SELECTING A SHAFT/PIT CONSTRUCTION METHOD FOR TRENCHLESS TECHNOLOGY

by

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ABSTRACT

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TRENCHLESS TECHNOLOGY

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The word shaft describes a vertical access point that is created by excavating, vertical boring, or blasting required before the start of tunneling or boring operations. Most trenchless technologies require entry shafts and exit shafts and in some cases and intermediate shaft Trenchless technologies are methods used for the construction and rehabilitation of underground utility pipes. Since pits and shafts are excavated below the ground surface level, Occupational Safety and Health Administration (OSHA) rules and regulations are enforced for the safety of the workers.

The focus of this research is to describe shaft and pit construction methods as applied to trenchless construction and to develop a decision support system (DSS) tool for the selection of an appropriate shaft construction method for specific project conditions. The user friendly DSS tool assists pipeline owners, design engineers, and contractors select a shaft construction method by using project specific information. The Type of trenchless construction, size of pipe, length of pipe, required depth, and site information will determine the proper sizing and shaft construction method. With the use of this developed DSS, and considering pipe size, depth, surface and subsurface conditions, etc., design engineers and contractors can conceptually choose a shaft or pit design.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter presents background information on trenchless technology and the importance of pits and shafts to trenchless construction methods. Additionally, this chapter provides the objectives, scope, research needs, and expected outcomes of this research.

1.2 Background

Trenchless Technology (TT) refers to the techniques for underground pipeline and utility construction, replacement, rehabilitation, renovation (renewal), repair, inspection, and leak detection with minimum or no excavation from the ground surface (Najafi & Gokhale, 2005). TT is divided into two main areas: Trenchless Construction Methods (TCMs) and Trenchless Renewal Methods (TRMs). Figure 1.1 lists different trenchless technologies. Trenchless construction was introduced in the United States in the early 1880s, since the first circular iron tunneling machine was invented in Britain. Since its recognition as an industry, trenchless technology has continued to improve and have found new applications (Kramer, et al, 1992). TT provides solutions that are less disruptive to the social and ecological environment and significantly reduce the life cycle cost of the project. As new technologies continue to develop and improve, it is expected that trenchless technologies will be utilized for increasing numbers of underground utility projects (Najafi & Gokhale, 2005).

All TCMs require shafts/pits except for the Horizontal Directional Drilling Method (HDD), which requires a small pit for collection of drilling fluids. For other TCMs, there are two main shafts/pits required, an entry shaft/pit, and an exit shaft/pit. In some cases, intermediate shafts/pits are also required. Usually, the shafts/pits sizes are determined by the type of TCM used. The TCMs discussed in this research are; Pipe Jacking (PJ), Horizontal Auger Boring (HAB), Microtunneling (MTBM), Pipe Ramming (PR), and Pilot Tube Microtunneling (PTMT).

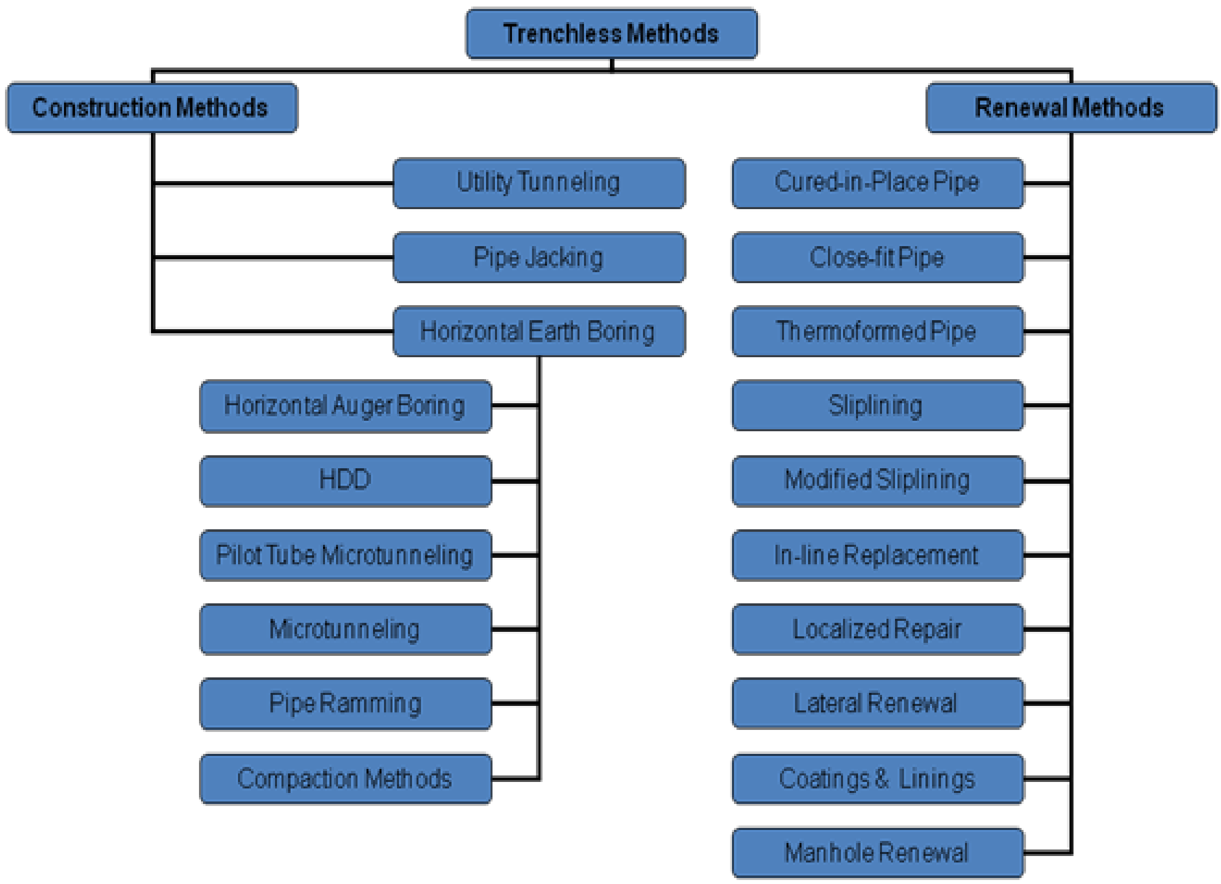


Figure 1.1: Trenchless Technology Methods (Najafi, 2011)

To better clarify the meaning of pits and shafts, a pit is a depression in the ground surface caused by excavating that is required before the start of tunneling or boring operations. A shaft is a vertical access point that is created by excavating, vertical boring, or blasting, with a suitable support system, to accommodate workers, machines, materials (spoils, air for ventilation, water, bentonite suspension, etc,), and power supply (Stein, 2005). While both shafts and pits are used interchangeably and constructed for the same purpose, generally, pits are shallower (less than 5 ft) and may have sloped walls instead of a more extensive wall support system commonly used in the shafts.

Since pits and shafts are excavated below ground surface, U.S. Occupational Safety and Health Administration (OSHA) rules and regulations are enforced for the safety of the workers. As such, for deep pits or shaft excavations, a protective system is required. OSHA defines a protective system as a method of protecting employees from cave-ins, or any material that could fall or roll from an excavation face into the shaft or pit (OSHA, 1999). Protective systems include sloping and benching systems, shoring systems, and any other systems that provide protection. Again, as the term "shaft" by definition best describes its use for trenchless construction methods, only this term will be used in this thesis.

1.3 Objectives

The main objective of this research is:

- To develop a decision support system (DSS) to assist in selecting a shaft size and construction method for trenchless construction methods (TCMs).

The other objectives of this research are:

- Collect available literature on shaft designs and construction methods using Engineering Village database, American Society of Civil Engineers (ASCE) database, Trenchless Industry Websites, Trade and Professional Organizations, Books, Articles, Trade Magazines, and other publications.
- Validate the DSS produced from literature search with interviewing trenchless contractors and equipment manufacturers.

1.4 Scope

The focus of this research is to describe shaft and pit construction methods as applied to trenchless construction, and to develop a decision support system (DSS) for proper selection and sizing of shaft construction method for specific project conditions.

1.5 Research Needs

Currently, there is not much research and academic literature on sizing and selection of a shaft construction method for trenchless construction projects. Design engineers do not get involved with specific details of shaft construction method in trenchless projects, and leave the decision making process to contractors. However, contractor's selection is more based on availability of their equipment and time and cost factors. This decision making may not consider all the attributes that may include the suitable sizing and construction method for the best benefit of the project. While OSHA provides guidelines for trench excavation, there are no OSHA rules and regulations described specifically for the shafts.

For example, Abraham, et al (2002) developed a decision support system (DSS) entitled SETT (Selection and Evaluation of Trenchless Technologies) to assist decision makers in selecting a specific trenchless construction method. This DSS was the result of a joint research study called "Development of a Decision Support System for Selection of Trenchless Technologies to Minimize Impact of Utility Construction on Roadways," for the Indiana Department of Transportation and the U.S. Department of Transportation Federal Highway Administration.

However the above research did not include any information on shaft design and construction methods. Prior to this research, there was no system to assist in the selection of applicable trenchless construction methods. It seems that shaft construction and sizing have been overlooked by researchers, as not much literature is available on this subject. However, if shafts cannot be properly constructed and sized, an alternate trenchless construction method may have to be selected at the early stages of project planning. The DSS developed herein assists decision makers select a shaft construction method for their trenchless project during the preliminary planning phases.

1.6 Expected Outcome

The expected outcome of this research is a user friendly decision support system (DSS) tool that assists pipeline owners, design engineers, and contractors in sizing and selecting a shaft construction method, by using project specific information. This tool allows users to enter data on the type of trenchless construction method, diameter of pipe, pipe section length, and required depth and site information, all of which allow the output to recommend a specific shaft size and construction method.

1.7 Chapter Summary

This chapter described pit and shaft terminologies, and identified the need for shaft sizing and construction selection for trenchless construction methods (TCMs). It also reviewed the objectives, scope, research needs, and expected outcome for this research.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

This chapter provides background and literature review on trenchless construction methods and their shaft requirements. Additionally it describes the different soil classification and reviews different shaft construction methods.

2.2 Trenchless Construction Methods (TCMs)

Trenchless Construction for a new project offers multiple methods and procedures to install new underground utility pipes without requiring an open-cut method. Open-cut excavations are required for entry shafts and exit shafts, and in some cases intermediate shafts.

2.2.1 Pipe Jacking (PJ)

Pipe jacking (PJ) is a trenchless technology method for installing a prefabricated pipe through the ground from an entry shaft to an exit shaft (Najafi & Gokhale, 2005). The term pipe jacking may be used to describe either a specific TCM or a process that is used as part of other trenchless methods (see Figure 2.1). When used to describe a specific trenchless method, pipe jacking refers to installation using hydraulic jacks located in the entry shaft to push the pipe forward while the spoils are excavated by hand mining or mechanically using a boring or tunneling machine. Horizontal auger boring, microtunneling, and pilot tube microtunneling are examples of separate trenchless methods that use a jacking mechanism to advance the pipe and cutter head (Iseley & Gokhale, 1997). The lead pipe will have a protective shield, and excavation is accomplished by hand mining or by mechanical means (such as a tunnel boring machine) or a cutter head.

The shaft size for pipe jacking is determined by the size of the jacking equipment (hydraulic jacks), diameter of pipe, length of pipe segments to be used, and thrust block size

(Iseley et al, 1999). Usually pipe segments come in 10 ft, 20 ft, or 40 ft lengths (Najafi & Gokhale, 2005). A thrust block is located at the back of the entry shaft to transmit the thrusting force to the shaft wall and to the soil behind it. Sufficient space should be available inside and around the shaft for safe loading, unloading and storage of materials, tools and equipment, and working crews. For a typical 10-ft pipe segment, a PJ entry shaft might be around 12 ft wide by 25 - 32 ft long, depending on the jacking and excavation equipment used (Najafi & Gokhale, 2005).

Clays and stable silty or sandy soils are the most favorable soil conditions for pipe jacking. For unstable soil conditions, dewatering may be necessary as well as closed-face and earth pressure balance machines, which are used to counterbalance the ground pressure (Abraham, et al, 2002). PJ is inappropriate in slightly weathered or unweathered rock (Najafi & Gokhale, 2005). Refer to Table 2.1 for more information on this method.

Table 2.1: Pipe Jacking Specifications (Najafi, 2010)

Method	**Diameter Range in.**	**Maximum Installation ft**	**Pipe Material**	**Applications**	**Accuracy of Installation**
Pipe Jacking	42 - 144	1,600 – 3,500	RCP*, GRP*, Steel	Pressure & gravity pipes	±1 in

* Refer to Appendix D for Acronyms and Abbreviations

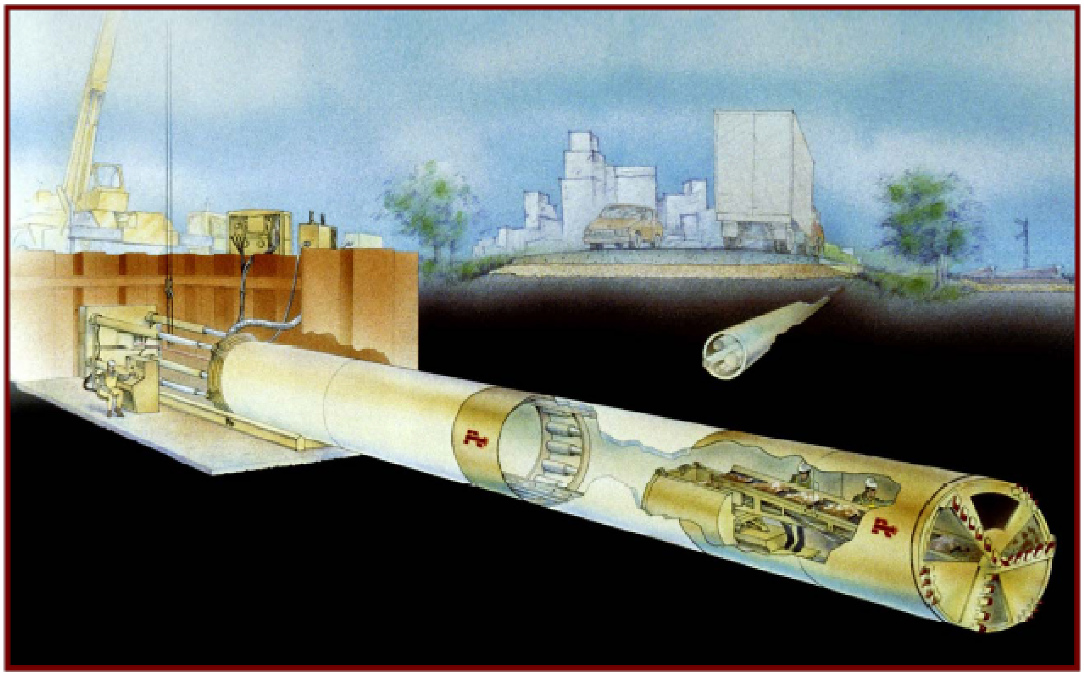


Figure 2.1: Pipe Jacking (Najafi, 2011)

2.2.2 Horizontal Auger Boring (HAB)

Horizontal Auger Boring (HAB) is a technique that forms a borehole from an entry shaft to an exit shaft by a rotating cutting head (see Figure 2.2). The spoils are transported to the entry shaft by continuous flight augers (CFA) (Iseley & Gokhale, 1997). There are two types of HAB methods; the track type which operates on a track that moves back and forth on a track, and requires a shaft, the cradle type HAB wherein the entire system is suspended by a crane and no shaft is required.

For the track type HAB, both entry and exit shafts are required. As said previously, the entry shaft should have enough space to facilitate the boring machine, pipe installation, storage, and workers to operate the machine and remove the spoils (ASCE, 2004). A thrust block is located at the back of the entry shaft to transmit the thrusting force from the track to the shaft wall. Usually pipe segments come in 10-ft, 20-ft, or 40-ft lengths. For 20-ft pipe segments, the entry shaft size might be 8 - 12 ft in width and 30 - 35 ft in length. Sufficient above-ground site space must be available for loading and unloading, and pipe storage (Najafi & Gokhale, 2005).

