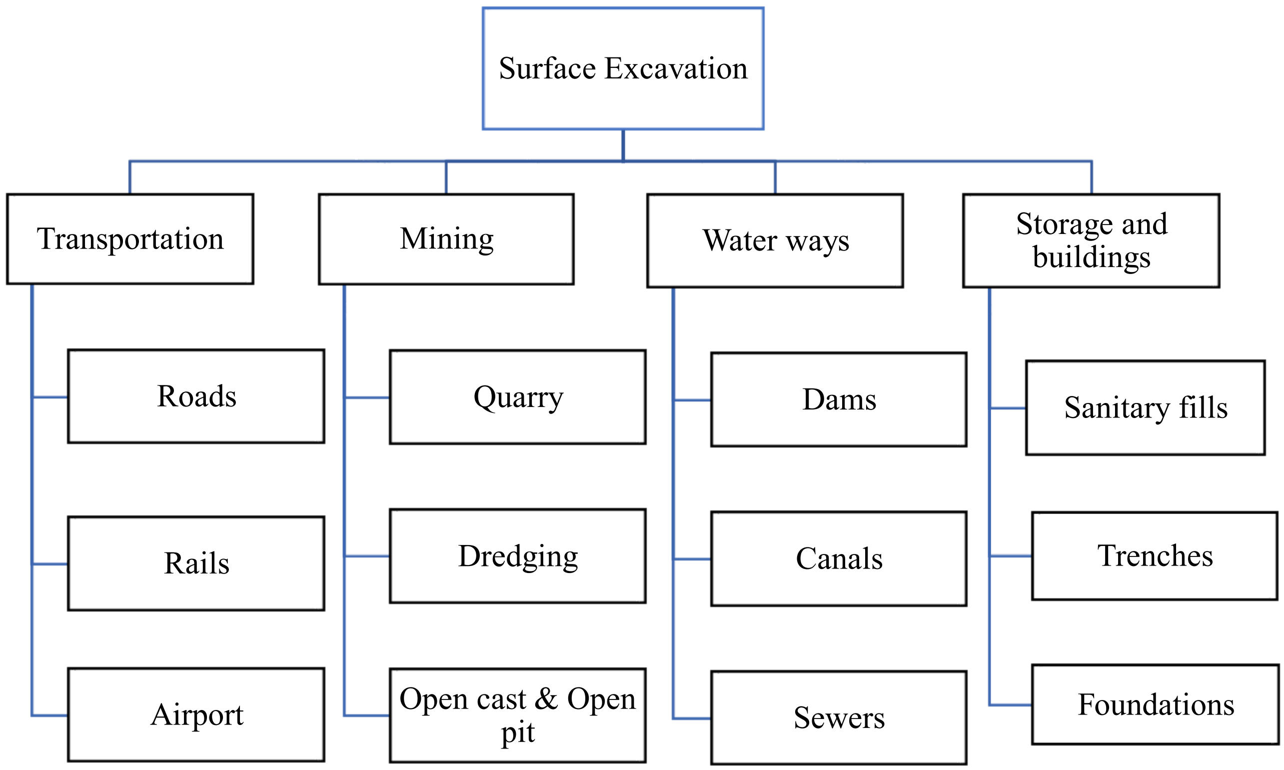


Figure 5.1: Classification of the surface excavations based on the purpose

5.6.1 Surface Excavation

Every year, billions of cubic meters or tonnage of surface excavation is conducted during construction of roads, rails, dams, foundations, among others (Tatiya, 2005). Any structure lies on the foundation, and building any foundation requires excavation. Excavation is required to remove the earth and rock material lying above the ground and to develop a smooth and uniform surface which is required for construction of the foundation of a building. Without a uniform ground surface where the structure is laid, a strong foundation is not possible.

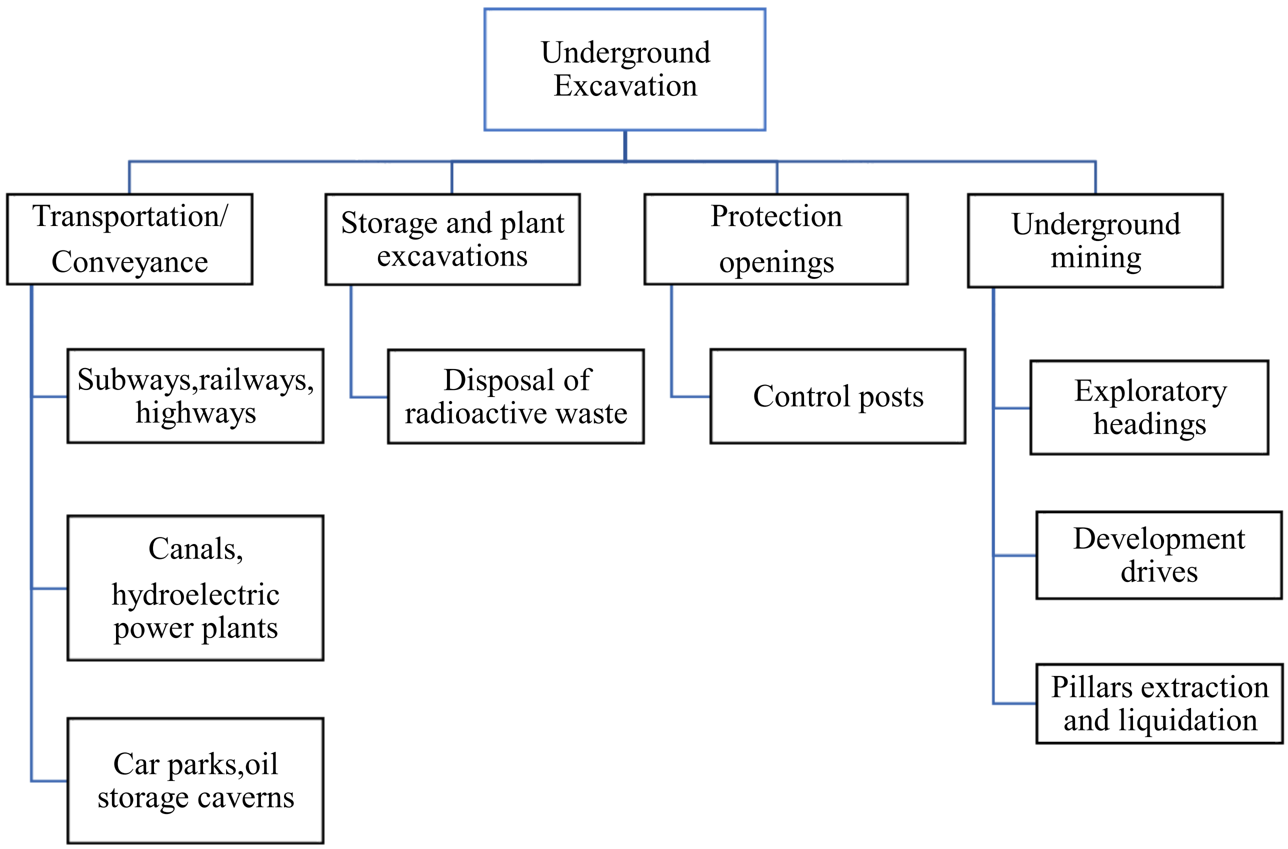


Figure 5.2: Classification of Underground Excavation

5.6.2 Underground Excavation/Sub-surface excavation

There are two categories of underground openings where tunnels are driven. The first type includes the passage to subways, underground roads, navigation, etc. This type of construction last for many years and requires a cautious and safe method of development, taking into account stability, ventilation, and illumination. Every year a few million meters of underground tunnels are driven globally (Tatiya, 2005). The second category of tunnels includes openings for exploring and exploiting mineral deposits (Tatiya, 2005). These tunnels are usually small in size; however, globally millions of meters of tunnels of this type are driven every year. Furthermore, a large proportion of utilities lie underground and laying these utilities requires subsurface excavation. Finally, subsurface excavation is most often used when rehabilitation work or line locating is performed on existing utilities.

5.7 Manual excavation tools for traditional excavation

5.7.1 Spade

A spade is an excavation tool that consists of a blade which is stunted and less curved than that of a shovel (Dictionary, 2019). It can be used for various purposes such as digging, trenching, preparing areas for planting and is specifically designed for lifting up the soil and removing dirt (Schicke, 2019). Spades have a wide application in excavation industries, where they are used as traditional tools for laying underground utilities. However, while using a spade for line locating of underground utilities, safety considerations are compromised as manual excavation can lead to damaging cables or utilities.

5.7.2 Shovel

Shovels are used for lifting excavated soil, digging soil, and moving bulk materials, and are similar to spades, differing only in the leading edge, which is curved. Before the invention of mechanical excavators, a shovel was the primary tool used for the excavation work, mining, and quarrying. There are many different types of shovels, including coal shovels, snow shovels, roofing shovels, and others, each specifically designed with respect to the function of the work. Depending upon the type of material to be excavated – for instance, loose gravel, sand or backfill – the appropriate manual hand shovel is an essential tool for working in the conditions. Shovels are most often used for moving loosened earth (Birkby, 2006). Furthermore, they can also be useful in excavation within a confined area, where access by other mechanical equipment is not possible. However, the labor productivity rate is lower when excavating manually using a shovel than for any mechanical excavator. Even after the invention of mechanical excavators, shovels are widely used in areas where the mechanical equipment cannot reach, such as in narrow excavations or under service utilities.