The most favorable soil conditions for HAB are firm sandy clay. But generally HAB can be used in a wide range of different soil conditions from dry sand to firm dry clay to solid rock (Najafi & Gokhale, 2005). Boulders or cobbles as large as one-third of the casing diameter can be accomplished (Abraham, et al, 2002). Refer to Table 2.2 for more information on this method.

Table 2.2: Horizontal Auger Boring Specifications (Najafi, 2010)

Method	**Diameter Range in.**	**Maximum Installation ft**	**Pipe Material**	**Applications**	**Accuracy of Installation**
Auger Boring	4 - 60	600	Steel	Road & rail crossing	± 1% of bore length

* Refer to Appendix D for Acronyms and Abbreviations

Figure 2.2: Horizontal Auger Boring Machine (Abraham, et al, 2002)

2.2.3 Microtunneling (MTBM)

The microtunneling boring machine (MTBM) enables pipe installation underground by jacking and utilizing its guided, remotely controlled, steerable guidance system (Najafi & Gokhale, 2005). MTBMs are divided into two types, the slurry method, and the auger method. The slurry method pumps a slurry mix that protects the tunnel face by the slurry pressure and transports the excavated spoils to the entry shaft, and then to the soil separation unit above ground. The auger method transports the excavated spoils from the lead pipe to the entry shaft by auger flights which are then hoisted up to the ground surface for disposal. The use of auger MTBM is limited and it is not as common as the slurry method.

As for any other pipe jacking operation, MTBMs require an entry shaft and an exit shaft (see Figure 2.3). Since the MTBM control unit is aboveground, no workers are needed in the entry shaft. Typical entry shafts for MTBMs are approximately 16 ft x 33 ft to 50 ft x 100 ft (Najafi & Gokhale, 2005).

The most favorable soil condition for the MTBM slurry method is wet sand, and for the MTBM auger method is stable sandy clay. A variety of cutter heads are available for the MTBM which will allow the machine to handle boulders and cobbles less than 1/3 of MTBM diameter (Iseley et al, 1999). Refer to Table 2.3 for more information on this method.

Table 2.3: Microtunneling Specifications (Najafi, 2010)

Method	**Diameter Range in.**	**Maximum Installation ft**	**Pipe Material**	**Applications**	**Accuracy of Installation**
Microtunneling	12 - 136	600 – 2,000	RCP, GRP, Steel, VCP*,DIP*, PCP*	Gravity pipes	±1 in

* Refer to Appendix D for Acronyms and Abbreviations

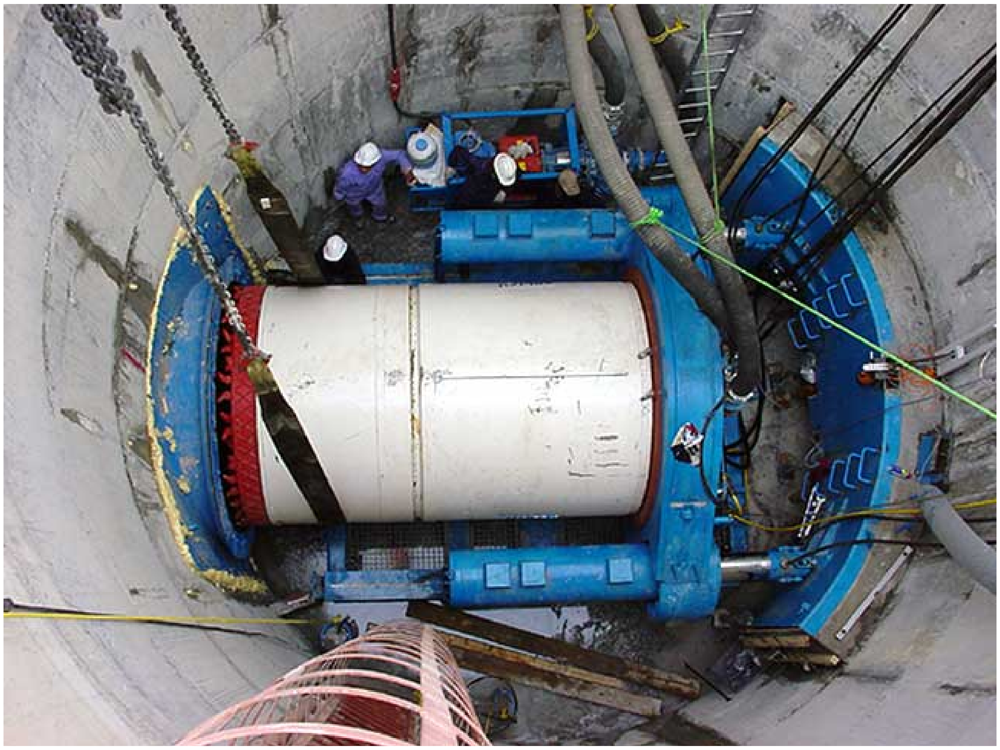


Figure 2.3: Microtunneling Machine (Allen Watson Ltd, 2012)

2.2.4 Horizontal Directional Drilling (HDD)

Horizontal Directional Drilling (HDD) is a steerable system for the installation of pipes, conduits, and cables in an arc shape path. First launched from a drill rig above ground is a fluid filled pilot bore directed to the intended location (see Figure 2.4); then a back reamer drills back to the rig with the pipe. Depending on the type of soil(s) and pipe size, the reaming procedure might be repeated in several passes. HDD is one of the trenchless construction methods that does not require an entry shaft or and an exit shaft. There are three different HDD classifications; small-diameter HDD (mini-HDD), medium-diameter HDD (midi-HDD), and large-diameter HDD (maxi- HDD).

The most favorable soil conditions for HDD are clay, fine sand, and silt (Najafi & Gokhale, 2005). A variety of drill bits can be installed to handle different types of soils, but circulation of drilling fluids and spoil removal must be adjusted with the rate of reaming and pipe pullback operations. Table 2.4 provides more information on the HDD method.

Table 2.4: Horizontal Directional Drilling Specifications (Najafi, 2010)

Method	**Diameter Range in.**	**Maximum Installation ft**	**Pipe Material**	**Applications**	**Accuracy of Installation**
Mini-HDD	2 - 12	600	PE, Steel, PVC*, Clay, FRP*	Pressure pipes and cables	Varies
Midi-HDD	12 - 24	600 – 2,000	PE, Steel, Ductile Iron	Pressure pipes	Varies
Maxi-HDD	24 - 60	2,000 – 6,000	PE, Steel	Pressure pipes	Varies

* Refer to Appendix D for Acronyms and Abbreviations

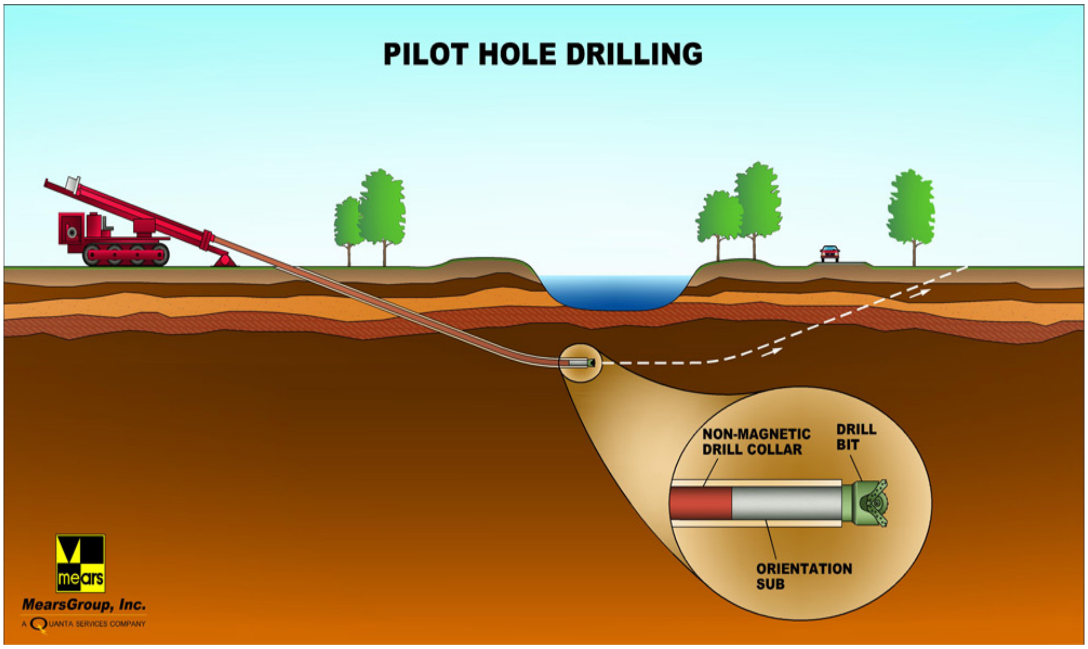


Figure 2.4: Horizontal Directional Drilling Pilot Hole Drilling (Mears Group Inc., 2012)

2.2.5 Pipe Ramming (PR)

Pipe ramming (PR) is a trenchless construction technique for inserting a steel pipe from an entry shaft by ramming or pushing the pipe through soil using a pneumatic percussion hammer, or simply a rammer (ASCE, 2008). The leading edge of the pipe can either be closed with a cone tip, or open. If the lead pipe is open, it will allow the spoils to enter the pipe. Spoils then can be removed by auger, compressed air or water jetting. Pipe ramming is most commonly used for shallow installations under roads and railroads (Najafi & Gokhale, 2005).

Pipe ramming requires an entry shaft and an exit shaft for spoil clearance (see Figure 2.5). The required work space for PR at the entry shaft typically is 6 to 12 ft in width by 33 to 66 ft in length, based mainly on the pipe section length and availability of space (Stein, 2005).

A significant feature of the pipe ramming technique is its versatility. It is suitable for a wide range of soil conditions, from stable to unstable soils. In certain conditions, installation experience through cobbles and boulders has been possible. The hammering effects tend to break up the boulders or force them out of the path either to the outside or inside the casing (Abraham, et al, 2002). However, it can be unsuitable at depths below the water table, especially in sands, as dewatering for the entry shaft may be required. Refer to Table 2.5 for more information on this method.

Table 2.5: Pipe Ramming Specifications (Najafi, 2010)

Method	**Diameter Range in.**	**Maximum Installation ft**	**Pipe Material**	**Applications**	**Accuracy of Installation**
Pipe Ramming	4 - 120	400	Steel	Road & railroad crossings	Dependent on setup

Figure 2.5: Pipe Ramming (Allen Watson Ltd, 2012)

2.2.6 Compaction Method (Impact Moling)

Impact moling is a technique using a compacting device that is forced through the soil typically from an entry shaft to an exit shaft by applying a static thrust force, a rotary force and/or dynamic impact energy; the soil along the alignment is displaced rather than being removed (Iseley & Gokhale, 1997). Impact moling is divided into three methods, the push rod method, the rotary method, and the percussion method. The push rod method utilizes a machine that pushes or pulls a solid rod or pipe through the soil to create the borehole by displacing the soil without rotation or impact. The rotary method combines the rotating drill rod and the compaction effect developed from utilizing a compaction bit. The percussion method or the impact moling method utilizes piercing tool that is self propelled by a pneumatic or hydraulic power source (Iseley et al, 1999).

Impact moling is used to install pipes of up to 8-in. diameter for a length of up to 250 ft. Installation should be made at a depth of at least 10 times the diameter of the product pipe or 3 to 4 ft, whichever is greater. This precaution is meant to prevent surface heave. The method is most frequently used to install small diameter pipes for gas, water, and cable lines (Conway, 2008) (see Figure 2.6).

The most favorable soils for impact moling are compressible soils such as soft silt or clay, mixed-grain, or well graded soils with high void ratios. Poorly graded or dense and hard are the worst soils because they are difficult to pierce and resist deformation (Iseley & Gokhale, 1997). Refer to Table 2.6 for more specific data on the compaction method. Figure 2.6 shows the machine used to execute the method.

Table 2.6: Compaction Method Specifications (Najafi, 2010)

Method	Diameter Range in.	Maximum Installation ft	Pipe Material	Applications	Accuracy of Installation
Compaction Methods	< 8	250	Any	Pipe or cable	±1% of bore length

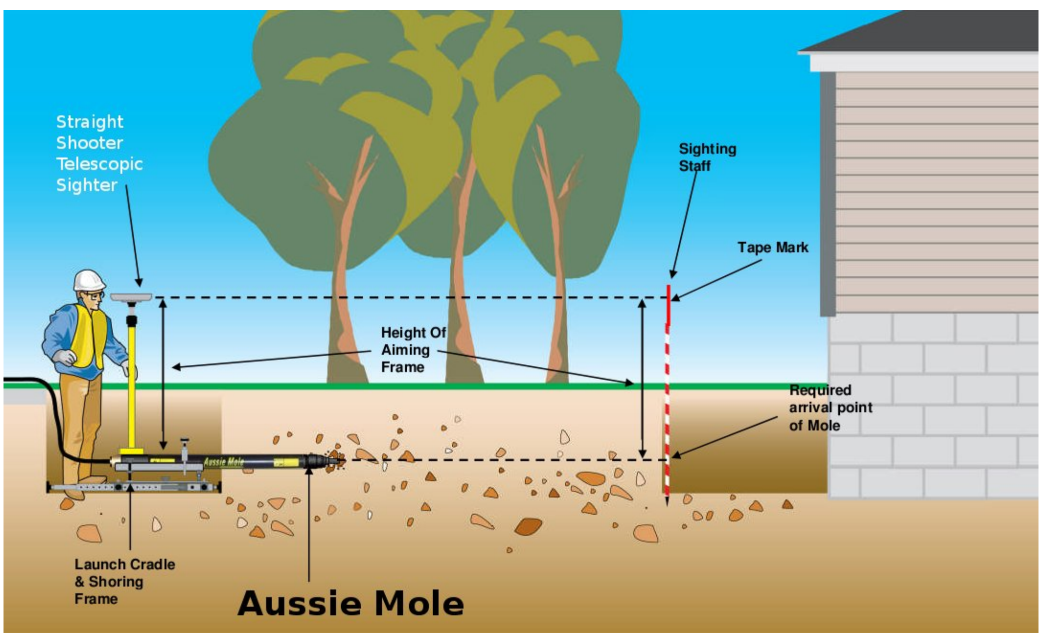


Figure 2.6: Compaction Machine (No Dig Equipment, 2012)

2.2.7 Pilot Tube Microtunneling (PTMT)

Pilot Tube Microtunneling (PTMT) uses features from three types of TCMs. A pilot bore head with a slanted face is used, similar to HDD. The guidance system is identical to that used in conventional MTBM, and the auger spoil removal system is similar to that used in HAB (see Figure 2.7). PTMT requires an entry shaft and an exit shaft; similar shaft requirements are used for the PTMT as used in the previous TCMs. The first step in the PTMT method is the installation of the pilot tube. During the installation process, the spoil is displaced by the slant-faced steering head. Once the pilot tubes reach the reception shaft, a reamer is installed and drills back to the entry shaft with the pipe.

The most favorable soil conditions for the PTMT are soft soils, and it is not considered suitable for soil with significant cobbles and boulders because these can impact steering. PTMT can be used above or below the water table (Najafi & Gokhale, 2005). Refer to Table 2.7 for more information on this method.

Table 2.7: Pilot Tube Microtunneling Specifications (Najafi, 2010)

Method	**Diameter Range in.**	**Maximum Installation ft**	**Pipe Material**	**Applications**	**Accuracy of Installation**
Pilot Tube Microtunneling	6 - 30	300	RCP*, GRP*, Steel, VCP*,PCP*	Small diameter gravity pipe	±1 in.