5.7.3 Hoe

The hoe is a hand tool used for shaping soil, mainly for agricultural and horticultural purposes. It is often used in the civil industries for excavating soil or trenching, among other applications. There are mainly two types of hoe: draw hoes and scuffle hoes (Deppe, 2015). A draw hoe has a blade at a right angle to the shaft, which makes it possible for the user to cut the ground and pull the loosened soil towards them (Deppe, 2015). On the other hand, a scuffle hoe is used to scrape the ground surface, disturbing the top surface of the soil and removing plant roots (Deppe, 2015).

Furthermore, hoes can be used in excavating the confined area around underground utilities. Since the operation of a hoe along with shovel and hoe is manual, there is more control and less safety risk than the for the use of a mechanical excavator, particularly in confined spaces or around utilities.

5.7.4 Trowel

A trowel is a traditional hand tool used in civil construction for digging small trenches in the soil. It is also used to apply mortar or plaster on brick walls.

5.7.5 Rake

A rake is a hand tool used to remove a small amount of the top surface of the soil. It consists of a horizontal rod with metal teeth and is used to level the ground surface.

5.7.6 Pickaxe

A pickaxe is one of the traditional excavators used for excavating soil in larger earthworks. Using a pickaxe, excavation is possible in dense and hard soils. A pickaxe has a hard, sharp metal spike attached perpendicularly to the handle. It is used in the construction of roads, railways, tunnels, and underground utilities. It is also used for laying electrical wires and fibre conduit underground.

5.7.7 Mattock

A mattock is a versatile hand tool for excavation consisting of shaft made of wood which is four to five feet long (Cormell, 2010). A metal head with two ends is attached perpendicularly to the shaft (Cormell, 2010). Two types of mattock are available for excavation, cutter mattocks and pick mattocks, which differ in the shape of blade, horizontal or pointed, respectively. Mattocks are used for excavating hard soil and in rocky terrain (Birkby, 2006). They are also used to excavate holes; however, since a large amount of manual effort is requiring, using a mattock can be tiring for workers (Wray, 2009). The frequent involvement of bending and stooping while using a mattock for excavation makes this an unsafe activity for workers.

5.8 Mechanical excavation tools for traditional excavation

Mechanical excavation tools (MET) use mechanical force for excavation and are commonly used for deeper excavations. They are available in a variety of configurations, with different boom and bucket sizes. Mechanical excavators are versatile machines, and various work tools and attachments in addition to the excavators have extended these capabilities even further (Poole, 2019). Mechanical excavators come in many sizes appropriate for a wide variety of excavations, from small to large projects. The descriptions of some excavator types are provided below:

5.8.1 Tracked Excavators

Tracked excavators come in different sizes, weighing between seven and 45 metric tons. The movement of this excavator type is performed by the tracks. Tracked excavators provide enough power and hauling capacity to handle a variety of tough jobs, for commercial construction projects and mining, among others (Poole, 2019). They have a system which can rotate the bucket a full 360 degrees, which enables the excavator to perform excavation in mines, oil and gas, and pipeline industries and allows the operator to easily excavate, move and dump materials like gravel or dirt while the excavator remains stationary. Tracked excavators have buckets, booms, and cabinets which varies in size and capacity according to the size and capacity of the excavator and the job requirements.

5.8.2 Wheeled Excavators

Wheeled excavators are like tracked excavators, except that the movement of excavator is accomplished using wheels. Wheeled excavators are mostly used for road construction, where the terrains are even or on hard terrains such as asphalt or concrete, since wheels are not suitable for uneven ground or hilly areas, or at sites with soft soils or sloped landscapes. For excavations on flat, hard construction sites, wheeled excavators provide easy maneuverability and greater speeds for transporting material to dump trucks (Poole, 2019).

5.8.3 Backhoe Excavators

Backhoe excavators consists of a digging bucket on the front and excavator boom on the back of the backhoe. Unlike tracked excavators, backhoe excavators rotate 200 degrees. Backhoe excavators are used to perform levelling and grading of soil and haul larger volumes of material quickly. With work tool attachments, backhoes can expand to perform more activities, making them incredibly versatile machines.

5.8.4 Bulldozer

The front part of a bulldozer consists of a heavy metal blade mounted on tractor. These blades can be of different types, including a straight blade, universal blade and semi-U blade (Trewhitt, 1999). The rear portion of bulldozer consists of a ripper, which is a claw-like device for loosening densely compacted soil (Trewhitt, 1999) .Among all mechanical excavation tools, bulldozers are the most large and powerful. Bulldozers are used in grading and levelling surfaces, road construction, and projects requiring powerful, high speed, easily movable, and stable equipment.

5.8.5 Dragline Excavators

Dragline excavators, also commonly called draglines, have long booms. The boom enables dragline excavators to be used for excavating at greater depths, in projects such as port construction, underground parking construction, and deep foundations for buildings.

5.9 Innovative excavation technologies

5.9.1 Suction excavation

Suction excavation is an excavation method that involves softening the earth using pressurized water or air, combined with a vacuum system to remove soil and debris (Hydro vs Air Excavation - Which is best for your industry?, 2018). Suction excavators utilize powerful suction through a wide rounded pipe, normally up to 30 centimeters or so in diameter, to remove soil. Suction excavation using pressurized air is currently widely used within the trenchless industry, and has great versatility, with the additional advantage of being safer than hand digging and other excavation technologies as it involves in creating dry working environment for manpower and utilizes innovative remote operation reducing the hazards during excavation. Suction excavation minimizes the risk of damaging underground utilities as the pressure of air and water used for excavation can be adjusted to the strength of utilities, making this method less prone to damaging underground utilities compared to excavation using mechanical digging or backhoe or other mechanical excavation tool. Air excavation also has the advantage of being a sustainable practice in the construction industry since air excavation create dry environment for workers and use pressurized air instead of water during excavation. Non-destructive digging practices are being promoted with the help of suction excavation technology. Suction excavation is also commonly known as vacuum excavation and can be further broken down into air excavation or hydro excavation (depending on whether air or water is used to soften the soil).

5.9.2 Hydro-excavation

Hydro excavation units have two separate systems, a high-pressure water system, and a vacuum source. In hydro excavation, highly pressurized water is used to liquefy soil, creating a slurry mixture which is then extracted using a powerful vacuum system (The Badger Hydrovac, 2020). The liquefied soil or debris is then transferred to a debris tank using air conveyance or vacuum.

This method provides a non-destructive method of excavation and is broadly used for increased accuracy in the excavation of soil and location of underground utilities since excavation can be done for the particular ground just above where the utilities lies, however, traditional excavation requires larger area excavation to daylight the utility (What is hydro excavation?, 2019).

Two types of vacuum systems are available, with the vacuum generated using a fan system or a positive displacement blower (What is hydro excavation?, 2019). Typically, the fan system can transfer a huge amount of air, resulting in faster excavations. On the other hand, the positive displacement blower is able to transfer air over longer distances.

Combination excavation technology combines pressurized water with an air vacuum: high-pressure water is used to cut the soil and break it up, and a vacuum then is used to remove the liquefied soil from the excavation area. The waste slurry is moved to a debris tank attached to the hydrovac truck or transferred to another dumper for dumping at a legal dump site.

5.9.3 Air-excavation

In air excavation, highly compressed air (rather than water) is used to loosen the soil, and the disturbed soil is sucked up using a vacuum system into a disposal tank. Pressurized air is converted into excavating power; however, pressurized air does not damage sensitive pipe coatings, underground utilities and even tree roots (Advantages of Air-vacuum, 2019). Air excavation can be used for line locating of underground utilities, and daylighting underground pipelines, among other applications. Air excavation is the preferred method for excavation near electrical wires, since air is nonconductive in nature, in contrast to water.

Air excavation has benefit of producing the dry disturbed soil during excavation which can be reused for backfilling the holes, or excavation site. The dry disturbed soil produced during air excavation is sucked by vacuum system, resulting in a clean work environment (Air excavation, 2019). In the case of non-contaminated disturbed soil, the disturbed soil can either be used for backfilling at excavation site or landfilling at legal dumping site (Air excavation, 2019). In case of contaminated disturbed soil, treatment of soil is necessary before landfilling or dumping at legal dump site.

5.10 Development of comparison metrics

It would be an advantage to industry to have comparative metrics to aid in selecting the most appropriate excavation method for a project. Some factors to consider when selecting an excavation method include lifecycle cost, soil conditions, availability of the technology, productivity rates, safety, environmental and social considerations, among others.

5.11 Life-cycle cost comparison for traditional vs suction excavation project

The cost associated with an excavation project requires clear identification of all cost factors associated with construction activities. When the pre-design team is aware of all cost items related to a project and included in the project budget, this results in increased cost-effectiveness for the project. Costs for various categories, including pre-construction costs, construction costs, and post-construction costs are listed in Table 5.1 (Mohammad & Kyoung, 2004; Kim, 2004).

Table 5.1: Life-Cycle cost of an excavation project

Preconstruction	Construction	Post Construction
• Engineering and design costs • Municipal or city permits • Planning and scheduling fees • Cost estimating fees • Legal • Shaping process • Development of Business case framework (project charter) • Setting up team dynamics • Subsurface Utility Engineering • Utility coordination documents	• Direct construction costs • Indirect construction costs • Social costs • Environmental costs • Construction Execution plan cost • Construction Management cost	• Operation • Maintenance

5.11.1 Preconstruction costs

Preconstruction costs have a significant impact on the overall life-cycle cost for a project. Suction excavation technology may provide an advantage in excavation due to increased accuracy, which may contribute to reducing rework and thus the overall cost of a project. The preconstruction cost also includes costs related to developing a communications plan, risk management plan, financial plan, information plan, contingency management plan, among others. Another addition to this great effort is the required logistics plan and site materials management plan for traditional excavation projects. However, suction excavation projects involve less manpower for operations and decreased space requirement for excavation. In general, both the planner and designer should develop provincially consistent guidelines, policies, and standards for both traditional excavation projects and suction excavation projects. However, a greater effort is required for traditional excavation projects due to larger scope of work, as excavation is typically conducted on a larger scale than for excavating in a particular location, Subsurface utility engineering is applied during the design phase of the project to locate, determine, and differentiate all existing utilities found within the area to be excavated. Due to this, the cost of subsurface utility engineering is higher for traditional excavation than for suction excavation. Table 5.2 (Kim, 2004) shows some of the preconstruction costs for traditional excavation and suction excavation that was similar for trenchless and open-cut pipeline construction project.

Table 5.2: Cost factors for preconstruction costs in traditional and suction excavation project

Cost Factor	Traditional Excavation	Suction Excavation
Preparation of survey work and site plans (including utility infrastructure location)	Major	Minor
Engineering drawings and design	Major	Minor
Municipal coordination issue (acquisition of easements, right-of-way, detour roads, etc.)	Major	Minor
Working area requirements	Major	Minor
Subsurface investigation requirements	Major	Minor
Preparation of bid documents	Major	Minor
Compliance with all regulations, guidelines, applicable codes, and owner standards cost	Major	Minor

5.11.2 Construction Costs

The total cost for a construction project is the sum of the direct, indirect, social and environment costs of the project. Each of the cost components includes various costs associated with the excavation method that are directly related to or indirectly impact the overall cost. The man, materials and machinery requirements for civil construction projects contribute, either directly or indirectly, towards the overall total cost for the project. For example, the direct cost of a construction project is also known as the bare cost. In terms of excavation, the direct cost of project for providing shoring support to trench walls or safety barricading around an excavation pit is higher for traditional excavation compared to suction excavation.

5.11.2.1 Direct Cost

Direct costs include costs and expenses which are directly related to the construction project, i.e. costs incurred on wages, materials, and machinery, among others. Table 5.3 and Table 5.4 provides the direct labor and equipment cost per unit volume of excavated soil. The hourly wage of labor and hydraulic equipment operator is $63.25 and $ 75.55, respectively. The rental cost of hydraulic excavator of 0.65 cubic meter capacity for a day is $ 1359.15. According to the RS means, the productivity rate per day for the hydraulic excavator with capacity of 0.65 cubic meters is 246 cubic meters. The analysis shows that the cost per cubic meter of excavation using hydraulic excavator comes out to be $ 17. Also, while using suction excavator the labor and equipment operator hourly wage is like the excavation by hydraulic excavator. However, hourly rental cost of suction excavator is in the range of $ 300 – 400. In this analysis hourly rate of $300 is considered for suction excavator and cost per cubic meter of excavation by suction excavator comes out to be $126.

Table 5.3: Cost per cubic meter of hydraulic excavator excavation *(RSMeans , 2020)*

Cost per cubic meter of excavation ($/m^3)						
S. N	**Labor component**	**Unit**	**Quantity**	**Productivity per day (m^3)**	**Rate (CAD)**	**Amount (CAD)**
1	Labor	Day	4		506	2024
2	Equipment Operator	Day	1		605	605
3	Hydraulic excavator - 0.65 cubic meter capacity	Day	1	246	1360	1360
4	Cost per cubic meter of excavation ($/m^3)					17

Table 5.4: Cost per cubic meter of suction excavation

Cost per cubic meter of excavation ($/m^3)						
S. N	**Labor component**	**Unit**	**Quantity**	**Productivity per day (m^3)**	**Rate (CAD)**	**Amount (CAD)**
1	Labor	Day	1		506	506

2	Equipment Operator	Day	1	28	605	604.4
3	Suction excavation	Day	1		2400	2400
4	Cost per cubic meter of excavation ($\$/m^3$)					126

The direct cost per cubic meter of excavation for suction excavation is much higher than for traditional excavation. Since the illustrated example only consider the one activity i.e excavation, if more activities related with the excavation like provision of shoring, dewatering the excavation site among others are considered, the cost of hydraulic excavator and suction excavator would likely be equal since activity like dewatering can be done effectively using suction excavation technology. Also, it is only possible to determine which system provides cost effectiveness for a given project when the indirect costs, including social and environmental costs, are considered. The factors related to direct costs was considered from the similar kind of previous studies that was conducted for the life-cycle cost comparison between open-cut and trenchless pipeline construction project (Kim, 2004).

Table 5.5: Cost factors for Direct Costs in traditional and suction excavation project

Cost Factor	Traditional excavation	Suction excavation
Mobilization and Demobilization	Major	Minor
Barricading, shoring and sloping trench walls	Major	Minor
Dewatering or rock removal	Major	Minor
Disturbed Soil Removal	Major	Minor
Cost of Detour Roads	Major	Minor
Backfill, Compaction and landfill	Major	Minor
Reinstatement of excavated surface	Major	Minor
Construction Equipment Costs	Minor	Major
Direct Labor	Major	Minor
Material Pricing	Minor	Major

5.11.2.2 Indirect costs

The indirect costs of the project are expenses incurred for project overhead and general overhead costs that are not directly connected with the construction project. In this study the cost factors related to indirect costs has been taken from the similar studies of comparison between excavation methods from (Kim, 2004).

Out of many indirect costs to a project, the following costs are taken into account in this comparison:

1. Cost of head office and field office establishment
2. Cost of providing temporary utilities, scaffolding materials, shoring and protective systems for excavation.
3. Cost of detour roads and reinstatement of excavated surface
4. Cost of camp operation, contractors' fees, overhead, and allowances/bonuses/incentives

If the indirect excavation costs are compared between traditional and suction excavation methods, the indirect costs are much higher for traditional excavation compared to suction excavation. Traditional excavation requires a greater amount of manpower than suction excavation, and this contributes to more costs in terms of field office, field supervision, and temporary facilities, among others. Table 5.6 lists various cost factors for indirect construction costs of traditional excavation and suction excavation.

Table 5.6: Cost factors for indirect construction costs of traditional and suction excavation project

Cost factor	Traditional excavation	Suction excavation
Head office costs	Major	Minor
Field office costs	Major	Minor
Field supervision costs	Major	Minor
Cost of temporary utilities	Major	Minor
Special costs	Major	Minor
Consultants service	Major	Minor
Camp operating cost	Major	Minor
Contractor fees and overhead	Major	Minor
Allowances/Bonuses/Incentives	Major	Minor
Scaffolding material cost	Major	Minor
Transportation personnel	Major	Minor

5.11.2.3 Social costs

Social costs are the costs related to and borne by society during the excavation. They are connected to interfaces between excavation activities and the economic conditions of the area. Suction excavation, in fact, involves increased road maintenance costs due to the effect of heavy payloads on the road surface. However, the use of suction excavation also prevents damage to utility lines and pipes during excavation. The factors that are applicable to the research has been adopted from the similar studies conducted by (Kim, 2004).

The following social costs are taken into account:

1. Cost of shoring or protective systems for excavation
2. Traffic congestion due to excavation activity
3. Number of road accidents caused due to excavation activity
4. Disturbance to commercial and recreational activities for the public
5. Costs due to damage to underground utility lines or pipes near the vicinity of the excavation location
6. Costs due to damage to surrounding infrastructure, other than underground utilities
7. Costs due to damage to the road surface under the movement of heavy machinery or trucks, ultimately increasing in the road maintenance cost

The cost of the safety aspects for the work site is higher for traditional excavation, due to the high cost associated with providing shoring or protective systems during excavation. Furthermore, traditional excavation requires large areas to be separated and barricaded for excavation, which causes the traffic congestion in the surrounding area. For excavation activities in urban areas, traditional excavation methods require large areas to accommodate excavation activities, resulting in narrower and more congested roadways and thus causing a higher probability of road accidents.

Table 5.7: Cost factors for social costs of traditional and suction excavation project

Cost factor	Traditional excavation	Suction excavation
Road damage	Major	Minor
Damage to Adjacent Utilities	Major	Minor
Damage to Adjacent Structures	Major	Minor
Vehicular traffic disruption	Major	Minor
Pedestrian Safety	Major	Minor
Business and Trade Loss	Major	Minor

Damage to detour road	Major	Minor
Site safety	Major	Minor
Public complaint	Major	Minor
Distortion to landscape	Major	Minor

5.11.2.4 Environmental costs

Environmental costs are related to the negative effects on the environment due to excavation activities. Suction excavation is considered to have less serious effects on the environment than traditional excavation due to less fuel consumption during the excavation and the corresponding emissions of gases to the environment. Table 5.8 presents the information regarding various environmental cost factors for traditional excavation and suction excavation. The factors related to environmental costs was considered from the similar kind of previous studies that was conducted for the life-cycle cost comparison between open-cut and trenchless pipeline construction project (Kim, 2004).

Table 5.8: Cost factors for environmental costs of traditional and suction excavation project

Cost factor	Traditional excavation	Suction excavation
Dust and air pollution	Major	Minor
Environmental impact	Major	Minor
Sound pollution (Noise and Vibrations)	Major	Minor
Waste disposal	Major	Minor
Waste use	Minor	Major

5.11.3 Post construction cost

Operation and maintenance costs are same for utilities laid by suction excavation or traditional excavation. However, when maintenance or rehabilitation is required for underground utilities that already has been laid, daylighting the utilities by suction excavation reduces the damage to the utilities than traditional excavation.