* Refer to Appendix D for Acronyms and Abbreviations

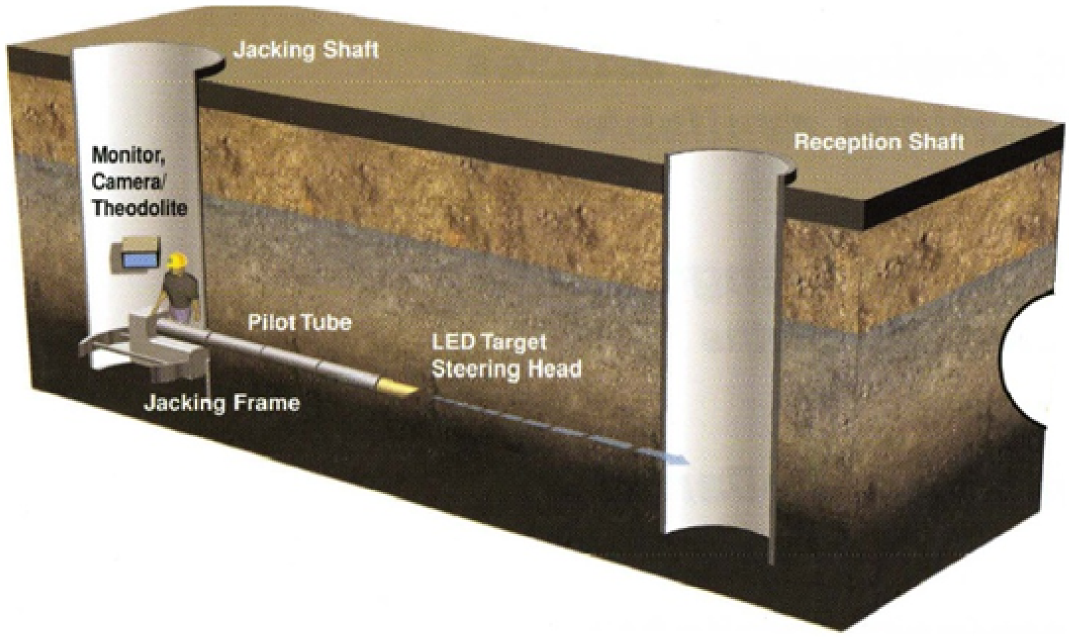


Figure 2.7: Pilot Tube Microtunneling (Najafi, 2011)

Iseley and Gokhale (1997) have developed a table to illustrate the applicability of different trenchless construction methods for various soil types (see Table 2.8).

Table 2.8: Applicability of Trenchless Construction Methods in Various Soil Conditions (Iseley & Gokhale, 1997)

Soil Type	**N Value (Standard Penetration Value as per ASTM D 1452)**	**HAB**	**HDD**	**MTBM**	**PJ**	**PR**
Cohesive Soils (Clay)	N < 5 (Soft)	P	P	R	P	R
	N = 5 - 15 (Firm)	R	R	R	R	R
	N > 15 (Stiff - Hard)	R	R	R	R	R
Cohesionless Soils (Sand/Silt)	N <10 (Loose)	P	P	R	P	R
	N = 10 - 30 (Medium)	R	R	R	R	R
	N > 30 (Dense)	R	R	R	R	R
High Ground Water		X	P	R	P	P
Boulders		≤ 33% D	P	≤ 33% D	P	≤ 90% D
Full-face Rock		≤ 12 ksi	≤ 15 ksi	≤ 30 ksi	≤ 30 ksi	X

R: Recommended

P: Possible

X: Unsuitable

D : Size of largest boulder versus minimum casing diameter

* This table is based on the assumption that work is performed by experienced operators using proper equipment.

2.3 Shaft Sizes

Shaft sizes depend on the trenchless machine size, project length, pipe segment length, and pipe diameter. Entry shafts are larger than intermediate and exit shafts, because of the trenchless machine, the measuring and control systems, the soil removal system, and in some TCMs, the thrust block. This research does not include intermediate and exit shafts information, but rather only focuses on entry shafts construction methods.

There are many different designs for shaft shapes: rectangular, circular, and oval. The length of the shaft is influenced by the type of machine, and pipe segment lengths. The width is determined by the size of the trenchless machine, the pipe diameter, workers clearance, soil removal system, and usually a sump pump.

One of the objectives of this research was to collect manufacturer's shaft dimension requirements on different trenchless machines. The main benefits from the information obtained were to document various trenchless machine shaft sizes and compare the specifications with the literature reviewed to choose the best sizes for a Decision Support System (DSS). Some manufacturers have specified shaft dimensions for their equipment, and some only provide the trenchless machine dimensions, so shaft size can be determined by a contractor.

Many trenchless machine manufacturers do not specify or recommend entry shaft sizes. Contractors decide on shaft sizes based on the trenchless equipment dimensions and project experience. After determining the entry shaft size, visiting the site for a jobsite layout is recommended. Outlining the shaft's at the site helps check for any clearance issues and obstacles in the path. It also assists in determining the site limitations such as right of way, environmental impacts, social impacts, adjacent buildings and structures, and if permit requirements.

2.3.1 Pipe Jacking Shaft Sizes

Table 2.9 illustrates the different pipe jacking entry shaft dimensions based on the sources listed.

Table 2.9: Pipe Jacking Entry Shaft Dimensions

Information Source	**Machine Model**	**Pipe Size in.**	**Project Length ft**	**Pipe Segment ft**	**Circular Shaft Diameter ft**	**Entry Shaft Width ft**	**Entry Shaft Length ft**
Herrenknecht Inc. (www.herrenknecht.com)	1200TC	48 - 56	800	10	28	12	26
	1400TC	48 - 56	800	10	28	12	26
	1500TC	56 -64	800	10	28	12	26
	1600TC	64 - 72	1,000	10	28	12	26
	1800TC	72 - 80	1,000	10	30	13	28
	1200TB	48 - 60	1,700	10	28	12	26
	1400TB	56 - 64	1,700	10	28	12	26
	1500TB	60 - 72	2,500	10	28	12	26
	1600TB	64 - 72	3,000	10	28	13	28
	1600TE	64 - 72	3,000	10	30	13	28
	1800TB	72 - 80	3,000	10	30	13	28
Iseley & Gokhale, (1997)	N/A	42 – 120	1,600	10	N/A	10 - 15	17 - 33
Najafi & Gokhale, (2005)	N/A	42 - 144	3,500	10	N/A	12	25 - 32

2.3.2 Horizontal Auger Boring Shaft Sizes

Table 2.10 illustrates the different horizontal auger boring entry shaft dimensions based on the sources listed.

Table 2.10: Horizontal Auger Boring Entry Shaft Dimensions

Information Source	Machine Model	Pipe Size in.	Project Length ft	Pipe Segment ft	Entry Shaft Width ft	Entry Shaft Length ft
American Augers (http://www.americanaugers.com)	150	24 – 30	N/A	20	10	34
	600	36 - 42	N/A	20	12	34
	900	48 - 60	N/A	20	12	36
	60	60 - 72	N/A	20	15	40
Najafi & Gokhale, (2005)	N/A	4 - 60	600	20	8 - 12	30 - 35

2.3.3 Microtunneling Boring Machines Shaft Sizes

Table 2.11 illustrates the different microtunneling boring machines entry shaft dimensions based on the sources listed.

Table 2.11: Microtunneling Boring Machines Entry Shaft Dimensions

Information Source	Machine Model	Pipe Size in.	Project Length ft	Pipe Segment ft	Semi-circular Shaft Length ft	Entry Shaft Width ft	Entry Shaft Length ft
Stein, (2005)	N/A	28	N/A	N/A	19	9	18
	N/A	32	N/A	N/A	19	9	18
	N/A	36	N/A	N/A	19	9	18
	N/A	40	N/A	N/A	22	10	20
	N/A	44	N/A	N/A	22	10	20
	N/A	48	N/A	N/A	22	10	20
	N/A	54	N/A	N/A	24	11	23
	N/A	60	N/A	N/A	24	11	23
	N/A	65	N/A	N/A	26	11	24
	N/A	72	N/A	N/A	26	11	24
	N/A	80	N/A	N/A	26	14	25
	N/A	88	N/A	N/A	26	14	25
Najafi & Gokhale, (2005)	N/A	12 - 136	600 - 2,000	N/A	N/A	33 - 100	16 – 50

2.3.4 Pipe Ramming Shaft Sizes

Terra Trenchless Technologies Inc. (http://www.terra-eu.com) provides pipe ramming equipment sizes for different models. For entry shaft length, contractors using these machines recommend adding the length of the machine with the pipe segment length, plus 2 - 3 ft for the air hose clearance attached to the back of the machine. For the width they recommend adding the pipe size diameter with 3 ft on both sides for workers clearance. Table 2.12 illustrates the different entry shaft dimensions.

Table 2.12: Pipe Ramming Entry Shaft Dimensions

Information Source	Machine Model	Pipe Size in.	Project Length ft	Machine Diameter in	Machine Length ft	Pipe Segment ft	Entry Shaft Width ft	Entry Shaft Length ft
Terra Products (http://www.terra-eu.com)	190	4 - 16	100	8	6	10	7	16
	220	8 - 24	200	9	6	10	7	16
	360	24 - 40	250	14	6	10	8	16
	565	40 - 80	350	26	8	10	9	18
Najafi & Gokhale, (2005)	N/A	4 - 140	400	N/A	N/A	20	10	30 - 35

2.3.5 Pilot Tube Microtunneling Shaft Sizes

No Dig Equipment Inc. (http://www.nodigequipment.com) provides entry shaft dimensions for pilot tube microtunneling machines. Table 2.13 illustrates the different pilot tube microtunneling entry shaft dimensions.

Table 2.13: Pilot Tube Microtunneling Entry Shaft Dimensions

Information Source	**Machine Model**	**Pipe Size in.**	**Project Length ft**	**Pipe Segment ft**	**Circular Shaft Diameter ft**	**Entry Shaft Width ft**	**Entry Shaft Length ft**
No Dig Equipment (http://www.nodigequipment.com),	B06	6 - 8	65	N/A	7	3	7
	B250	6 - 12	200	N/A	8	5	8
	B750	12 - 30	200	N/A	8	5	8
Najafi & Gokhale, (2005)	N/A	6 - 30	300	N/A	N/A	N/A	N/A

2.4 Types of Soils

Understanding the nature of the soil is very important for the shaft excavation work. For deep shafts, geotechnical investigations are required for the purpose of determining the type of soils. The geotechnical reports specify the strength and material properties that are used to choose the wall support system for the shaft (Turner, 2008). The Unified Soil Classification System (USCS) identifies soils according to grain size, distribution, and behavior of soil as characterized by plasticity (Duncan, 1998) (see Table 2.14). Soils are separated into four general classifications of gravel, sand, silt, and clay. Gravel components may have a distinctive rounded and smooth shape, easy to touch, and do not exhibit any cohesion. Sand, unlike gravel, exhibits variations between grains and are described as round, angular, smooth, or sharp, and can be easily separated when loose. Sands are divided into three classifications based on particle size--loose, medium, or dense.

Table 2.14: Unified Soil Classification System (USCS) Soil Groups (Duncan, 1998)

<table>
<tr><th colspan="3">Major Divisions</th><th>Group Symbol</th><th>Typical Names</th></tr>
<tr><td rowspan="8">Course-Grained Soils More than 50 % retained on the 0.075 mm (No. 200) sieve</td><td rowspan="4">Gravels 50% or more of course fraction retained on the 4.75 mm (No. 4) sieve</td><td rowspan="2">Clean Gravels</td><td>GW</td><td>Well-graded gravels and gravel-sand mixtures, little or no fines</td></tr>
<tr><td>GP</td><td>Poorly graded gravels and gravel-sand mixtures, little or no fines</td></tr>
<tr><td rowspan="2">Gravels with Fines</td><td>GM</td><td>Silty gravels, gravel-sand-silt mixtures</td></tr>
<tr><td>GC</td><td>Clayey gravels, gravel-sand-clay mixtures</td></tr>
<tr><td rowspan="4">Sand 50% or more of course fraction passes the 4.75 (No. 4) sieve</td><td rowspan="2">Clean Sands</td><td>SW</td><td>Well-graded sands and gravelly sands, little or no fines</td></tr>
<tr><td>SP</td><td>Poorly graded sands and gravelly sands, little or no fines</td></tr>
<tr><td rowspan="2">Sands with Fines</td><td>SM</td><td>Silty sands, sand-silt mixtures</td></tr>
<tr><td>SC</td><td>Clayey sands, sand-clay mixtures</td></tr>
<tr><td rowspan="6">Fine-Grained Soils More than 50 % passes on the 0.075 mm (No. 200) sieve</td><td colspan="2" rowspan="3">Silts and Clays Liquid Limit 50% or less</td><td>ML</td><td>Inorganic silts, very fine sands, rock four, silty or clayey fine sands</td></tr>
<tr><td>CL</td><td>Inorganic clays of low to medium plasticity, gravelly/sandy/silty/lean clays</td></tr>
<tr><td>OL</td><td>Organic silts and organic silty clays of low plasticity</td></tr>
<tr><td colspan="2" rowspan="3">Silts and Clays Liquid Limit greater than 50%</td><td>MH</td><td>Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts</td></tr>
<tr><td>CH</td><td>Inorganic clays or high plasticity, fat clays</td></tr>
<tr><td>OH</td><td>Organic clays of medium to high plasticity</td></tr>
<tr><td colspan="3">Highly Organic Soils</td><td>PT</td><td>Peat, muck, and other highly organic soils</td></tr>
<tr><td colspan="3">Prefix:

G = Gravel,
S = Sand,
M = Silt,
C = Clay,
O = Organic
PT = Peat</td><td colspan="2">Suffix:

W = Well Graded,
P = Poorly Graded,
M = Coarse material with non-plastic fines or fines with low plasticity
C = Coarse material with plastic fines
L = Relatively low liquid limit
H = Relatively high liquid limit</td></tr>
</table>

Silt components have loose sedimentary material with particles usually 1/20 millimeter or less in diameter. Clay is the end product of the chemical decomposition of rock. Clays are subdivided into soft, firm, and hard (Duncan, 1998). Rocks are naturally a group of minerals, often consolidated, cemented, and or bonded together. They are subdivided into two types, weathered or unweathered (Stein, 2005). A weathered rock involves the breakdown of rocks through direct contact with atmospheric conditions, such as heat, water, ice and pressure. Boulders are a smooth rounded mass of rock that has a diameter greater than 10 in. and that has been shaped by erosion and transported by ice or water from its original position.

To avoid any human injury, structure, and equipment hazards during the shaft's excavation, OSHA rules and regulations apply. Understanding OSHA's soil classification system is necessary to choose the correct shoring methods. This soil classification system is based on the soils attributes and environmental conditions, primarily water content, and blow count values (N) from the standard penetration test (SPT). The system relies on four categories; stable rock, Type A, Type B, and Type C (Turner, 2008) . Table 2.15 identifies OSHA's classification types.

Table 2.15: OSHA's Classification Types (Turner, 2008)

Relative Density			**Consistency**		
Sand & Gravel	**SPT (N)**	**OSHA Soil Type**	**Silt & Clay**	**SPT (N)**	**OSHA Soil Type**
Very loose	0 - 4	Type C	Very soft	0 - 2	Type C
Loose	5 - 10	Type C	Soft	3 - 4	Type C
Medium dense	11 - 30	Type B	Medium stiff	5 - 7	Type B
Dense	31 - 50	Type B	Very Stiff	16 - 32	Type A
Very dense	50+	Type B	Hard	32+	Type A

2.5 Structural Calculations

Structural calculations are critical for shaft design and construction. These calculations assist in choosing the proper wall support system for shafts. Wall support systems require careful evaluation of various possible failure modes, such as base heaving, wall structural failure, hydraulic failure, etc. The loads that need to be taken into account are; earth and water pressure, traffic, and jacking force loads for trenchless construction methods (TCMs).