5.11.4 Safety during operation

Traditionally, the triple constraints of any civil construction projects are considered to be cost, time and quality. However, the lack of safety in construction works indirectly results in time and cost increases to construction activities and the overall project (Enshassi, Factors Affecting Safety on Construction Projects, 2003). Since civil works present serious hazards to the worker, occupational health and safety has evolved as an additional constraint on construction projects.

Suction excavation uses less manpower during operation and requires one worker to hold the hose pipe and one operator. The human effort for suction excavation is much less in comparison to traditional excavation. Traditional excavation uses traditional tools such as shovels for the excavation, which requires more crew members. Even after following the safety guidelines and ensuring every worker wear the personal protective equipment, traditional excavation still carries the possibility of hazards or accidents due to involvement of more human factors during the excavation. Hence, suction excavation is safer than traditional excavation methods.

5.12 Conclusions

The comparison of traditional excavation and suction excavation methods carried out in this research shows that considering lifecycle costs, environmental considerations, and productivity and safety of a project, suction excavation is more cost effective than traditional excavation methods. More research is needed to compare traditional and suction excavation methods using the Analytical Hierarchy Process or conducting a survey among the contractors doing such projects to determine the most cost-effective and environmentally friendly method for excavation.

Chapter 6: Conclusions

The key findings of this research are summarized below:

- Using the detail estimates, the cost comparisons between excavation per cubic meter for daylighting underground utilities between mechanical excavators, hand tool and suction excavator indicates that the excavation by suction excavation is cheaper than hand tool and mechanical excavator by 38% and 14% respectively.
- The comparison of traditional excavation using hand tools/mechanical excavators and suction excavation carried out after taking into account the lifecycle costs, environmental considerations and safety during the execution of project shows that the suction excavation is more cost effective, safe and productive than traditional excavation method.
- A comparison of hydro and air excavation, considering the direct, indirect, social and environmental costs involved in underground utility construction project, concluded that air excavation is the appropriate method for excavation project in urban areas. The comparison was performed using AHP, where expert opinions are synthesized to generate the priority on finalizing which method is more advantageous than another.
- Pilot online survey responses collected from contractors, manufacturers, and utility providers in the field of suction excavation technologies for making a comparison between hydro and air excavation technologies concluded that application of air excavation is better solution in underground utility project than hydro excavation except in cold winter conditions.

A comparison between different excavation methods for daylighting underground utilities (excavation using hand tools, mechanical excavation, and suction excavation) was conducted to determine the most cost-efficient method of excavation. The cost per cubic meter of performing the excavation for daylighting using suction excavation is relatively lower than performing the excavation by mechanical excavation or hand excavation.

The conventional method for construction of underground utilities has been open-cut methods using mechanical tools and machinery. Innovations in technology in recent years have led to suction excavation being feasible for underground utilities projects. However, local municipalities and government agencies have been slow to recognize the cost benefits of suction excavation compared to traditional excavation. This is due to lower construction costs at the beginning of the project for traditional construction methods. It would be an advantage to industry to have comparative metrics to aid in selecting the most appropriate excavation method for a project. The factors including lifecycle cost, availability of the technology, productivity rates, safety, environmental and social considerations, among others have been compared between traditional and suction excavation technologies to determine the best excavation technology. By comparing the life-cycle cost of an excavation project, preconstruction, construction and post-construction cost were included and compared for both traditional and suction excavation, respectively. The conclusion was reached that suction excavation is more cost effective than traditional excavation methods.

To further validate the results obtained in the previous chapters, the Analytical Hierarchy Process (AHP), which is a multi-criteria-decision making analysis to determine the best alternative, was used to determine the best option for the installation of underground utilities in urban areas. In this comparison between hydro and air excavation technologies, direct, indirect, environmental and social costs associated with excavation were considered. The results indicate that air excavation is the most cost-effective method for excavation project in urban areas.

The pilot survey is performed for the thesis and very large area of improvements are available in future actual surveys. From the survey results, the excavation rate for air excavator is higher than hydro excavator, however, the hourly rental cost of air excavator is greater than hydro excavator by $100. With respect to the responses collected, two scenarios are analyzed and the total savings in cost and time from excavation to management of slurry or dry earth is greater in air excavation than hydro excavation. The air excavation neglects the requirement of water during the excavation operation, due to which air excavator time on site is increased. The excavation by air is considered environmentally friendly as the emission of carbon footprints, need of fresh water during excavation and requirement of regulated disposal management facility is reduced. The total cost and time savings for two scenarios are because of higher excavation rate of air excavation. Historically, air excavator has been considered a less efficient and less cost effective due to reduced power and performance in performing specific job. Since the history of hydro excavation lies since more than 50 years, government agencies, contractors are hesitated to adopt the new technology in spite knowing the benefit air excavation provides. However, due to advancement in innovative technology the air excavation technology has slowly gaining to aware the utility providers, government agencies, contractor about its benefit. The disadvantage of air excavation is unsuitability of conducting excavation during cold winter condition.

For future work, a comparison between hydro and air excavation with respect to the production rate of each corresponding excavator could be performed at the same time, considering identical conditions on site.

References

Advantages of air-vacuum. (2019). Retrieved from Airforced daylighting: https://web.archive.org/web/20200513152027/http://www.airforced.ca/air-vac.html

Advantages of Air-vacuum. (2019). Retrieved from Airforced daylighting: https://web.archive.org/web/20200422035256/http://www.airforced.ca/air-vac.html

Air excavation. (2019). Retrieved from Vac-tron equipment: https://web.archive.org/web/20200422035633/https://www.vactron.com/applications/air-excavation/

Air excavation. (2019). Retrieved from Vac-tron equipment: https://web.archive.org/web/20200513152326/https://www.vactron.com/applications/air-excavation/

Air excavation,root inspection & root pruning. (2017). Retrieved from Green crown consulting arborist: https://web.archive.org/web/20200513152549/https://greencrown.ca/air_excavation_root_inspection__root_pruning/

Air excavation,root inspection & root pruning. (2017). Retrieved from Green crown consulting arborist: https://web.archive.org/web/20200422041211/https://greencrown.ca/air_excavation_root_inspection__root_pruning/

Aka hydrovacing . (2017, March 15). *The history of Hydro Excavation (aka Hydrovacing)*. Retrieved from Hydrovacnation : https://www.hydrovacnation.ca/the-history-of-hydro-excavation-aka-hydrovacing/#:~:text=The%20History%20of%20Hydro%20Excavation%20(aka%20Hydrovacing),-March%2015%2C%202017&text=Hydro%20excavation%20started%20in%20the,referred%20to%20as%20Hydraulic%20Mining

Alan Atalah, C. C.-J. (2004). Comparison study of installing fiber optic cable in university campuses using trenchless technique relative to open cut. *ASCE*.

Albers, L., & Nijkamp, P. (1989). Multidimensional analysis for plan or project evaluation. How to fit the right method to the right problem. In L. N. Albers, *Metodi di valutazione nella pianificazione urbana e territoriale, Teoria e casi studio.* Bari: IRIS-CNR.

Alperen, E. A. (2016). Waste to energy technologies for municipal solid waste management in Gaziantep . *Renewable and Sustainable Energy Reviews, 54*, 809-815. Retrieved from https://doi.org/10.1016/j.rser.2015.10.097

American Society of Civil Engineers. (2000). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). *ASTM International*. West Conshohocken, Pennsylvania, USA. doi:10.1520/D2487-00

Amos, D., Albert, P. C., Ernest, A. E., Emmanuel, O. K., Erika, P., & David, E. J. (2019). Review of application of analytic hierarchy process in construction. *International Journal of Construction Management*, 436-452. doi:10.1080/15623599.2018.1452098

Ariaratnam, N. J. (2008, May). Cost and Risk Evaluation for Horizontal Directional Drilling versus Open Cut in an Urban Environment. *ASCE*, 85-92. doi:10.1061/(ASCE)1084-0680(2008)13:2(85)

Association, A. W. (2001). *Reinvesting in Drinking Water Infrastructure.* Denver: American Water Works Association.

Association, A. W. (2001). *Reinvesting in Drinking Water Infrastructure* . Denver: AWWA Water Industry Technical Action Fund .

Berkenbosch, R. (2018). *Hydrovac slurry management* . Edmonton : Environmental Services Association of Alberta .

Biogreen . (2020). *What is pyrolysis?* Retrieved from Biogreen : https://web.archive.org/save/http://www.biogreen-energy.com/what-is-pyrolysis/

Birkby, R. C. (2006). Tools. In R. Birkby, *Lightly on the land: The SCA trail-building and maintenance manual* (pp. 75-102). leichester, Great britain : cordee. Retrieved from https://books.google.ca/books?id=xD6ThtJNgLkC&printsec=frontcover&source=gbs_vpt_buy#v=onepage&q&f=false

Bottero, M., & Peila, D. (2005). The use of the Analytic Hierarchy Process for the comparison between microtunnelling and trench excavation . *Tunnelling and Underground Space Technology* , 501-513.