Geotechnical reports determine the soil characteristics and help contractors in the shaft design. The presence of water is one of the most important criteria for the choice of the type of wall and construction method. For below watertable, a watertight type of wall must be design and constructed (Ergun, 2008). Earth pressure is usually determined by using the active earth pressure coefficient taking into account using a positive wall friction angle. Active earth pressure develops when the wall moves outwards from the shaft. If the wall support system moves into the soil and the soil is compressed, it mobilizes its shear strength and develops a passive pressure. The lateral earth pressure is equal to vertical earth pressure times the appropriate earth pressure coefficient. There are published equations, tables and charts for calculating or selecting the appropriate earth pressure coefficients.

When choosing the type of wall support system, consideration must be given for the final construction as well as the installation and removal phases. Depending on the specific trenchless construction method, an extensive thrust block may be required to resist jacking loads. Thrust block transfers jacking forces to the shaft wall support system. Soil stabilization methods may be used if soils around shafts cannot accommodate the jacking forces. Since a proper shaft wall protection system must be designed by a qualified professional engineer based on specific project site and soil conditions, the DSS developed as part of this research, does not address earth and water pressure loading conditions. It is however, recognized that soil conditions and shaft size and depth have great impacts in the selection of type of wall protection that can be used.

2.6 Shaft Construction

The entry shaft construction is usually the first construction task for a trenchless construction project. Designing and constructing an accurate shaft is necessary to avoid issues during the boring or jacking process. If the shaft is not designed and constructed accurately, the project most likely will fail. The construction of the entry shaft must be in accordance with the rules and regulations set forth in the (OSHA) Code of Federal Regulations, Construction Standards for Excavations, 29 CFR part 1926, subpart P. There are specific requirements for shaft construction, protection, barricades, traffic controls, installation, and type of ladders used in the shaft, and for personal safety equipment. Additional information can be obtained from your regional department of labor office or OSHA Website (Turner, 2008). In the interest of minimizing environmental disturbance and construction costs, designers and contractors should consider several factors including selection of location, shaft size, and shaft construction method and support at the same time.

Before starting the entry shaft construction, a site condition surface survey, subsurface geotechnical report, and utility locating should be incorporated in the design process (ASCE, 2004). Once all the investigations are completed, design and excavation phases can follow. As said earlier, there are many different designs for entry shaft shapes including rectangular, circular, and oval. Sufficient space should be available for loading, unloading and storage of materials and equipment (Najafi & Gokhale, 2005). Inside the shaft, clearance to facilitate the trenchless construction machine operation, access for spoil removal, and a sump pump is expected. Depending on the TCM, the bottom of the entry shaft may include a layer of crushed stone or gravel to make it firm enough to support the trenchless machine, however, some methods may require a concrete floor. Some TCMs require the thrust wall to be constructed with steel sheeting, in addition to concrete or timber to properly resist jacking pressures. A properly installed ladder, and sometimes for deep shafts (more than 50 ft), an elevator is required for entering and exiting.

The most common way to excavate an entry shaft is by using a backhoe or an excavator. For stiff soils and medium hard rock ripping might be required, and for very hard rock conditions, blasting may be used. The depth of the shaft may vary depending on the project. For shallow entry shafts, that are less than 5 ft, no support system is required as per OSHA's rules and regulations. Shafts exceeding 5 ft in depth will require a protective system to support the walls, and shafts more than 20 ft deep will require a licensed civil or structural engineer's stamped drawings for construction approval. Harris (1994) classified wall support system methods depending on soil types and depth ranges. Shallow depth ranges less than or equal to 5 ft., medium depth ranges from 5 ft to 15 ft, and more than 15 ft is considered deep. There are two methods of wall support systems, open sheeting that is not completely sealed (not a watertight system), and a closed sheeting that is completely sealed (a watertight system). Table 2.16 provides the wall support methods for various ground conditions.

Table 2.16: Wall Support Methods for Various Ground Conditions (Harris, 1994)

Depth Range	**Sand Loose**	**Sand Medium**	**Sand Dense**	**Clay Soft**	**Clay Medium**	**Clay Hard**	**Rock Un-weathered**	**Rock Weathered**
Shallow (up to 5 ft)	C	A	A	C	B - C	B - C	A	A
Medium (5 ft - 5 ft)	C	B	B	C	B - C	B - C	A	A
Deep (over 15 ft)	C	C	C	C	C	C	B	A

Abbreviations:
A = No support necessary
B = Open sheeting. Not watertight system.
C = Close sheeting. Completely sealed watertight system.

There are two shaft construction categories, temporary shafts and permanent shafts, as are described in the following sections (Puller, 2003).

2.6.1 Temporary Shafts

Temporary shafts secure the shaft's excavation and temporarily support the walls from cave-ins. After completing the trenchless construction project, the support system is removed, and the excavated shaft is refilled or reconstructed as an access point or manhole. Most of the wall support system materials are reused unless damaged during the installation or removal process. This category is usually used for trenchless construction projects with durations of less than two years (Stein, 2005).

2.6.1.1 Sloping or Benching

Sloping is defined as an inclined or angle considered with reference to a vertical or horizontal plane, i.e., slant (OSHA, 1999). Table 2.17 presents OSHA's the maximum allowable slopes for excavations less than 20-ft deep based on soil types.

Table 2.17: Slope Angles (OSHA, 1999)

Soil Type	**H/V Ratio**	**Slope Angle**
Stable Rock	Vertical	90°
Type A	¾:1	53°
Type B	1:1	45°
Type C	1½:1	34°

Another option per OSHA is benching, which is similar to sloping, but instead of smooth walls, steps are created. The type of soil determines the horizontal to vertical ratio of the benched side. The bottom vertical height of the shaft must not exceed 4 ft for the first bench, and the subsequent benches may be up to a maximum of 5 ft vertical in Type A soils and 4 ft in Type B soils to a total shaft depth of 20 ft. All subsequent benches must be below the maximum allowable slope for that soil type. For Type B soil the trench excavation is permitted in cohesive soil only (OSHA, 1999). Figures 2.8, 2.9, and 2.10 illustrate the different types of soils and different shoring and sloping techniques.

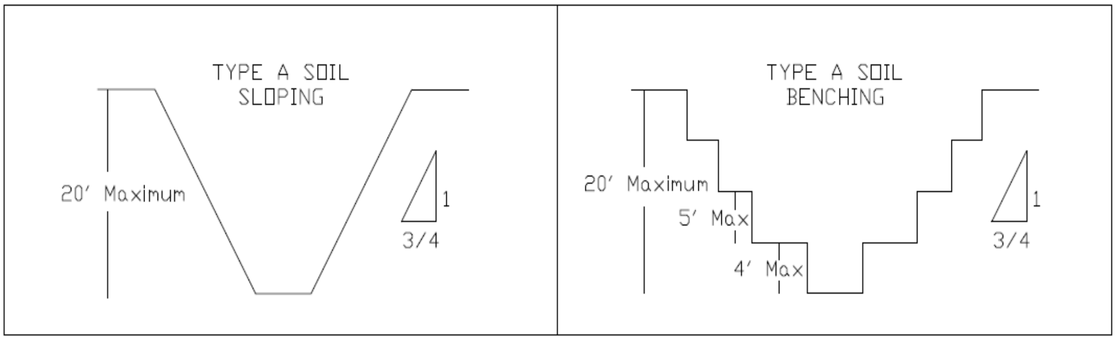


Figure 2.8: Type A Sloping and Benching (OSHA, 1999)

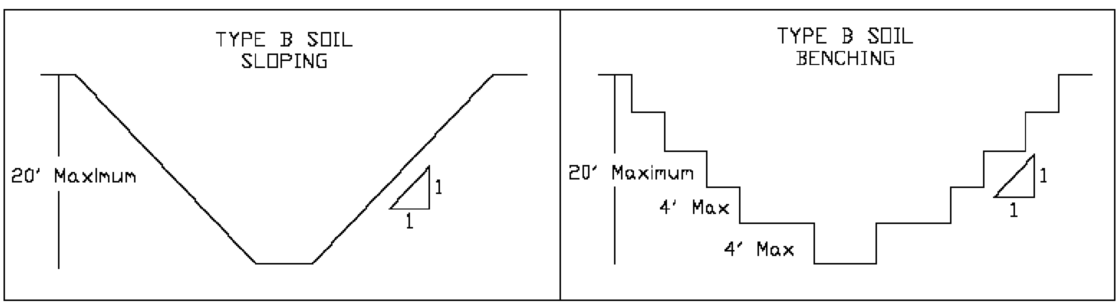


Figure 2.9: Type B Sloping and Benching (OSHA, 1999)

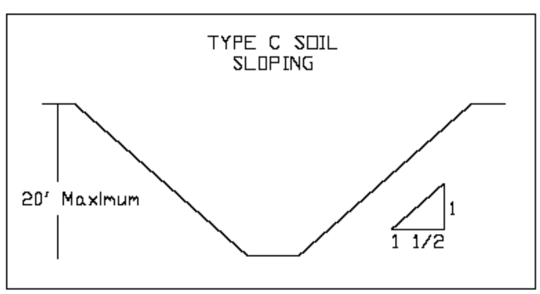


Figure 2.10: Type C Sloping (OSHA, 1999)

2.6.1.2 Vertical or Horizontal Sheeting

Vertical and horizontal sheeting or planks are usually made from wood or corrugated metal and are installed vertically or horizontally (see Figure 2.11). The planks are progressively installed during the excavation work or driven in soft cohesive soils into the ground or slipped in simultaneously during excavation. The loads acting on the vertical planks are diverted into horizontal walers, and horizontal planks loads are diverted into vertical beams from timber or steel and supported by wooden or steel bracing. Depending on soil type and depth walers or beams holding the planks in place are often needed every 5 to 16 ft, depending on the soil type and depth. Wood and Metal planks are suited for unstable soils like, loosely compacted, non-cohesive or soft cohesive soils free of groundwater for shaft depths up to 16 ft (Stein, 2005). Abbot (1994) and Chung et. al., (2004) suggest the depth ranges for timber and metal sheeting is 20 ft.

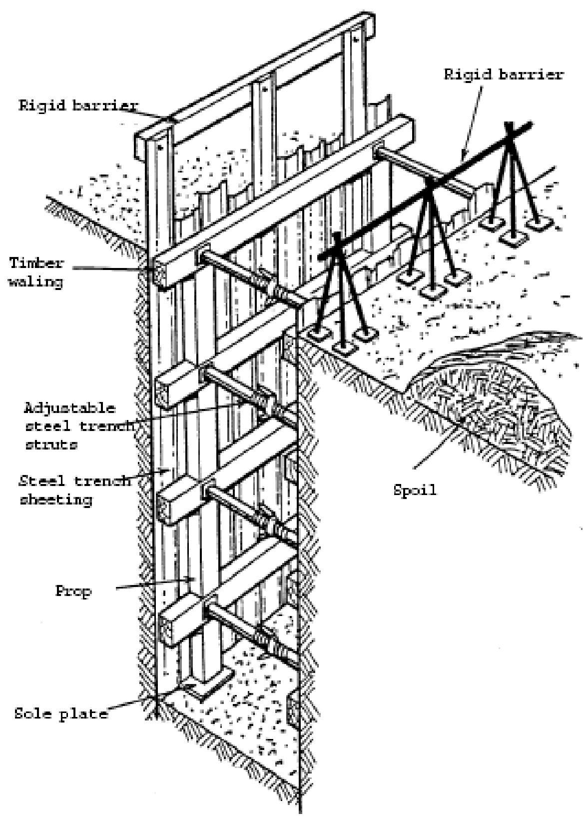


Figure 2.11: Vertical Steel Shoring (OSH, 1995)

2.6.1.3 Steel Liner Plates

Liner plates are prefabricated corrugated steel plate segments that can be bolted together into shaft rings (see Figure 2.12). There are two liner plate forms; 2-Flange, and 4-Flange. This method can be installed similar to the horizontal sheeting method, progressively with the excavation from top to bottom, or by assembling the segments above ground and lowering the structure into the excavated area. Liner plates range from 4 – 16 ft. 2-Flange depth reach up to 13 ft, and 4-Flange reach up to 10 ft in unstable soils and 39 ft in stable soils (Stein, 2005).

Figure 2.12: Steel Liner Plates

2.6.1.4 Trench Boxes

Trench boxes are prefabricated steel rectangular shaped boxes that are lowered or dropped in the entry shaft during excavation to keep the walls from caving in (see Figure 2.13). The trench box has sharp cutting edges at the bottom and is placed over the entry shaft location; as the excavation process starts the trench box's weight pushes it down. Trench boxes are simpler to install and have fewer cross braces than the sheeting method. A single trench box panel is usually sufficient, and for deeper projects two or more panels can be used. These panels are usually guided on a slide rail system (Stein, 2005). This method can be used for excavation sizes up to 10 ft wide by 20 ft long and for depths up to approximately 20 ft (Abbott, 1994), 23 ft (Stein, 2005), or 30 ft (Chung et al, 2004). The most common sizes used are 8 ft high by 20 ft length, since larger sizes require permits to transport to the project site. Trench boxes can be used for almost all soils and are water tight systems (Stein, 2005).

Figure 2.13: Metal Trench Box (Conway, 2008)

2.6.1.5 Slide Railing Systems

Slide railing systems are metal sheet panels connected to slide posts (see Figure 2.14). The panels move up and down in one or more grooves and are supported by struts (Stein, 2005). The preferred soil conditions are loose sands and gravels and soft cohesive soils. Slide rail systems can reach depths up to 40 ft, in water free conditions (Turner, 2008).

Figure 2.14: Slide Railing System (Shoring Solutions, 2012)

2.6.1.6 Sheet Piles

Sheets piles are interlocking steel sheets that are driven into the ground by pushing and hammering them with a backhoe bucket or conventional pile driver machine (see Figure 2.15). Sheet piles gather the soil load similar to sheeting and have a structure shape that is capable of carrying the loads into the ground and up the wales (Turner, 2008). After all sheets are installed, the excavation starts, and bracing is installed when the required level of excavation is reached. Sheet piles are suitable for shallow excavation typically less than 15 ft generally without any bracing and wales, while deeper excavations require cross bracing and wales and can reach depths up to 50 ft (Abbott, 1994) and (Chung et al, 2004), or up to 60 ft (Stein, 2005) and (Turner, 2008). This method is suitable for all kinds of soil types except for dense sand and hard clay materials (Smith & Andres, 1993). Sheet piles are watertight, can limit groundwater inflow, and can be used as a temporary or permanent method.

Figure 2.15: Steel Sheet Piles (Midwest Mole Inc., 2012)

2.6.1.7 Soldier Piles and Lagging

Soldier piles are steel beams driven or placed in the ground around the parameter of the entry shaft and placing lagging in-between (Smith & Andres, 1993). The steel beams can be W beams or H-piles driven into the ground or installed in drilled holes. For laggings, wood planks, reinforced concrete planks, or steel sheeting can be installed (see Figure 2.16). This method can be used for almost all cohesive and non-cohesive soils depending on the type of lagging selection and can reach depths up to 50 ft (Chung et al, 2004).

Figure 2.16: Soldier Piles with Steel Lagging

2.6.1.8 Corrugated Metal Pipe Shafts

After or during the excavation, a corrugated metal pipe (CMP) is lowered in the shaft (see Figure 2.17). This method is a watertight method that does not allow soils or water enters the shaft (Abbott, 1994). The maximum diameter range is 30 ft, and can reach depths up to 79 ft (Reed, 2012) and (Stein, 2005).