Canada, G. o. (2019, December 02). *Health and Safety programs*. Retrieved from Canadian Centre for Occupational Health and Safety: https://web.archive.org/web/20200422042250/https://www.ccohs.ca/oshanswers/hsprograms/trenching_excavation.html

CDEnviro. (2020). *CO:FLO*. Retrieved from CDEnviro: https://web.archive.org/web/20200513152947/https://www.cdenviro.com/products/coflo

CDEnviro. (2020). *Decanter*. Retrieved from CDEnviro: https://web.archive.org/web/20200513153033/https://www.cdenviro.com/products/decanter

CDEnviro. (2020). *G:MAX*. Retrieved from CDEnviro: https://web.archive.org/web/20200513153720/https://www.cdenviro.com/products/gmax

CDEnviro. (2020). *Hydro:Flo*. Retrieved from CDEnviro: https://web.archive.org/web/20200513154515/https://www.cdenviro.com/products/hydroflo

CDEnviro. (2020). *Hydro:TIP*. Retrieved from CDEnviro: https://web.archive.org/web/20200513154633/https://www.cdenviro.com/products/hydrotip

CDEnviro. (2020). *Regional Waste Recycling*. Retrieved from CDEnviro: https://web.archive.org/web/20200513154850/https://www.cdenviro.com/case-studies/regional-waste-recycling

Cheng, M., Tsai, M., & Sutan, W. (2009). Benchmarking-based process reengineering for construction management . *Automat Construction*, 605-623.

Cormell, C. (2010). Composting for dummies . In C. cormell, *Tools of the trade* (pp. 15-28). John Wiley & Sons, Inc.

CSMG. (2010). *Economics of Shared Infrastructure Access.* London: CSMG A TMNG Global Company . Retrieved February 2010, from https://www.ofcom.org.uk/__data/assets/pdf_file/0020/25283/csmg.pdf

Deppe, C. (2015). Hoe. In *The resilient gardener:Food production and self-reliance in Uncertain times* (p. 101). Chelsea green publishing.

Dictionary. (2019). *Spade*. Retrieved from Dictionary: https://web.archive.org/web/20200422041932/https://www.dictionary.com/browse/spade

Donoahue, C. (2020, April 21). AHP pairwise comparison matrix fill out. (R. Rijal, Interviewer)

Electrical Safety Authority. (2008). *Guideline for Excavating in the Vicinity of Utility Lines* .

Enshassi, A. (2003). Factors Affecting Safety on Construction Projects. *Islamic University of Gaza*. Retrieved from http://hdl.handle.net/20.500.12358/26611

Enshassi, A. (2004). Factors affecting safety on Construction Projects. Gaza Strip, Palestine. Retrieved from http://hdl.handle.net/20.500.12358/26611

Eranti, E., & Lee, G. (1986). Cold weather construction: Techniques and Restrictions . In E. Eranti, & G. Lee, *Cold Region Structural Engineering* (pp. 409-469). New york : Mcgraw-Hill Book Company .

Gouma, S., Fragoeiro, S., Bastos, A., & Magan, N. (2014). Microbial Biodegrafation and Bioremediation. In S. Gouma, S. Fragoeiro, A. Bastos, & N. Magan, *Bacterial and Fungal Bioremediation Strategies* (pp. 301-323). Science Direct.

Government of Alberta. (2018, January 29). *Hydrovac Waste.* Retrieved from https://web.archive.org/web/20191213045335/https://open.alberta.ca/dataset/fbb7e433-f9d9-4656-a58a-fb951f84c7b7/resource/256a599f-85a5-483e-a67c-887632dc7a5c/download/hydrovacwaste-jan29-2018.pdf

Gregory, W. (2020, June 5). AHP interview. (R. RIjal, Interviewer)

GTI. (2012). *Vacuum excavation best practice and guideline* . Illinois: Gas technology Institute .

Heiner, A. (1972). Strength and Compaction Properties of Frozen Soil. *Transportation Research Board*, 116. Retrieved from https://trid.trb.org/view/21764

Hydro vs Air Excavation - Which is best for your industry? (2018, 04 12). Retrieved from Vactron Equipment: https://web.archive.org/web/20200513154155/https://www.vactron.com/hydro-vs-air-excavation-which-can-provide-a-safer-alternative-for-your-industry/

Hydro vs Air Excavation - Which is best for your industry? (2018, 04 12). Retrieved from Vactron Equipment: https://web.archive.org/web/20200422041803/https://www.vactron.com/hydro-vs-air-excavation-which-can-provide-a-safer-alternative-for-your-industry/

Hydro VS Air Excavation - Which is best for your industry? (2018). Retrieved from https://web.archive.org/web/20200422041814/https://www.vactron.com/hydro-vs-air-excavation-which-can-provide-a-safer-alternative-for-your-industry/

Inc, H. (2019, May 8). *Importance of Construction Excavation*. Retrieved from HGC Incorporated: https://web.archive.org/web/20200422042419/http://www.freelranchquarry.net/

Infrastructure Health and Safety Association . (2013). *Excavating with Hydrovacs in the Vicinity of Underground Electrical Plant* .

Iseley, T., & Budhu, G. (1994). Traditional Vs Trenchless - A Cost Comparison Concept. *No Dig International, 5*(8), 23-5. Retrieved from http://worldcat.org/issn/09604405

Jetnews. (2012). *Historical Persective.* St. Louis: WJTA-IMCA.

Ken, W. (2018, September). *Discover the Brute Power and Profitability of Hydroexcavation Services* . Retrieved from Pumper: https://www.pumper.com/editorial/2018/09/discover-the-brute-power-and-profitability-of-hydroexcavation-services#:~:text=In%202017%2C%20hydroexcavating%20work%20%E2%80%94%20mostly,company's%20%2420%20million%20in%20sales.

Khan, Z. (2010). *Analysis and Modeling of Labor Productivity in Construction Operations.* VDM Verlag.

Khanjan, K. K. (2013). Waste to energy status in India. *Renewable and Sustainable Energy Review, 31*, 113-120. Retrieved from https://www.sciencedirect.com/science/article/pii/S1364032113007697

Kim, M. N. (2004). Life-Cycle-Cost comparison of Trenchless and Conventional Open-Cut Pipeline Construction Projects . *ASCE.* Pipeline Engineering and Construction .

Lovell, C. (1968). *Feasibility of Cold-Weather Earthwork.* Retrieved from http://onlinepubs.trb.org/Onlinepubs/hrr/1968/248/248-002.pdf

Maddison, D., Johansson, O., Calthrop, E., Pearce, D., Litman, T., & Verhoef, E. (1995). *The true cost of Road Transport in the United Kingdom.* Earthscan.

Metje, N., Ahmad, B., & Crossland, S. M. (2015). Causes, impacts and cost of strikes on buried utility assets . *Institution of Civil Engineers* , 165-174.

Mohammad, N., & Kyoung, K. O. (2004). Life-Cycle-Cost Comparison of Trenchless and Conventional Open-Cut Pipeline Construction Projects . *ASCE Pipeline Engineering and Construction* .

Mohammed, K. A. (2001). Selecting the appropriate project delivery method using AHP. *International Journal of Project Management* , 469-474.

Nate, H. (2018, February 20). *Excavators that suck.* Retrieved from On-Site: http://web/20200627032720/https://www.on-sitemag.com/features/excavators-that-suck/

Nathalle, M.-W., Ingrid, P., Vicent, M., & Mohamed, M. (2012). *A Socio-Economic Cost Assessment Regarding Damages to Underground Infrastructures* . Montreal : CIRANO.

Neil, W. J., & Samuel, A. (2008). Cost and Risk Evaluation for Horizontal Directional Drilling versus Open Cut in an Urban Environment. *American Society of Civil Engineers*, 85-92.

Ning, L. F., Tae-Hyung, K., Stein, S., & William, L. J. (2009). Tensile Strength of Unsaturated Sand . *Journal of Engineering Mechanics*, 1410-1419.

Nuh Bilgin, H. C. (2014). *Excavation in Mining and Civil Industries.* Boca Raton: CRC Press.

Ox Equipment. (2019). *Vacuum Excavation Challenge Case Study* . Ontario: Ox Equipment .

Ox Equipment. (2020). *Dry Suction leads the way in excavation technology*. Retrieved from MTS DINO Series: https://web.archive.org/web/20200513153140/https://www.ox-equipment.com/trucks/

Perry, F., & Grace, D. K. (2014). Greenhouse Gas Emissions from Excavation on Residential Construction. *Australasian Journal of Construction Economics and Building*. doi:10.5130/ajceb.v14i4.4195

Poole, G. (2019, April 08). *Guide to the different types and sizes of excavators*. Retrieved from CAT: https://web.archive.org/web/20200422042512/https://www.gregorypoole.com/guide-to-the-different-types-and-sizes-of-excavators/

Ramanathan, R. (2001). A note on the use of the analytic hierarchy process for environmental impact assessment. *Journal of Environmental Management*, 27-35. doi:10.1006/jema.2001.0455,

Ramvac by Sewer Equipment. (2020). *Full size hydro excavators.* Retrieved from Ramvac: https://web.archive.org/web/20200513153349/https://www.sewerequipment.com/ramvac-full-size-hydro-excavators/

Ring-O-Matic. (2019). *Vacuum Excavators(water and air)*. Retrieved from Ring-O-Matic: https://web.archive.org/web/20200513155348/http://www.ring-o-matic.com/hydrovac.html

Rival Hydrovac. (2020). *Rival Hydrovac specifications*. Retrieved from Rival Hydrovac: https://web.archive.org/web/20200513154937/https://rivalhydrovac.com/rival-hydrovac-specifications/

RIval Hydrovac. (2020). *Rival Hydrovac specifications*. Retrieved from Rival Hydrovac: https://web.archive.org/web/20200513154937/https://rivalhydrovac.com/rival-hydrovac-specifications/

Robert, M. A. (1997). Bidding strategies for conventional and trenchless technologies considering social costs. *Canadian Journal of Civil Engineering*, 819-827. doi:https://doi.org/10.1139/l97-036

RSMeans . (2020). RSMeans data from Gordian . Edmonton, Alberta, Canada.

Saaty, L. T., & Vargas, G. L. (2012). The Seven Pillars of the Analytic Hierarchy Process . In L. T. Saaty, & G. L. Vargas, *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process* (pp. 26-27). Springer Science & Business Media.

Saaty, T. L. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation* (2nd ed.). McGraw-Hill, 1980.

Saaty, T. L. (2000). Fundamentals of Decision Making and Priority Theory With the Analytic Hierarchy Process. In T. L. Saaty. Pittsburg: RWS Publications.

Saaty, T. L. (2000). Relative Measurement, An example. In T. L. Saaty, *Fundamentals of Decision Making and Priority Theory With the Analytic Hierarchy Process.* RWS Publications.

Saaty, T. L., & Vargas, L. G. (2012). How to make a decision. In T. L. Saaty, & L. G. Vargas, *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process* (pp. 1-29). New york: Springer Science+Business Media New York .

Schicke, C. (2019). *What is a Spade used for?* Retrieved from Hunker: https://web.archive.org/web/20200422042608/https://www.hunker.com/13404565/what-is-a-spade-used-for

SmartVac. (2020). *SmartVac Tandem Axle Specifications*. Retrieved from SmartVac: https://web.archive.org/web/20200513155023/https://www.smartvac.ca/tandem-axle-specs

Sosnowski, L. (1987). *US Patent No. US4753181A.*

Statistics Canada. (2019, December 09). Retrieved from Statcan: https://web.archive.org/web/20200422042015/https://www150.statcan.gc.ca/n1/daily-quotidien/191209/dq191209a-eng.htm?indid=3592-1&indgeo=0

SuperVac. (2020). *Hydro excavator standard series*. Retrieved from Supervac: https://web.archive.org/web/20200513153951/https://supervac.co/trucks-and-equipments/hydro-excavator/

Tatiya, R. R. (2005). *Surface and Underground Excavations- Methods,Techniques and Equipment* . Boca Raton: CRC press .

The Badger Hydrovac. (2020). Retrieved from BADGER DAYLIGHTING: https://web.archive.org/web/20200513155107/https://www.badgerinc.com/what-is-hydrovac-excavation/

The Badger Hydrovac. (2020). Retrieved from BADGER DAYLIGHTING: https://web.archive.org/web/20200513155107/https://www.badgerinc.com/what-is-hydrovac-excavation/

The Badger Hydrovac. (2020). Retrieved from BADGER DAYLIGHTING: https://web.archive.org/web/20200422042102/https://www.badgerinc.com/what-is-hydrovac-excavation/

Thomas, L. S., & Luis, G. V. (2012). Models, Methods, Concepts & Applications of the Analytic Hierarchy Process. In T. L. Saaty, & L. G. Vargas. New York: Springer Science+Business Media New York.

Thomas, S. L., & Luis, V. G. (2001). The Eigenvector solution for Weights and consistency . In S. L. Thomas, & V. G. Luis, *Models, Methods, Concepts & Application of the Analytical Hierarchy Process* (pp. 8-10). New York : Kluwer Academic Publishers in 2001 .

Trewhitt, P. (1999). *Armored Fighting Vehicles.* Dempsey_Parr.

United Nations . (2018). *World Urbanization Prospects 2018* . United Nations .

United Nations . (2019). *World Population Prospects 2019: Highlights* . New York : United Nations Department of Economic and Social Affairs .

United States Environmental Protection Agency. (1995). *An Introduction to Environmental Accounting As A Business Management Tool.* Washington: Office of Pollution Prevention and Toxics (MC 7409).

Vac.con. (2020). *XX-cavator*. Retrieved from Vac.con more power to you: https://web.archive.org/web/20200513160636/https://vac-con.com/new-trucks/xx-cavator/

Vaccon. (2020). *XX-cavator*. Retrieved from Vac.con more power to you: https://web.archive.org/web/20200513160636/https://vac-con.com/new-trucks/xx-cavator/

Vaseli, H. (2015). Application of Micro-Trenching for Fiber to the Home. *University of Alberta*. Edmonton, Alberta, Canada: Education and Research Archive.

Vermeer. (2020). *XR2 Vacuum Excavator.* Retrieved from Vermeer: https://web.archive.org/web/20200513160321/https://www.vermeer.com/getmedia/16f2b2c4-61c7-41e3-b5fd-803b268787a9/xr2-vacuum-excavator-spec-sheet?ext=.pdf

Westech Vac Systems. (2020). *Products*. Retrieved from Westech: https://web.archive.org/web/20200513154805/https://westechvac.com/Products/StraightVac(LVT)/tabid/180/Default.aspx

What is hydro excavation? (2019). Retrieved from Hydroexcavation online hydro excavation resource: https://web.archive.org/web/20200422042150/https://hydroexcavation.com/information/

What is hydro excavation? (2019). Retrieved from Hydroexcavation online hydro excavation resource: https://web.archive.org/web/20200513160147/https://hydroexcavation.com/information/

Wray, R. (2009). The planting job. In *Christmas trees for pleasure and profit* (pp. 75-92). Rutgers University Press.

Yaehne, S. (2020, June 2). AHP interview . (R. Rijal, Interviewer)

Appendix A

Air excavation VS Hydro excavation

Questionnaire for AHP Interview

Questionnaire: Relative importance of criteria with respect to "Goal: **Most cost effective method of excavation for rehabilitation and installation of underground utilities in urban areas**

	absolutely more important	little absoultely more important	very strongly more important	quite a lot strongly more important	strongly more important	little strongly more important	moderately more important	little moderately more important	indifference	little moderately more important	moderately more important	little strongly more important	strongly more important	quite a lot strongly more important	very strongly more important	little absolutely more important	absolutely more important	Importance of factors amoung each others for underground utilities project.
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
C1: Direct Construction Cost																		C2: Indirect construction cost
C1:Direct Construction Cost																		C3: Social Cost
C1:Direct Construction Cost																		C4:Environmental Cost
C2: Indirect construction cost																		C3: Social Cost
C2: Indirect construction cost																		C4:Environmental Cost
C3: Social Cost																		C4:Environmental Cost

The number of pairwise comparisons is 6

	absolutely more important	little absoultely more import	very strongly more importan	quite a lot strongly more imp	strongly more important	little strongly more importan	moderately more important	little moderately more impor	indifference	little moderately more impor	moderately more important	little strongly more importan	strongly more important	quite a lot strongly more imp	very strongly more importan	little absolutely more import	absolutely more important	
Questionnaire: Relative importance of criteria "C1: Direct construction cost " with respect to alternatives.**(Which method has less direct construction cost?)**																		
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
E1: Air excavation																		E2: Hydro excavation
Questionnaire: Relative importance of criteria "C2: Indirect construction cost " with respect to alternatives.**(Which method has less indirect construction cost?)**																		
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
E1: Air Excavation							+											E2: Hydro excavation
Questionnaire: Relative importance of criteria "C3: Social cost " with respect to alternatives.**(Which method has less social cost?)**																		
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
E1: Air Excavation																		E2: Hydro excavation
Questionnaire: Relative importance of criteria "C3: Environmental Cost " with respect to alternatives.**(Which method has less environmental cost?)**																		
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
E1: Air Excavation																		E2: Hydro excavation

C2: Indirect construction cost
C21: Cost related to the damage to the private property
C22: Damage to other nearby Utility
C23: Deterioration of road surface and redution in the life cycle
C24: Increase in road maintenance cost
C25:Relocation of services that arises with the works

C4: Environmental costs
C41: Air pollution
C42:Soil pollution
C43: Water pollution
C44: Sound pollution(noise/vibration)

C3: Social costs (related to transportation)
C31: Choice of new routes for public transport
C311:Problem of circulation
C312: Loss of time due to an increase in circulation and traffic jams
C313:Measures for diversion of traffic circulation

C1: Direct construction cost
C11: Cost related to the direct labour involved in the project
C12: Cost related to the material
C13: Cost related to machinery for the project

C3: Social Costs (Related to safety)
C32: Disturbance of commericial area
C33: Distortion of landscape due to excavation
C34: Settlement damage caused in the vicinity of excavation area

C3: Social Costs (related to safety)
C321: Public safety
C322: Public health
C323: Worker safety

Direct construction cost

Questionnaire: Relative importance of criteria in "C1: Direct Construction cost " with respect to subcriteria.**(Which is most important elements in direct construction cost?)**

	absolutely more important	**little absoultely more important**	**very strongly more important**	**quite a lot strongly more important**	**strongly more important**	**little strongly more important**	**moderately more important**	**little moderately more important**	**indifference**	**little moderately more important**	**moderately more important**	**little strongly more important**	**strongly more important**	**quite a lot strongly more important**	**very strongly more important**	**little absolutely more important**	**absolutely more important**	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
C11: Cost related to the direct labour involved in the project																		C12: Cost related to the material
C12: Cost related to the material																		C13: Cost related to machinery for the project
C13: Cost related to machinery for the project																		C11: Cost related to the direct labour involved in the project