Figure 2.17: Corrugated Metal Pipe Shaft (Reed, 2012)

2.6.1.9 Concrete Sinking Shafts

Concrete sinking shafts are reinforced concrete segments sunk or lowered as a whole in the shaft (Stein, 2005). Sinking shafts can be open bottom or closed bottom, and can be circular or rectangular shaped. The segments are factory prefabricated components divided into circular or square segments of concrete or reinforced concrete. They can be bolted or pinned together (see Figure 2.18). This method can be used for any ground water levels. Circular concrete shafts require 8 ft diameter area or larger (Chung et al, 2004). The depth ranges can reach up to 131 ft and can be used for all soil conditions. They are suitable for pipe jacking methods that and for projects requiring multiple boreholes from the same shaft (Stein, 2005).

Figure 2.18: Circular Concrete Shaft (Allen Watson Ltd, 2012)

2.6.1.10 Ground Freezing

The ground freezing method is a process by which the soil's pore water is frozen in-situ to create a frozen soil material and impart strength and impermeability to the soil mass (Braun, 2011). The usual thickness of the frozen wall depends on the subsoil and the structural requirements and is usually from 3 ft to 10 ft thick (Stein, 2005). This ground freezing can form any shaft shape and be used for any type of soils and rocks. Once the trenchless project is completed, the soil and ground water are turned back to their original conditions (Braun, 2011). Anchoring or bracing the shaft walls is possible. Frozen walls are mostly suitable in saturated unstable soils. Refer to Table 2.5 for with depths less than 656 ft (Stein, 2005). Figure 2.19 illustrates the ground freezing method.

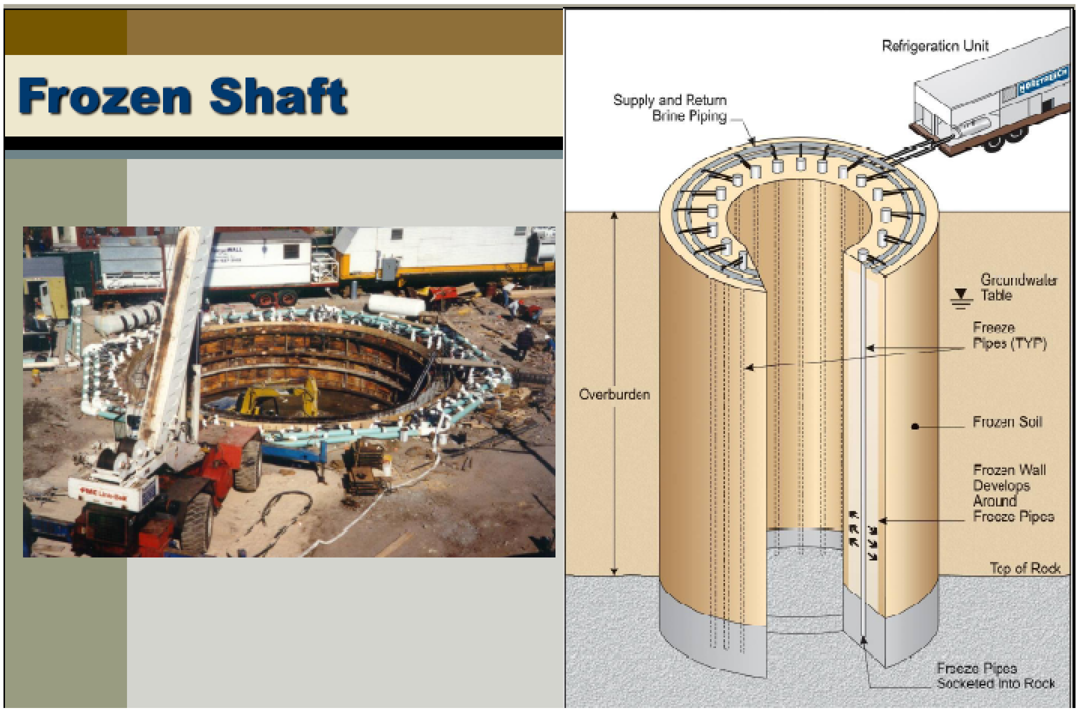


Figure 2.19: Shaft Ground Freezing (Braun, 2011)

2.6.2 Permanent Shafts

Permanent shafts are non-removable linings that are left partially or wholly in the ground after the completion of the trenchless construction project (Stein, 2005). Permanent shafts are usually used for long trenchless construction projects and trenchless renewal projects.

2.6.2.1 Pile Walls (Secant Piles)

Bored pile walls are made up of in-cast concrete piles placed next to each other. The piles are constructed either by boring or excavating (grabbing bucket), and then reinforcement is positioned and concrete is tremied into place (Harris, 1994). Bentonite slurry may be necessary when boring or excavating in unstable soil conditions. Bored walls are created in all soil types and reach depths up to 262 ft (Stein, 2005).

2.6.2.2 Concrete Slurry Walls

A concrete slurry wall is a technique used to build reinforced-concrete walls underground to help support the soils from caving in before digging the entry shaft. The slurry is a mixture of bentonite (special clay material) and water. First, a trench is excavated to the desired depth for one side of the shaft's walls, and then immediately, the slurry mix is pumped in. After the trench is completely filled with the slurry mix, a reinforced rebar cage is lowered into the slurry wall, and then the wall is filled with concrete from the bottom up using a tremie. The concrete displaces the bentonite slurry, which is pumped out and recycled. This process is repeated until all sides of the shaft's walls form a closed box or ring. The final step is to excavate the spoils in-between the walls to create a shaft. Slurry walls can reach a depth of up to 400 ft in depths and are used in areas of soft earth close to open water or with a high ground watertable (Smith & Andres, 1993).

2.6.2.3 Jet Grouting Injection

The soil structure is loosened by means of jet spray. Mixing the soil is achieved while pulling the drill string, and columns are formed due to the rotation. The dimension of the high pressure injection bodies as well as their strength depend greatly on the in- situ soil types. This method is possible in most types of soils and in ground water which can reach a depth up to 98 ft (Stein, 2005). Jet grouting should be avoided for use in shallow depths due to high pressure subsoil movement which can damage existing structure or utility services (Puller, 2003).

2.6.2.4 Shotcrete and Soil Nailing

Shotcrete is a concrete mix pumped through a hose to the surface wall of the entry shaft to stabilize the soil preventing it from caving-in. The shotcrete wall will have soil nails inserted through the wall that are from reinforced steel rebar tendons drilled and grouted into the soil to hold the shotcrete wall (Smith & Andres, 1993). The excavation is done in 5 to 10 ft lift increments. After each lift is excavated, shotcrete is applied, and one row of soil nails is installed. The tendon lengths are 50 to 70% of the excavation height (Chung et al, 2004). In some deep entry shafts, long tendons might extend beyond the projects property lines making it necessary to obtain permission to install. Soil nailing should be used in firm ground, hardpan, glacial till, or rock, and should not be used in soft clay (Smith & Andres, 1993). Soil nailing can be used for any design entry shaft and can reach long depths. This method is mostly used as a permanent method for building shafts (Stein, 2005).

2.7 Decision Support System (DSS)

A decision support system (DSS) is a coherent system of computer-based technology (hardware, software, and supporting documentation) used by managers as an aid to their decision making in structured, semi-structured, or unstructured decision tasks (Bennet, 1983). Decision support systems are not intended to replace decision makers but to extend their decision making capabilities. Decision support systems use data in spreadsheets or databases, prepare a mathematical model using this data, solve or analyze this model using problem-specific methodologies, and can assist the user in the decision-making process through a graphical user interface (GUI). There are several DSS types which include the optimization and suggestion systems. Optimization systems use algorithms to generate optimal solutions subject to constraints. The decision maker supplies assumptions and DSS generates "best" outcome (i.e., analytic hierarchy process, simple multi-attribute rating technique).

The analytical hierarchy process includes and measures all important tangible and intangible factors as well as quantitatively measurable and qualitative factors (Saaty, 1980). The suggestion system uses decision tables or trees in linear framework and makes a recommendation. Decision support systems have been used in various types of construction projects (Hasan, 2010).

Decision support systems are valuable tools for making reasonable decisions. For water pipelines, Covilakam (2011) developed a decision support system to evaluate structural monitoring methods for large diameter water transmission pipelines. She surveyed pipeline professionals to create the decision support system. Based on identified risk factors, a hierarchical risk model was developed. The hierarchy has four levels: 1) overall goal of the problem, 2) the factors, 3) sub factors, and 4) alternatives. The method of relative weights was used to rank the project delivery method from the most appropriate to the least appropriate method (Covilakam, 2011).

For trenchless technologies, Hasan (2010) developed a decision support system to evaluate project delivery methods for trenchless construction methods. The DSS user is asked to respond to a range of questions spread over various factor areas with a ranking from 0 to 3, where the 0 means that the scenario stated in the question is not applicable to the project; 1 means that the probability of the scenario is not very likely to occur; 2 means the probability of the scenario occurring is in the medium range; and 3 means that there is a high likelihood that the given scenario will occur in the project. The score of each of the factor areas is then totaled and converted into a percentage so that it can be evaluated on a common basis. The factor areas are assigned relative weights. The percentage score for each factor area is then multiplied by the relative weight of that area ending up with a score for that project delivery method in that particular factor area. The score of each project delivery method is then totaled for all the factor areas. The final scores of the delivery method determine which method is most suitable for the project based on the input project characteristics (Hasan, 2010).

Also for trenchless technologies, a software tool called The Trenchless Assessment Guide (TAG) was developed to assist in the selection of a trenchless technology method. The Web-based tool TAG-R, which is a comprehensive, fully automated decision support system for assessing the suitability of nearly 70 construction methods, used for the installation and rehabilitation of municipal water, wastewater, and drainage distribution and collection systems. The core of the TAG-R decision support system is an extensive method database that contains detailed information for each technology, most of which are trenchless in nature. The methods are divided into categories, each housed in a separate database, namely: gravity sanitary/storm/combined) sewers; pressure (potable/non-potable) water pipes; sewer laterals and connection seals; and manholes (Matthews & Allouche, 2011).

Jain (2010) developed a decision support system to evaluate trenchless renewal methods for potable water distribution pipes. The decision support system follows the hierarchical structure with the most serious pipe problems being addressed. It provides a cost breakdown for each trenchless renewal method, and life cycle costs of the project are determined by considering operation and maintenance costs (Jain, 2010).

Abraham et. al. (2002) developed a decision support system for trenchless construction methods to assist decision makers in selecting a specific trenchless construction method. The DSS entitled Selection and Evaluation of Trenchless Technologies has six main criteria to identify the decision-making, regarding the use of trenchless technology. First, the criteria were identified, which are: 1) site conditions, 2) diameter of pipe, 3) depth of installation, 4) drive length, 5) soil conditions, and 6) typical applications. Then, the framework for decision making using the identified criteria was established. Based on user's input, the SETT tool will facilitate the decision making process and output the recommended trenchless construction method or methods to use (Abraham, et al, 2002).

The selection of an appropriate method for developing a decision support system is not an easy task and depends on decision matrix, as well as on the objectives of the decision makers (Fülöp, 2012). The DSS developed as part of this research, uses decision tables in linear framework and makes recommendations.

2.8 Chapter Summary

This chapter reviewed the existing literature on different types of TCMs and soil types. Minimum shaft size requirements from different TCM manufacturers were presented. Additionally it described different shaft construction methods, and a brief description of decision support systems.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discusses the methodology for developing the decision support system (DSS) for this research. The DSS helps select sizing and a shaft construction method for different trenchless construction methods (TCM). To help develop this DSS, Chapter 2 presented a background and literature review on shaft design and construction. To help verify the DSS's results, a survey questionnaire was developed on shaft construction methods and sent out to multiple trenchless contractors. Survey results are presented in chapter 4.

3.2 Survey Questionnaire

The survey questionnaire was sent out to a list of contractors from the Trenchless Technology 2011-2012 No-Dig Directory (Krzys, 2011). The survey targeted contractors that completed trenchless construction projects in the United States. The survey included a PDF file that could be downloaded to the contractor's computer, answered and emailed back. The main goal from this survey was to gather information from different contractors on the type of wall support systems used for the entry shaft construction based on their trenchless construction project.

The survey was made up of 18 questions. Appendix A presents the survey cover letter, questions, and instruction pages. The survey allowed contractors to choose one of the TCMs that require shafts; then asked several questions about the project overview, site conditions, entry shaft size, and the type of wall support system used. The survey was used to understand the different methods used for trenchless construction and act as a reality check for the decision support system developed bases on the literature search.

3.3 Development of the DSS

One of the main objectives of this research was to create a DSS that will select the applicable shaft construction method. The DSS system can be used by owners, contractors or any decision maker during the preliminary planning and budgeting stages of a trenchless construction project. The entire program consists of five stages: gathering project information, determining type of TCM, recording pipe information, recording soil conditions, and developing a project summary. To simplify the results, the DSS outputs only temporary shaft construction methods which include sloping, horizontal metal sheeting, 2-flange steel liner plates, trench boxes, slide railing, sheet piles, soldier piles with timber laggings, soldier piles with metal laggings, CMP shafts, concrete sinking shafts, and ground freezing.

3.3.1 Decision Making Criteria

There are three primary criteria that affect decision making for the results in this DSS. These include: type of TCMs, pipe information, and soil conditions.

3.3.1.1 Type of TCMs

As said in Chapter 2, all TCMs require an entry shaft and an exit shaft except for the horizontal directional drilling method. In this research, the focus was only on entry shaft construction methods for pipe jacking (PJ), horizontal auger boring (HAB), microtunneling (MTBM), pipe ramming (PR), and pilot tube microtunneling (PTMT). Choosing a specific TCM depends on each project pipe diameter, pipe type, maximum installation, pipe material, type of application, level of accuracy.

3.3.1.2 Pipe Information

Pipe information includes project depth, project length, pipe size, and pipe segment length. Depending on the pipe's information, the DSS determines the shaft's dimensions and refines the wall support system selections. Depending on the depth installation, the DSS determines if a wall support system is required, and outputs the applicable types of wall support systems. From the OSHA safety rules and regulations guidelines, excavations more than 5 ft deep require a wall support system for the safety of the workers, and as said earlier, any excavation deeper than 20 ft requires a licensed structural engineer's stamped drawings for approval. The same applies to entry shafts, and a wall support system is required until the project ends. For depths less than or equal to 5 ft, no wall support systems are required; however, the contractor should be aware that in some very loose sands and gravels and soft clays, a wall support system might be required.

As a summary of information presented in Chapter 2, there are many wall support systems that exist for different depths: 2-Flange steel liner plates can reach depths up to 13 ft, and horizontal metal sheeting can reach 16 ft (Stein, 2005). Sloping is used for depths ranging up to 20 ft (OSHA, 1999). Trench boxes can be installed up to 30 ft (Chung et al, 2004) and slide railing systems (Turner, 2008) can also be installed at that depth. Sheet piles can reach depths up to 60 ft (Stein, 2005), and soldier piles up to 50 ft (Chung et al, 2004). Corrugated metal pipe (CMP) shafts can reach depths up to 79 ft, sinking concrete shafts can achieve depth around 131 ft, and ground freezing method's depth can range up to 656 ft (Stein, 2005). Entering the projects depth, helps select the applicable wall support system within their depth ranges. A summary table showing the different wall support systems and depths ranges presented in Table 3.1.

The project length, pipe size, and pipe segment length determines the dimensions of the shaft. Based on the TCM selected, Tables 3.2 - 3.5 provide footprint (width and length) of the shaft. The DSS uses Table 3.2 for pipe jacking, Table 3.3 for horizontal auger boring, Table 3.4 for microtunneling, Table 3.5 for pipe ramming, and Table 3.6 for pilot tube microtunneling.