Indirect Construction cost

Questionnaire: Relative importance of criteria "C2: Indirect construction cost" with respect to subcriteria.**(Which is most important elements in indirect construction cost?)**

	absolutely more important	little absoultely more important	very strongly more important	quite a lot strongly more important	strongly more important	little strongly more important	moderately more important	little moderately more important	indifference	little moderately more important	moderately more important	little strongly more important	strongly more important	quite a lot strongly more important	very strongly more important	little absolutely more important	absolutely more important	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
C21:Cost related to the damage to the private property																		C22:Damage to other nearby infrastructures
C21:Cost related to the damage to the private property																		C23: Deterioration of road surface and redution in the life cycle
C21:Cost related to the damage to the private property																		C24: Increase in road maintenance cost
C21:Cost related to the damage to the private property																		C25:Relocation of services that arises with the works
C22: Damage to other nearby infrastructures																		C23: Deterioration of road surface and redution in the life cycle
C22: Damage to other nearby infrastructures																		C24: Increase in road maintenance cost
C22: Damage to other nearby infrastructures																		C25:Relocation of services that arises with the works
C23: Deterioration of road surface and redution in the life cycle																		C24: Increase in road maintenance cost
C23: Deterioration of road surface and redution in the life cycle																		C25:Relocation of services that arises with the works
C24: Increase in road maintenance cost																		C25:Relocation of services that arises with the works

Social Costs

Questionnaire: Relative importance of criteria in "C3: Social cost" with respect to subcriteria in Problems of circulation.**(Which is most important elements in Social cost?)**

	absolutely more important	little absoultely more important	very strongly more important	quite a lot strongly more important	strongly more important	little strongly more important	moderately more important	little moderately more important	indifference	little moderately more important	moderately more important	little strongly more important	strongly more important	quite a lot strongly more important	very strongly more important	little absolutely more important	absolutely more important	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
C311:Choice of new routes for public transport																		C312: Problems of circulation
C311:Choice of new routes for public transport																		C313: Loss of time due to an increase in circulation and traffic jams
C311:Choice of new routes for public transport																		C314: Measures for diversion of traffic circulation
C311:Problems of circulation																		C315: Loss of time due to an increase in circulation and traffic jams
C311:Problems of circulation																		C316: Measures for diversion of traffic circulation
C311:Loss of time due to an increase in circulation and traffic jams																		C317: Measures for diversion of traffic circulation

Social Costs

Questionnaire: Relative importance of criteria in "C3: Social costs" with respect to subcriteria.**(Which is most important elements in Social cost?)**

	absolutely more important	**little absoultely more important**	**very strongly more important**	**quite a lot strongly more important**	**strongly more important**	**little strongly more important**	**moderately more important**	**little moderately more important**	**indifference**	**little moderately more important**	**moderately more important**	**little strongly more important**	**strongly more important**	**quite a lot strongly more important**	**very strongly more important**	**little absolutely more important**	**absolutely more important**	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
C321: Disturbance of commericial area																		C322:Distortion of landscape due to excavation
C321: Disturbance of commericial area																		C323: Settlement damage caused in vicinity of excavation area
C322: Settlement damage caused in vicinity of excavation area																		C323: Distortion of landscape due to excavation

Social Costs

Questionnaire: Relative importance of criteria in "C3: Social costs" with respect to subcriteria.**(Which is most important elements in Social cost?)**

	absolutely more important	**little absoultely more important**	**very strongly more important**	**quite a lot strongly more important**	**strongly more important**	**little strongly more important**	**moderately more important**	**little moderately more important**	**indifference**	**little moderately more important**	**moderately more important**	**little strongly more important**	**strongly more important**	**quite a lot strongly more important**	**very strongly more important**	**little absolutely more important**	**absolutely more important**	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
C321: Public safety																		C322: Public health
C321: Public Safety																		C323: Worker Safety
C322: Public health																		C323: Worker safety

Environmental costs

Questionnaire: Relative importance of criteria in "C4: Environmental costs" with respect to subcriteria. **(Which is most important elements in Environmental cost?)**																		
	absolutely more important	**little absoultely more important**	**very strongly more important**	**quite a lot strongly more important**	**strongly more important**	**little strongly more important**	**moderately more important**	**little moderately more important**	**indifference**	**little moderately more important**	**moderately more important**	**little strongly more important**	**strongly more important**	**quite a lot strongly more important**	**very strongly more important**	**little absolutely more important**	**absolutely more important**	Importance of factors amoung each others
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
C41: Air pollution																		C42:Soil pollution
C41: Air pollution																		C43: Water pollution
C41: Air pollution																		C44: Sound pollution(Noise/vibration)
C42:Soil pollution																		C43: Water pollution
C42:Soil pollution																		C44: Sound pollution(Noise/vibration)
C43: Water pollution																		C44: Sound pollution(Noise/vibration)

Environmental costs

Questionnaire: Relative importance of criteria in "C4: Environmental costs" with respect to subcriteria. **(Which is most important elements in Environmental cost?)**																		
	absolutely more important	**little absoultely more important**	**very strongly more important**	**quite a lot strongly more important**	**strongly more important**	**little strongly more important**	**moderately more important**	**little moderately more important**	**indifference**	**little moderately more important**	**moderately more important**	**little strongly more important**	**strongly more important**	**quite a lot strongly more important**	**very strongly more important**	**little absolutely more important**	**absolutely more important**	Importance of factors amoung each others
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
C414: Cost related to disposal of disturbed soil																		C415:Cost related to treatment of contaminated soil
C415:Cost related to treatment of contaminated soil																		C416:Cost related to treatment of slurry(mixture of soil and water)
C416:Cost related to treatment of slurry(mixture of soil and water)																		C414: Cost related to disposal of disturbed soil

Comparative Study of Hydro Excavation and Air Excavation Technologies

Survey of Hydro Excavation and Air Excavation Technologies

You have been selected to respond to a survey developed by CETT researchers at the University of Alberta on a comparative study of Hydro excavation and the Air excavation Technologies. Hydro excavation technology is widely used in the trenchless industry, oil and gas sector, in cold climate, and severe working conditions. However, the slurry waste produced during hydro excavation poses a problem in terms of proper disposal of a registered dumping site. Furthermore, Air excavation technology does not produce slurry waste during excavation and promotes sustainability by using pressurized air instead of water during the excavation works. Both Hydro excavation and Air excavation can be useful under certain conditions (i.e., considering the type of soil, moisture content of soil, etc.)

By completing this survey, you will assist researchers in forming a simple, user-friendly interface that will help users like municipalities, utility construction contractors, consultants among others to select the most environmentally friendly, cost-effective method for excavation under user-specified conditions.

Background:

This survey forms part of an overall research project under the NSERC Associate Industrial Research Chair in Underground Trenchless Construction and part of the MSc.thesis of Roshan Rijal. Excavation is an important aspect of many different construction projects, and the choice of the appropriate excavation technology can impact the overall delivery of a project in terms of cost and schedule. Hydrovac is a well-established technology; however, air excavation has many advantages, including no production of liquid waste, and less environmental impact. This survey focuses on collecting information related to production rate, the hourly rental cost, etc. of hydro excavation and air excavation under different conditions, i.e. ground conditions, moisture content, and applicable temperature ranges. The primary objective of this survey is to investigate excavation methods in detail to gain a thorough understanding of when it is appropriate to apply air excavation and hydro excavation technologies.

Note:

This survey is a pilot version for testing purposes, with limited distribution and your

participation in testing the survey and giving feedback is appreciated. The survey contains a total of 20 questions as well as some information responses over nine pages and is expected to take approximately 5-10 minutes to complete.

The Survey is organized as follows:

Section 1 – Hydro excavation Technology

Section 2 – Air excavation Technology

Section 3 – General information related to ex

CETT Innovation & Excellence in Trenchless Technology

Comparative Study of Hydro Excavation and Air Excavation Technologies

Consent Statement

* I have read this form and the research study has been explained to me. I have been given the opportunity to ask questions about the survey. I have been told who to contact to withdraw my responses (up to 30 days after submission of the survey) or if I have any additional questions. I understand that by completing and submitting this survey, I have given consent for the data I have provided to be used for the purposes of this study, as described in the information provided.

Note: To download the survey information/consent information form, click here. To download the complete survey in.pdf format, click here.

Unit System

* Please indicate your preferred unit system.

Please indicate the type of excavator for which you would like to provide the information.

- ◯ Hydro excavation
- ◯ Air excavation
- ◯ Both

Section 1 : Hydro excavation technology

This section include questions about the hydro excavation systems. It asks the survey respondent for information on the productivity rates for hydro excavation under different soil conditions. Furthermore, it also contains questions related to waste management, cost for treatment of solid waste, and backfilling costs.

1. Please provide the information on the excavator.

Model no	
Manufacturer	

2. Please indicate the total manpower required while performing the excavation work.

3. Please indicate the setup and cleanup time required for excavator prior to excavation and after excavation respectively.

4. What is the excavation rate in sand and gravel? (m^3/hr)

Please specify and give extra information on your answer/findings.

5. Please indicate the temperature range of the ground at which the excavator can perform the excavation in sand & gravel.

	Maximum	Minimum
Degree Celsius		

6. What would be the impact of density be for the excavation rate for sand and gravel compared to the rate provided in Question 4? (+/-)

Please specify and give extra information on your answer/findings.

7. Please indicate the impact of moisture content in the ground for the excavation rate compared to the rate provided in Question 4. (+/-)

Please specify and give extra information on your answer/findings.

8. What is the excavation rate in silt and clay? (m^3/hr)

Please specify and give extra information on your answer/findings.

9. What would be the impact of density be for the excavation rate for silt and clay compared to the rate provided in Question 8? (+/-)

Please specify and give extra information on your answer/findings.

10. Please indicate the temperature range of the ground at which the excavator can perform the excavation in silt and clay.

	Maximum	Minimum
Degree Celsius		

11. Please indicate the impact of moisture content in the ground for the excavation rate compared to the rate provided in Question 8.(+/-)

Please specify and give extra information on your answer/findings.