Table 3.1: Wall Support Systems Depth Ranges

Type of System	**Depth Ranges**
2-Flange Steel Liner	Up to 13 ft
Horizontal Metal Sheeting	Up to 16 ft
Sloping	Up to 20 ft
Trench Boxes	Up to 30 ft
Slide Railing System	Up to 40 ft
Soldier Piles with Timber Lagging	Up to 50 ft
Soldier Piles with Steel Lagging	Up to 50 ft
Sheet Piles	Up to 60 ft
CMP Shafts	Up to 79 ft
Concrete Sinking Shafts	Up to 131 ft
Ground Freezing	Up to 656 ft

Table 3.2: Pipe Jacking Shaft Dimensions

Method	**Pipe Size in.**	**Project Length ft**	**Pipe Segment ft**	**Circular Shaft Diameter ft**	**Entry Shaft Width ft**	**Entry Shaft Length ft**
Pipe Jacking (www.herrenknecht .com)	48 - 64	800	10	28	12	26
	64 - 72	1,000	10	28	12	26
	72 - 80	1,000	10	30	13	28
	48 - 64	1,600	10	28	12	26
	60 - 72	2,500	10	28	12	26
	64 - 80	3,000	10	30	13	28

Table 3.3: Horizontal Auger Boring Shaft Dimensions

Method	Pipe Size in.	Project Length ft	Pipe Segment ft	Entry Shaft Width ft	Entry Shaft Length ft
Horizontal Auger Boring (http://www.americanaugers.com)	24 – 30	N/A	20	10	34
	36 - 42	N/A	20	12	34
	48 - 60	N/A	20	12	36
	60 - 72	N/A	20	15	40

Table 3.4: Microtunneling Boring Machines Shaft Dimensions

Method	Pipe Size in.	Pipe Segment ft	Semi-circular Shaft Length ft	Entry Shaft Width ft	Rectangular Shaft Length ft
Microtunneling Boring Machines (Stein, 2005)	28 -36	10	18	9	18
	36 - 48	10	21	10	21
	54 - 65	10	23	11	24
	72 - 88	10	26	13	25

Table 3.5: Pipe Ramming Dimensions

Method	Pipe Size in.	Project Length ft	Machine Diameter in.	Machine Length ft	Pipe Segment ft	Entry Shaft Width ft	Entry Shaft Length ft
Pipe Ramming (http://www.terra-eu.com)	8 - 16	100	8	6	10	7	16
	8 - 24	195	9	6	10	7	16
	24 - 40	230	14	6	10	8	16
	40 - 80	325	26	8	10	9	18

Table 3.6: Pilot Tube Microtunneling Dimensions

Information Source	Pipe Size in.	Project Length ft	Pipe Segment ft	Circular Shaft Diameter ft	Entry Shaft Width ft	Entry Shaft Length ft
Pilot Tube Microtunneling (http://www.nodigequipment.com),	6 - 8	65	N/A	7	3	7
	6 - 12	200	N/A	8	5	8
	12 - 30	200	N/A	8	5	8

Above tables may include pipe segment lengths for 10- or 20-ft. The DSS system will add or subtract the correct pipe segment length to the shaft's length for the correct dimensions. Pilot tubes are made of small pipe sections (such as 3 ft) so they can be accommodated in smaller shafts (Najafi, 2010).

3.3.1.3 Soil Conditions

After determining the pipe's installation depths, detailed information on soil conditions and groundwater levels are important to determine the type of shaft construction method. A geotechnical report is recommended for 5-ft shafts and deeper. The soil conditions selection in the decision support system are based on the types of soils in Table 2.8

Two-Flange steel liner plates are suited for stable soils but are not water tight (Stein, 2005). Sloping can be done in any type of soils unless the shaft is within groundwater levels. Table 3.7 helps determine OSHA slope requirements for different soil conditions. Metal horizontal sheeting is generally suited for unstable soils like loosely compacted non-cohesive or soft cohesive soils free of groundwater. Trench boxes can be used for almost all kinds of soils and are water tight systems (Stein, 2005). Slide railing can be used for most soil conditions, but is not a water tight system. Sheet piles can handle all types of soils, but cannot be installed in dense sand and hard clay, because the installation procedure will damage the sheets (Smith & Andres, 1993). Soldier piles are used for almost all cohesive and non-cohesive soils depending on the type of lagging (Chung et al, 2004). Concrete sinking shafts are used for any type of soils and are water tight systems (Chung et al, 2004). Ground freezing walls are created in unstable soils that are saturated with groundwater (Stein, 2005).

Table 3.7: Slope Requirements for OSHA Soil Types

Type of Soil	**Soil Description**	**OSHA Slope Requirements**
Sand	Loose	1½:1
	Medium	1:1
	Dense	1:1
Clay	Soft	1½:1
	Firm	1:1
	Hard	¾:1
Boulders	Less than 2 - 4 in	1½:1
	Larger than 4 - 6 in	1½:1
Rock	Unweathered	¾:1
	Weathered	Vertical Walls

The groundwater level determines the shaft construction methods that can be used. If the water level is below the excavation of the entry shaft depths, then the majority of the support systems are applicable. If the water level is within the excavations depths, then only the closed water tight shaft construction methods are used. This field input is important for the DSS's results; an error message will appear if not entered. Table 3.8 shows different types of support systems for various soils.

Table 3.8: Applicability of Shaft Construction Methods for Different Soil Conditions

Type of System	**Sand Loose**	**Sand Medium**	**Sand Dense**	**Clay Soft**	**Clay Medium**	**Clay Hard**	**Rock**	**Water Tight**
2-Flange Steel Liner	N	N	Y	Y	Y	Y	Y	N
Horizontal Metal Sheeting	N	Y	Y	Y	Y	Y	Y	N
Sloping	Y	Y	Y	Y	Y	Y	Y	N
Trench Boxes	Y	Y	Y	Y	Y	Y	Y	Y
Slide Railing System	Y	Y	Y	Y	Y	Y	Y	N
Sheet Piles	Y	Y	Y	Y	N	N	N	Y
Soldier Piles with Timber Lagging	Y	Y	Y	Y	Y	Y	Y	N
Soldier Piles with Steel Lagging	Y	Y	Y	Y	Y	Y	Y	Y
CMP Shaft	Y	Y	Y	Y	Y	Y	Y	Y
Concrete Sinking Shafts	Y	Y	Y	Y	Y	Y	Y	Y
Ground Freezing	Y	Y	Y	Y	Y	Y	Y	Y

3.3.1.4 Conceptual Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP), developed by Thomas Saaty (Saaty, 1980), addresses how to determine the relative importance of a set of activities in a multi-criteria decision problem. The process makes it possible to incorporate judgments on intangible qualitative criteria alongside tangible quantitative criteria. The main goal for this decision support system is to output the shaft size and construction method. Depending on the depth and soil conditions, some situations output multiple construction methods with no preference or best choice.

The decision support system using conceptual analytic hierarchy process has four levels: 1) the problem goal, 2) factors 3) sub factors, and 4) alternatives. The method of relative weights is used to rank the different shaft construction methods from the most appropriate to the least appropriate. There are two main factors to determine the final goal, shaft size, and shaft construction method. The shaft size includes three main sub factors, project length, pipe size, and pipe segment length. The shaft construction method also includes three sub factors, pipe depth, soil conditions, and ground water levels. There are 10 shaft construction method alternatives, 2-flange steel liner, horizontal metal sheeting, sloping, trench boxes, slide railing system, soldier piles with timber lagging, soldier piles with steel lagging, sheet piles, CMP shafts, concrete sinking shafts, and ground freezing. These methods were described in chapter 2. Figure 3.1 illustrates the conceptual analytical hierarchy process model.

After the hierarchy for the DSS is constructed, a set of pairwise comparison matrices are developed based on a scale suggested by Saaty (1980). Each element in an upper level is used to compare the elements in the level immediately below. In the AHP, multiple pairwise comparisons are based on a standardized comparison scale of nine points. In each level, the criteria are compared pairwise according to their levels of influence and based on the specified criteria in the higher level. Table 3.9 shows the comparison scale.

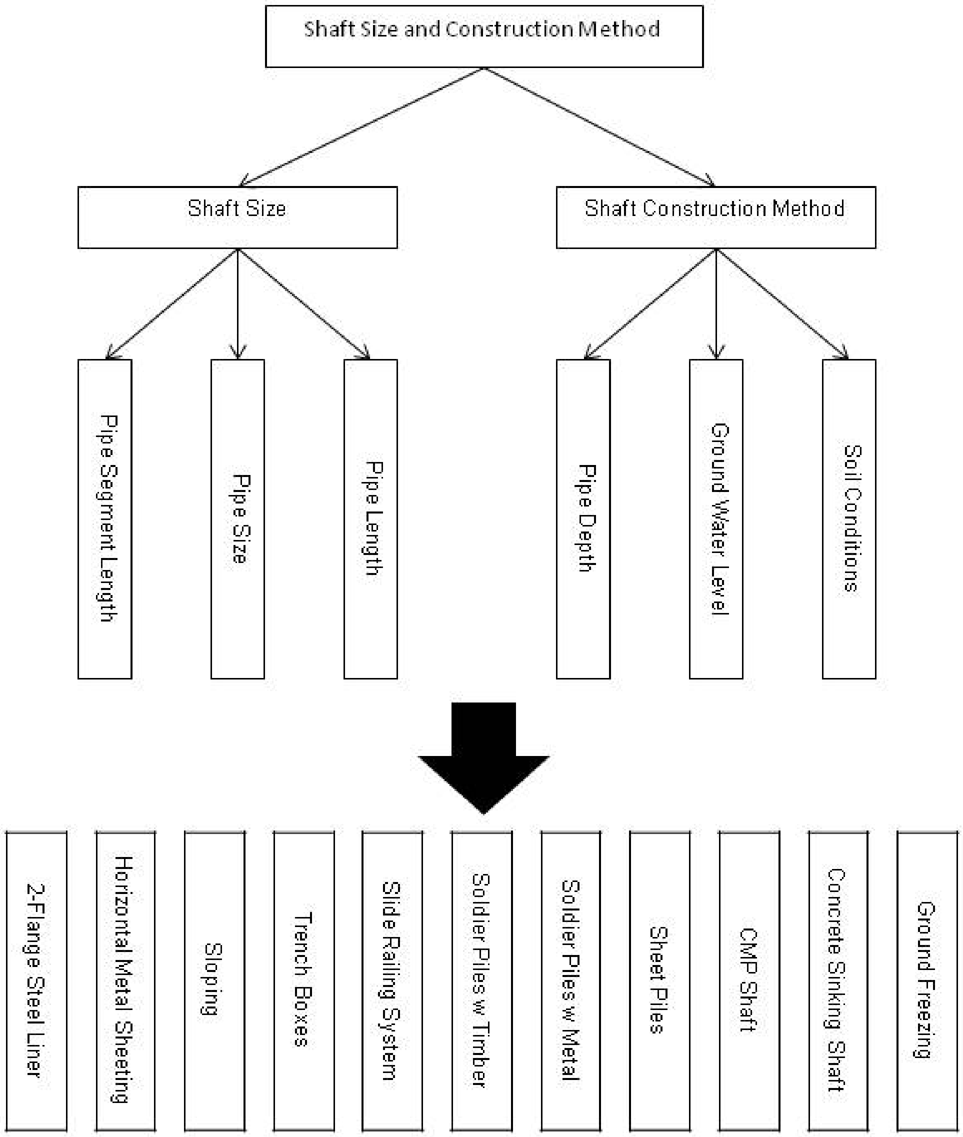


Figure 3.1: Conceptual Analytical Hierarchy Process

Table 3.9 Scale of Relative Importance for Pair-wise Comparison (Saaty, 1980)

Intensity	Definition	Explanation
1	Equal importance	Two activities contribute equally to the object
3	Moderate importance	Slightly favors one over another
5	Essential or strong importance	Strongly favors one over another
7	Demonstrated importance	Dominance of the demonstrated in practice
9	Extreme importance	Evidence favoring one over another of highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed

After judging which parameter is preferred over the other, a matrix is formed. Then to calculate the resultant weights, the weights of the factors and sub-factors are calculated. The next step is to extract the relative importance implied by the previous comparisons. Given a judgment matrix with pairwise comparisons, the corresponding maximum eigenvector is approximated by normalizing the elements in each column of the matrix and then averaging over each row. Each element in the column is divided by the sum of the elements in the column (Covilakam, 2011).

In the AHP, the pairwise comparisons in a judgment matrix are considered to be adequately consistent if the corresponding consistency ratio (CR) is less than 10% (Saaty, 1980). The CR coefficient is calculated as follows. The first step is to estimate the consistency index (CI). This is done by adding the columns in the judgment matrix and multiply the resulting vector by the vector of priorities (i.e., the approximated eigenvector) obtained earlier. This yields an approximation of the maximum eigenvalue, denoted by λ_{max}. Then, the CI value is calculated by using the formula: CI = (λ_{max} - n)/ (n - 1). Next the consistency ratio CR is obtained by dividing the CI value by the Random Consistency index (RCI). The resultant weight for the sub-factors is a product of weights of factor and weight of sub-factors (Covilakam, 2011). Survey questionnaire recipients must be selected carefully based on their knowledge and working experience. According to the respondents' number of years of experience, a weight is assigned to each response to reflect the level of experience for each shaft construction method (Hegab, 2010).

The conceptual model in this research included only a brief description of the analytical hierarchy process and developed the hierarchy decision structure framework. It does not address calculating the relative weights and constructing a pairwise table for rankings. It is however, recognized that a more extensive survey is needed to develop this method for this specific application.

3.3.2 DSS Flow Diagram

Figures 3.2 through 3.6 illustrate the DSS logic flow diagram for selection of an appropriate shaft size and construction method.

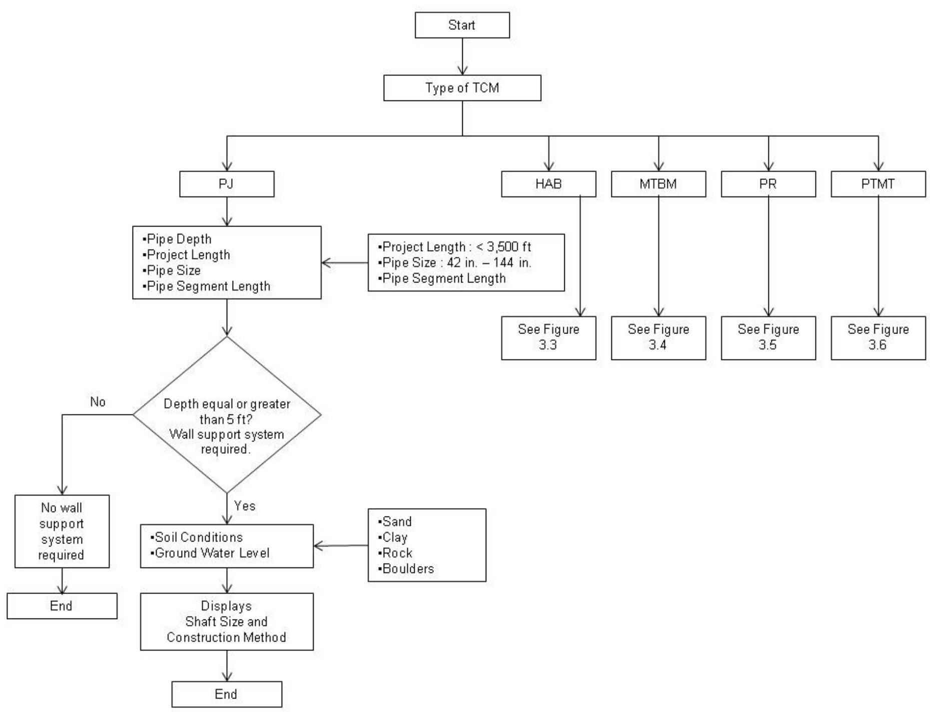


Figure 3.2: Flow Chart for Selection of Shaft Size and Construction Method for Pipe Jacking

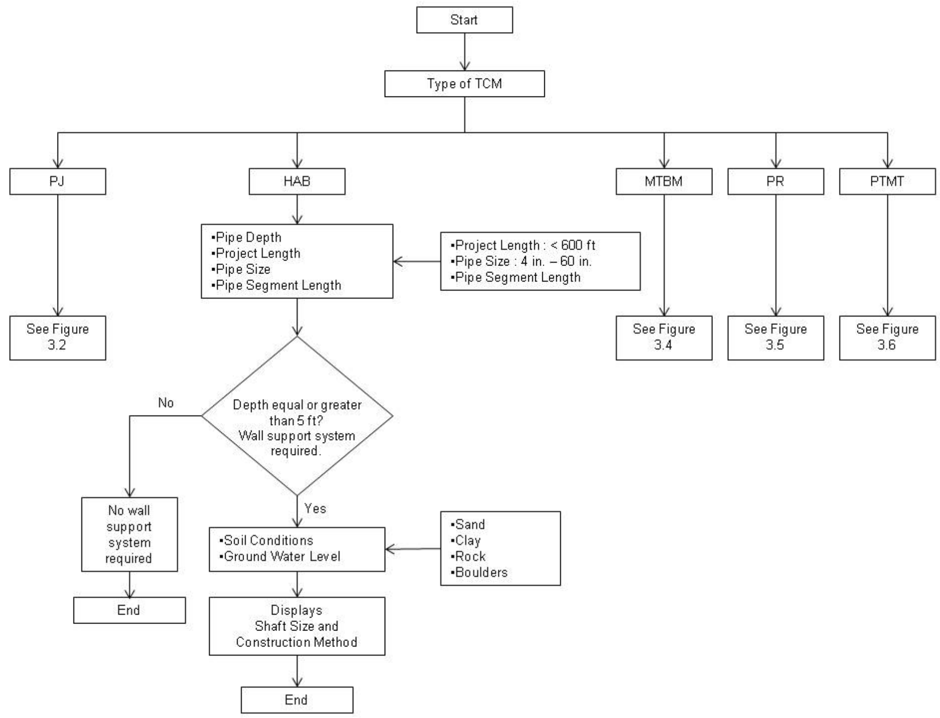


Figure 3.3: Flow Chart for Selection of Shaft Size and Construction Method for HAB

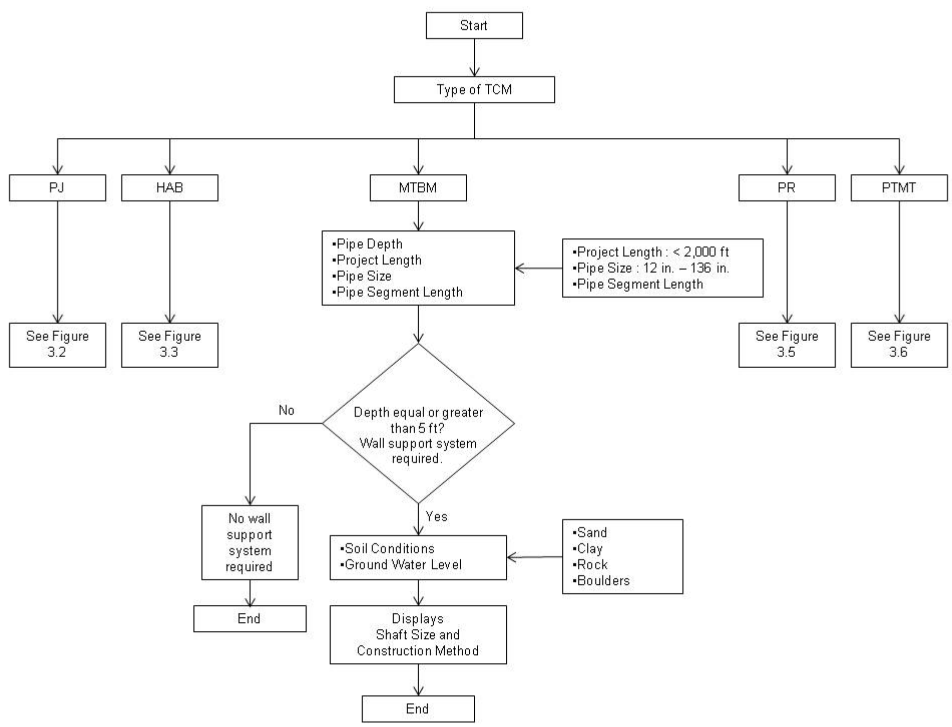


Figure 3.4: Flow Chart for Selection of Shaft Size and Construction Method for Microtunneling

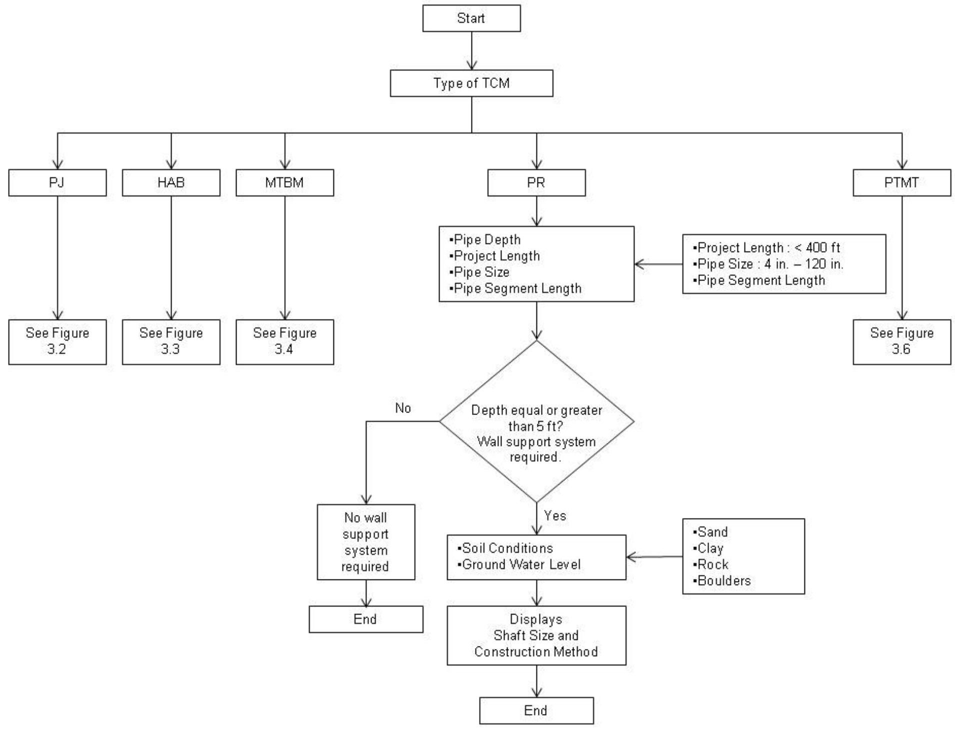


Figure 3.5: Flow Chart for Selection of Shaft Size and Construction Method for Pipe Ramming

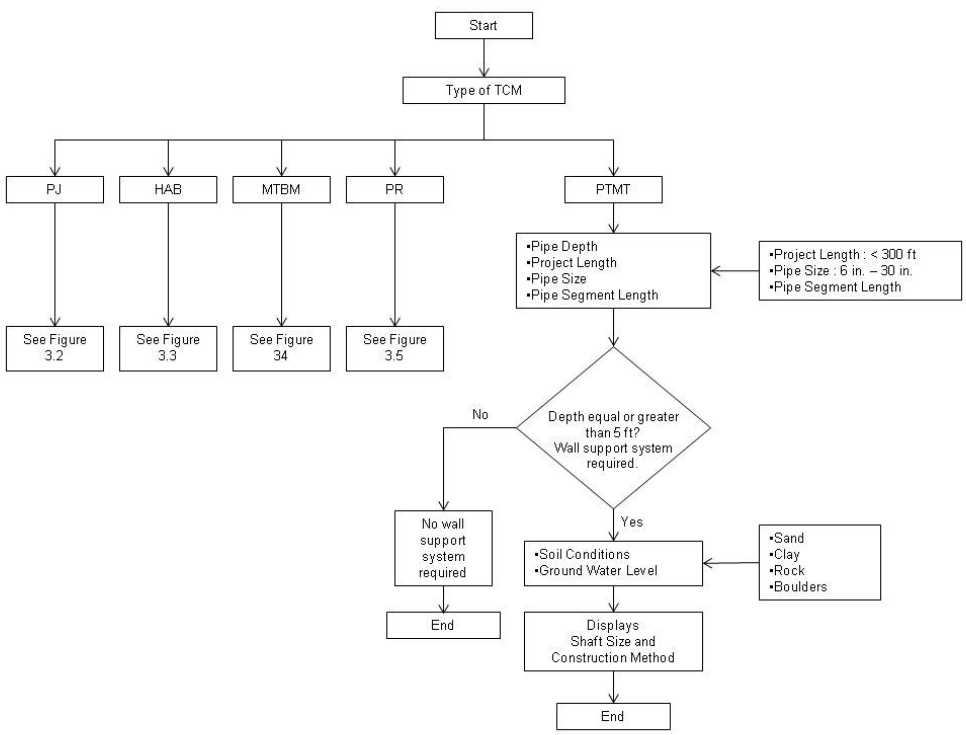


Figure 3.6: Flow Chart for Selection of Shaft Size and Construction Method for PTMT

3.3.3 DSS Tool

To create a user friendly Decision Support System (DSS), the results must be clear and realistic. By entering the project information, the system outputs the result. A spreadsheet tool using MS Excel entitled “Trenchless Technology Shaft Construction (TTSC),” was developed to assist in the decision making process.

The Excel worksheets allow users to select the data that applies to their project, and then the interactive worksheets use built in formulas and functions to create an accurate output result in the summary sheet.

3.3.3.1 Project information

Once the user runs the TTSC file, the first worksheet tab is the project information sheet and it will appear as shown in Figure 3.7.

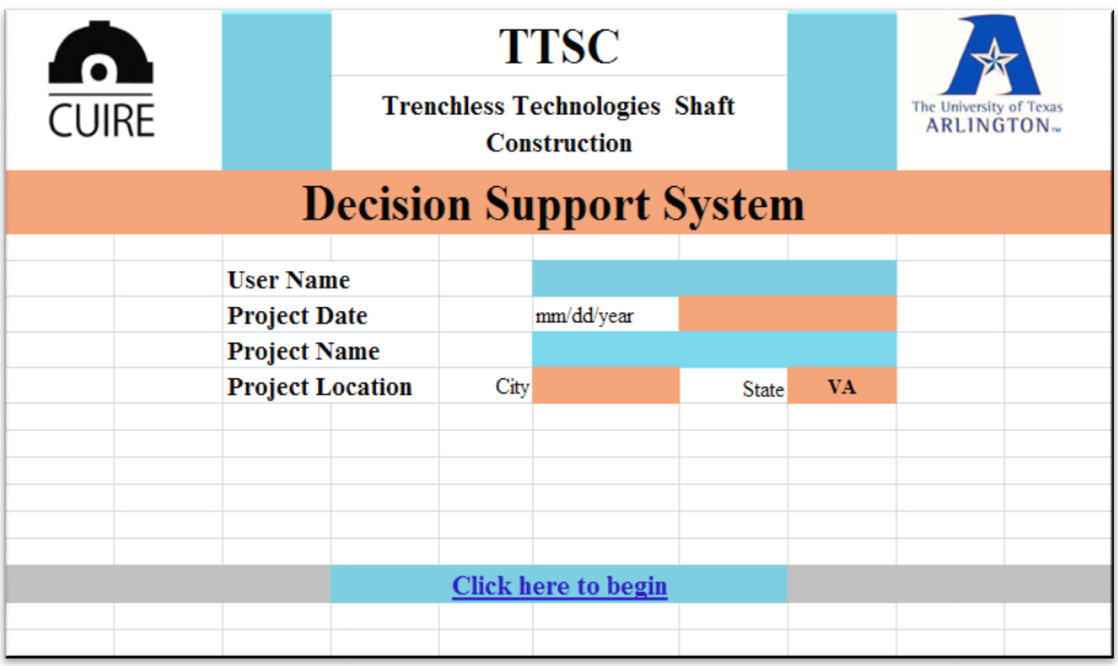


Figure 3.7: DSS Project Information Page

The first data entry will be the project’s information. The user is required to insert his other name, the date, the project’s name, and the projects location. This information is not mandatory but beneficial when the file is saved for historical data. Then after entering all the data on this worksheet tab, the user can click the “Click here to begin” button to continue to the next worksheet tab.

3.3.3.2 Type of Trenchless Construction Method (TCM)

The second set of data needed, is the type of TCM used for the project. The worksheet will show four TCM types; 1) PJ, 2) HAB, 3) MTBM, 4) PR, and 5) PTMT. The drop down menu will allow the user to choose one of those TCM. Then to continue with the process the user can click the “Next” button to continue with the evaluation and move to the next worksheet tab, or click the “Back” button to go back and alter or modify the data input. Figure 3.8 illustrates the different TCM selections for the DSS.

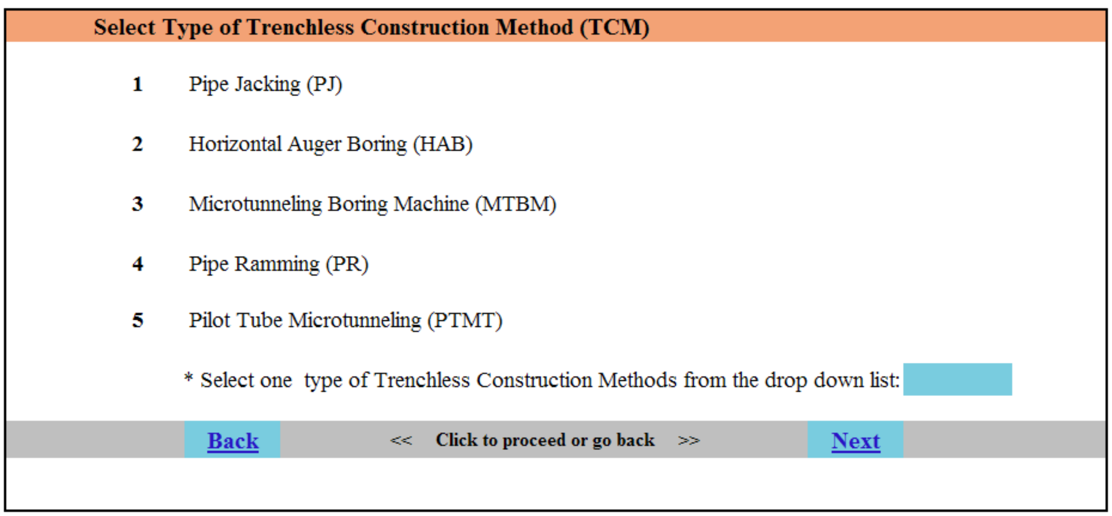


Figure 3.8: DSS Type of TCM Page

3.3.3.3 Pipe Information

The third worksheet tab requires the input of pipe data information for the project. The user will insert the project’s depth, project’s length, pipe size, and pipe segment length. When inserting the data into the box, a pop up box will appear and display the minimum and maximum data that can be entered. This information is mandatory and will not allow the user to continue unless completed. Inserting the correct information for the project is necessary to output the correct results. Figure 3.9 illustrates the layout of the pipe information sheet.

Inserting the project's depth in feet (ft) will determine if a wall support system is required and which types of wall support systems are applicable at the depth range chosen. To determine the length of the entry shaft, the user will have to input the project's length in feet (ft), and the pipe segment length in feet (ft). To determine the width of the entry shaft the user will have to input the pipe diameter size in inches (in). Depending on the type of TCM used a correction adjustment can be made as factors are added to the length and width of the pipe segment to calculate the correct size of the entry shaft.