12. Please indicate the approximate water consumption by a hydro excavator during excavation.

	Sand and Gravel	Silt and Clay
liters/m³		

Hourly Rental Cost and Waste Management

13. Please indicate the hourly rental cost for the hydro excavator in the indicated areas.

	Urban area	Rural area
$/hour		

14. Is the cost of transporting slurry waste from the excavation site to the slurry waste management facility included in the hourly rental cost indicated in Question 13?

- Yes
- No

15. What is the transportation cost per unit distance per unit slurry waste from the excavation site to the waste management facilities? ($\$/m^3/km$)

Please specify and give extra information on your answer/findings.

16. Please indicate whether there is an option for the slurry waste generated during excavation to be separated on the excavation unit.

- Yes
- No

17. What percentage of the solids are separated after the slurry waste is fed to slurry separation equipment on the truck?

18. Does the standard of the slurry waste after separation of solids comply with the limits acceptable for disposal at the dumping site without further treatment?

- Yes
- No

19. Is the liquid separated from the slurry reused during the excavation?

- Yes
- No

20. Please provide the approximate cost per unit for the treatment of slurry waste at the waste management facility in your area.

	Non-contaminated slurry	Contaminated slurry
$/m³		

* 21. Would you like to provide additional information related to air excavation technologies?

- [ ] Yes
- [ ] No

Section 2: Air excavation Technology

Productivity

This section includes questions about Air excavation systems. It asks survey respondent for information on the productivity rates for suction excavation under different soil conditions,temperature ranges,moisture conditions, and ground conditions.

1. Please provide the information on the excavator.

Model no

Manufacturer

2. Please indicate the total manpower required while performing excavation work.

3. Please indicate the setup and cleanup time required for excavator prior to excavation and after excavation respectively.

4. What is the excavation rate in sand and gravel?(m^3/hr)

Please specify and give extra information on your answer/findings.

5. Please indicate the temperature range of the ground at which the excavator can perform excavation in sand & gravel.

	Maximum	Minimum
Degree Celsius		

6. What would the impact of density be for the excavation rate for sand and gravel compared to the rate provided in Question 4? (+/-)

Please specify and give extra information on your answer/findings.

7. Please indicate the impact of moisture content in the ground for the excavation rate compared to the rate provided in Question 4.(+/-)

Please specify and give extra information on your answer/findings.

8. What is the excavation rate in silt and clay? (m^3/hr)

Other (please specify)

9. Please indicate the temperature range of the ground at which the excavator can perform the excavation in silt and clay.

	Maximum	Minimum
Degree Celsius		

10.What would be the impact of density be for the excavation rate for silt and clay compared to the rate provided on Question 8? (+/-)

Please specify and give extra information on your answer/findings.

11. Please indicate the impact of moisture content in the ground for excavation rate compared to the rate provided in Question 8.(+/-)

Please specify and give extra information on your answer/findings.

Hourly Rental Cost and Waste Management

12. Please indicate the hourly rental cost for the air excavator in the indicated areas.

	Urban area	Rural area
$/hour		

13. Is the cost of transporting slurry waste from the excavation site to the slurry waste management facility included in the hourly rental cost in Question 12?

- Yes
- No

14. What is the cost of transportation per unit distance per unit of dry spoil waste from the excavation site to the dumping site? ($\$/m^3/km$)

Please specify and give extra information on your answer/findings.

15. Do you reuse the dry excavated soil?

- Yes
- No

16. What is the fill cost for dry excavated soil at dumping site?($\$/m^3$)

17. If you store the excavated soil, what is the cost of storage?($\$/m^3$)

Section 3: General Information

This section contains questions for general information related to the excavators and contractors.

i) Please provide the general information of the company :

Name of the Company

Country

Province or Territory

State

Municipality-(City/Town)

ii) How did you hear about this survey?

iii) Please provide us with any additional comments you have related to this survey.

Please indicate the type of excavator on which you would like to provide the information

- ◯ Hydro excavator
- ◯ Air excavator
- ◯ Both

Section 1: Hydro excavation Technology

This section provides a questionnaire about the Hydro excavation system. It asks the survey respondent for information on the productivity rates of hydro excavation under different soil conditions. Furthermore, it also contains questions related to waste management, cost for treatment of solid waste, and backfilling costs.

1. Please provide the information on the excavator.

Model no

Manufacturer

2. Please indicate the total manpower required while performing excavation work.

3. Please indicate the setup and cleanup time required for excavator prior to excavation and after excavation respectively.

4. What is the excavation rate in sand and gravel? (ft^3/hr)

Please specify and give extra information on your answer/findings.

5. Please indicate the temperature range of the ground at which the excavator can perform the excavation in sand & gravel.

	Maximum	Minimum
Degree fahrenheit		

6. What would the impact of density be for the excavation rate for sand and gravel compared to the rate provided in question 4? (+/-)

Please specify and give extra information on your answer/findings.

7. Please indicate the impact of moisture content in the ground for excavation rate compared to the rate provided in question 4.

Please specify and give extra information on your answer/findings.

8. What is the excavation rate in silt and clay? (ft^3/hr)

Please specify and give extra information on your answer/findings.

9. Please indicate the temperature range of the ground at which the excavator can perform excavation in silt and clay.

	Maximum	Minimum
Degree fahrenheit		

10. What would be the impact of density for excavation rate for silt and clay compared to the rate provided in Question 8?

Please specify and give extra information on your answer/findings.

11. Please indicate the impact of moisture content in the ground for excavation rate compared to the rate provided in Question 8. (+/-)

Please specify and give extra information on your answer/findings.

12. Please indicate the approximate water consumption by the hydro excavator during excavation.

	Sand and Gravel	Silt and Clay
gallons/ft^3		

Hourly Rental Cost and Waste Management

13. Please indicate the hourly rental cost for the hydro excavator in the indicated areas.

	Urban area	Rural area
$/hour		

14. Is the cost of transporting slurry waste from the excavation site to the slurry waste management facility included in the hourly rental cost indicated in Question 13?

- Yes
- No

15. What is the transportation cost per unit distance per unit slurry waste from the excavation site to the waste management facilities? ($/ft³/miles)

Please specify and give extra information on your answer/findings

16. Please indicate whether there is an option for slurry waste generated during excavation to be seperated on the excavation unit.

- Yes
- No

17. What percentage of the solids are separated after the slurry waste is fed to slurry separation equipment on the truck?

18. Does the standard of the slurry waste after separation of solids comply with the limits acceptable for disposal at the dumping site without further treatment?

- Yes
- No

19. Is the liquid separated from the slurry reused during the excavation?

- Yes
- No

20.Please provide the approximate cost per unit for the treatment of slurry waste at the waste management facility in your area.

	Non-contaminated slurry	Contaminated slurry
$/ft³		

* 21. Would you like to provide additional information related to air excavation technologies?

- [ ] Yes
- [ ] No

Section 2: Air excavation Technology

This section includes questions about Air excavation systems. It asks survey respondents for information on productivity rates for excavation in different soil conditions, temperature ranges, moisture conditions, ground conditions etc.

1. Please provide the information on the excavator.

Model no

Manufacturer

2. Please indicate the total manpower required while performing excavation work.

3. Please indicate the setup and cleanup time required for excavator prior to excavation and after excavation respectively.

4. What is the excavation rate in sand and gravel? (ft^3/hr)

Please specify and give extra information on your answer/findings.

5. Please indicate the temperature range of the ground at which the excavator can perform the excavation in sand & gravel.

	Maximum	Minimum
Degree fahrenheit		

6. What would be the impact of density be for the excavation rate for sand and gravel compared to the rate provided in Question 4? (+/-)

Please specify and give extra information on your answer/findings.

7. Please indicate the impact of moisture content in the ground for excavation rate compared to the rate provided in Question 3.(+/-)

Please specify and give extra information on your answer/findings.

8. What is the excavation rate in silt and clay? (ft^3/hr)

Please specify and give extra information on your answer/findings.

9. Please indicate the temperature range of the ground at which the excavator can perform the excavation in silt and clay.

	Maximum	Minimum
Degree fahrenheit		

10.What would be the impact of density be for the excavation rate for silt and clay compared to the rate provided in Question 7? (+/-)

Please specify and give extra information on your answer/findings.

11. Please indicate the impact of moisture content in the ground for excavation rate compared to the rate provided in Question 8.(+/-)

Please specify and give extra information on your answer/findings.

Hourly Rental Cost and Waste Management

12. Please indicate the hourly rental cost for the air excavator in the indicated areas.

	Urban area	Rural area
$/hour		

13. Is the cost of transporting dry spoil from the excavation site to the dumping site included in the hourly rental cost in question 11?

- Yes
- No

14. What is the transportation cost per unit distance per unit dry spoil waste from the excavation site to the dumping site? ($\$/ft^3/miles$)

Please specify and give extra information on your answer/findings.

15. Do you reuse the dry excavated soil?

- Yes
- No

16. What is the fill cost for dry excavated soil at dumping site?($\$/ft^3$)

17. If you store the excavated soil, what is the cost of storage?($\$/ft^3$)

Section 3: General Information

This section contains questions for general information related to the excavators and contractors.

i) Please provide the general information of the company :

Name of the Company	
Country	
Province or Territory	
State	
Municipality-(City/Town)	

ii) How did you hear about this survey?

iii) Please provide us with any additional comments you have related to this survey.

Survey Complete!

Thank you for your participation in the Survey of Hydro Excavation and Air Excavation Technologies. We greatly appreciate your time, and look forward to sharing the results of this research.By submitting the survey your consent to participate is implied.