Pipe Information				
1	Project Depth	Insert the pipe depth for the project	**0**	**Feet (ft)**
2	Project Legnth	Insert the pipe length for the project	**0**	**Feet (ft)**
3	Pipe Size	Insert the pipe size	**0**	**Inch (in)**
4	Pipe Segment Length	Choose the pipe segment length from the drop down list	**10**	**Feet (ft)**
	Back	**<< Click to proceed or go back >>**	**Next**	

Figure 3.9: DSS Pipe Information Page

3.3.3.4 Soil Conditions

The fourth worksheet tab requires the user to input information about the existing soil conditions. After entering the required depth for the project, the DSS will choose the applicable wall support system or systems that can be used and eliminate the rest of the systems. Then, after entering the soil conditions at the project site, the DSS will select the applicable wall support system or systems for the final result. Knowing the groundwater level is very important for the DSS to choose the correct wall support system. The DSS will compare between the project pipe depth input and the groundwater level depth input data, to decide whether a water tight system is needed or not at the entry shaft. Figure 3.10 shows the DSS soil condition page.

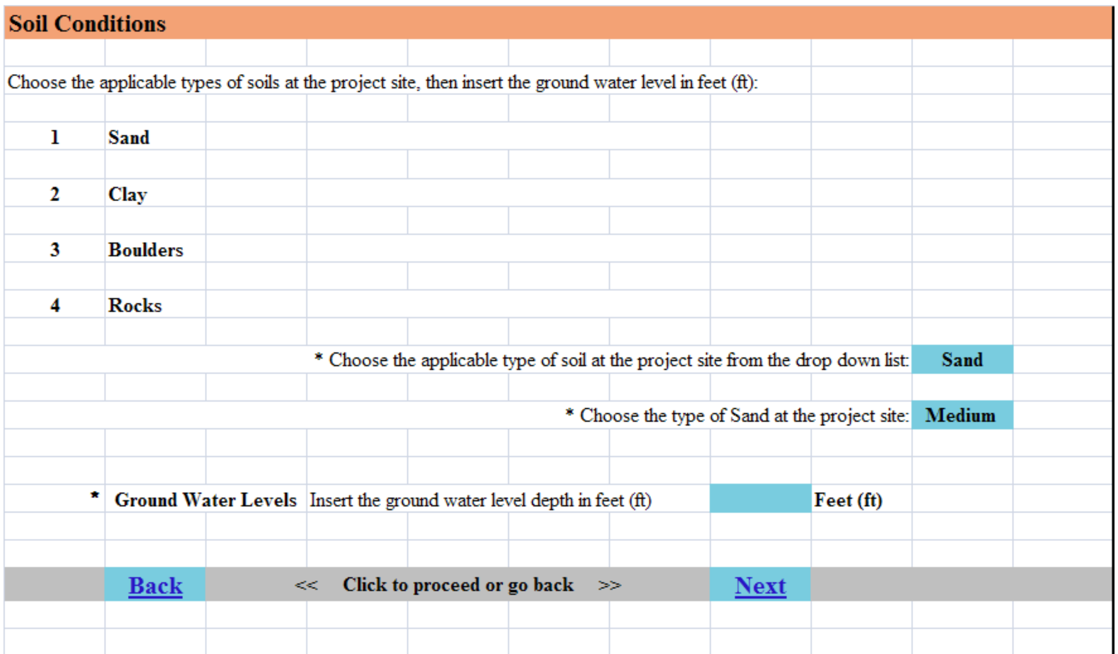
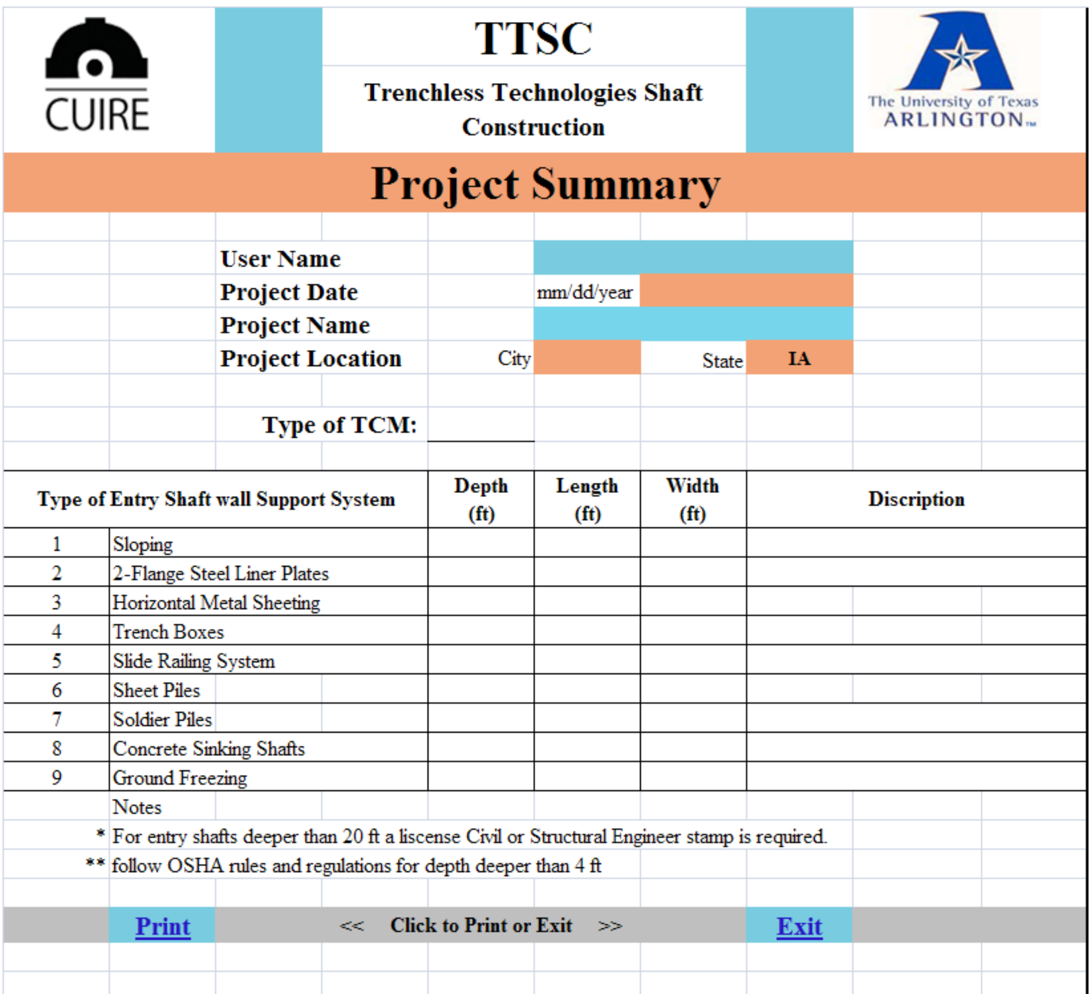


Figure 3.10: DSS Soil Condition Page

3.3.3.5 Project Summary

Project summary is the final worksheet tab for the DSS. After entering all the data into the previous worksheets, the DSS evaluates the project's data and outputs the results. The project summary page as shown in Figure 3.11, lists the project information, the type of wall support system or systems that can be used, and the dimension of the entry shaft. If there are possible concerns that need to be addressed, an asterisk will appear at the bottom of the page with the message. For an example if the depth of the installation pipe is deeper than 20 ft, an asterisk will appear with a message stating that the entry shaft is deeper than 20 ft and requires a licensed structural engineer's stamped approval for construction. After reviewing the results, the user can click the "Print" button to print out the summary page, or the "Exit" button to exit the DSS tool. Since the DSS user interface is created and operated in MS Excel, the user can manipulate the DSS using Excel's tool bars and functions.



CUIRE

TTSC

Trenchless Technologies Shaft Construction

The University of Texas ARLINGTON

Project Summary

User Name

Project Date mm/dd/year

Project Name

Project Location City State **IA**

Type of TCM:

Type of Entry Shaft wall Support System		**Depth (ft)**	**Length (ft)**	**Width (ft)**	**Discription**
1	Sloping				
2	2-Flange Steel Liner Plates				
3	Horizontal Metal Sheeting				
4	Trench Boxes				
5	Slide Railing System				
6	Sheet Piles				
7	Soldier Piles				
8	Concrete Sinking Shafts				
9	Ground Freezing				

Notes

* For entry shafts deeper than 20 ft a liscense Civil or Structural Engineer stamp is required.

** follow OSHA rules and regulations for depth deeper than 4 ft

Print << **Click to Print or Exit** >> **Exit**

Figure 3.11: DSS Project Summary Page

3.4 Chapter Summary

This chapter discussed the methodology and creation of the decision support system (DSS), which is one of the primary outcomes for this research. The DSS was created from the literature reviewed in chapter 2. The following chapter presents the survey results and two case studies to validate the developed DSS.

CHAPTER 4

RESEARCH RESULTS

4.1 Introduction

This chapter presents the survey results. These results are categorized into two areas, the results obtained from the survey analysis, the results obtained from manufacturer, and a case study to validate the DSS.

4.2 Analysis of Survey Results

The survey respondents were spread out over nine states in the United State, as shown in Figure 4.1.

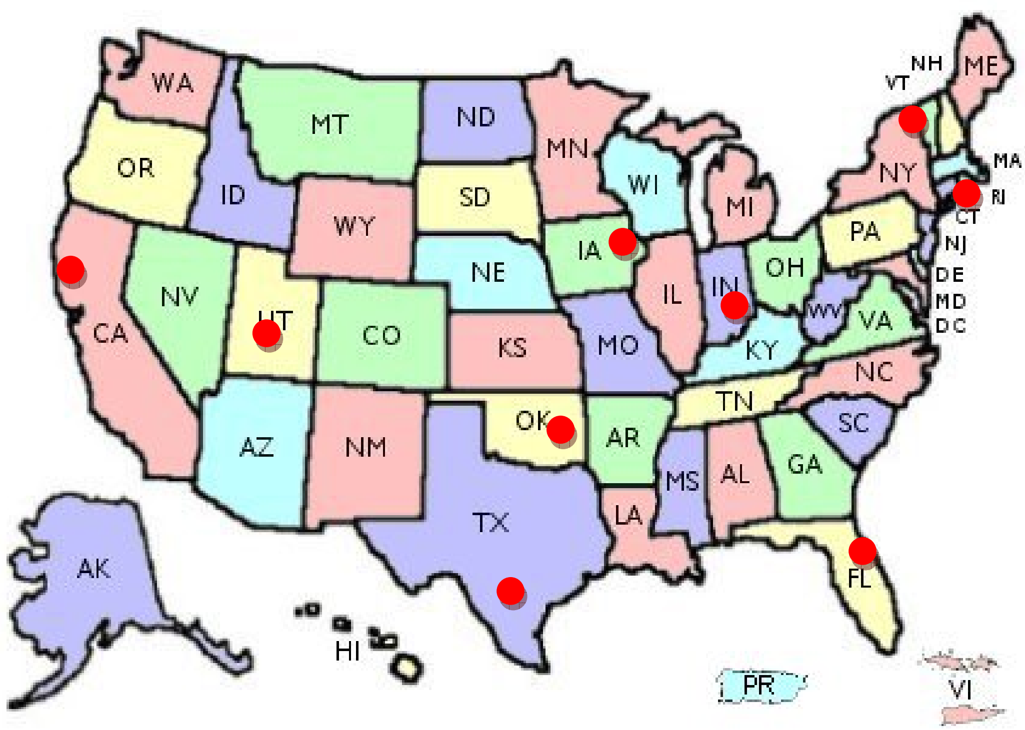


Figure 4.1: Map of the United States Showing the Areas of Survey Response

The survey respondents belonged to various areas of the trenchless construction industry. Out of the 60 companies that were asked to participate, only 10 completed the survey. This is a 17% response rate. One reason for the low outcome may have been that industry professionals may have some concerns commenting on excavation safety due to possible liability issues.

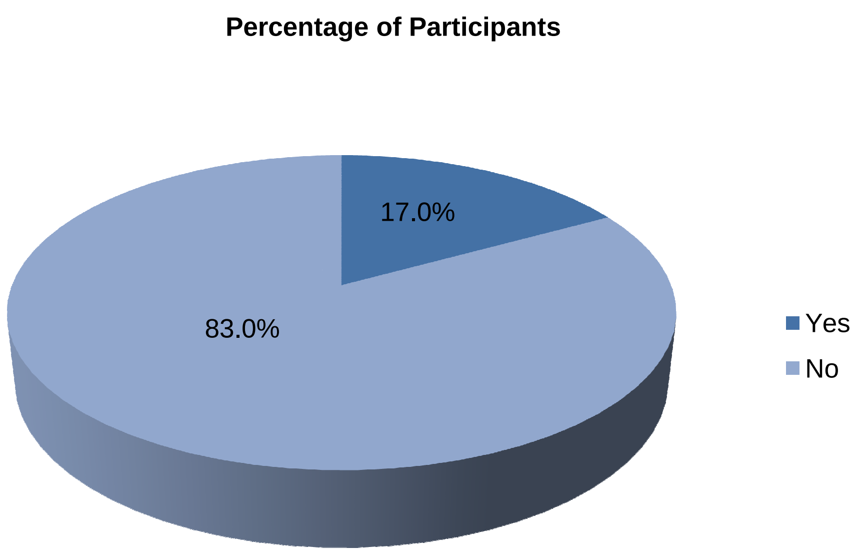


Figure 4.2: Percentage of Participants

Some trenchless companies specialized in one or more trenchless construction methods. Out of the 10 survey participants, their projects included five pipe jacking jobs, three pipe ramming, one horizontal auger boring, and one microtunneling trenchless project. Each had different soil conditions with different wall support systems for their shaft construction. Table 4.1 summarizes the survey results.

Additional information on shaft construction methods were obtained by interviewing professionals working in trenchless related fields. Most of the interview respondents preferred sloping and inserting trench boxes because of cost, availability, and minimum skills required to complete the task. Some trenchless construction contractors are sub-contractors for a general contractor and they are not responsible for the shaft's construction.

Table 4.1: Survey Response Summary

Response	Project Type	Project Depth ft	Pipe Size in.	Pipe Segment Length ft	Soil Condition	Water table Depth ft	Shaft Size ft	Wall Support System
1	Pipe Jacking (PJ)	25	80	20	Clay, Medium	12 ft	14 X 45	Slide Railing System
2	Pipe Jacking (PJ)	35	58	20	Sand Loose	None	12 X 34	Sheet Piling
3	Pipe Jacking (PJ)	10	54	8	Sand Medium	None	12 x 26	Sheet Piling
4	Pipe Jacking (PJ)	12	36	10	Sand Medium	None	12 X 28	Sheet Piling
5	Pipe Jacking (PJ)	15	36	20	Soft Clay	None	10 X 30	Trench box
6	Horizontal Auger Boring (HAB)	10 ft	16	20	Clay, Medium	None	10 X 34	1.5 : 1 Sloped Walls
7	Micro-tunneling (MTBM)	50	72	10	Clay Dense	None	14 x 25	Soldier Pile with Timber Lagging
8	Pipe Ramming (PR)	10	42	10	Clay Dense	None	10 x 20	Vertical Walls
9	Pipe Ramming (PR)	10	32	20	Sand Medium	None	10 X 28	Vertical Sheeting
10	Pipe Ramming (PR)	20	20	20	Sand Medium	None	10 X 28	1.5 : 1 Slope Walls

4.3 DSS Validation

The survey provided valuable information on different trenchless construction projects, and provided the basis for a reality check for the Decision Support System (DSS). The results from the survey can be compared with the results from the DSS by entering the respondent's project information in the DSS.

4.3.1 DSS Validation 1: Heartland Drive Sanitary Sewer Line

This project uses a Horizontal Auger Boring machine to install a sewer line in Coralville, Iowa. Installing a 16-inch diameter, 20-ft pipe segments 10-ft deep, the project started March 1st 2012 and ended March 23rd 2012. The project's entire pipe length was 420 ft. The soil encountered was stiff clay. The shaft size was 10 ft wide by 34 ft long, and the construction method was 1.5 to 1 sloped walls.

The first stage of the DSS is entering the project information. The data on this sheet is not required, but recommended for project identification in the project summary sheet. The DSS stage is illustrated in Figure 4.3.

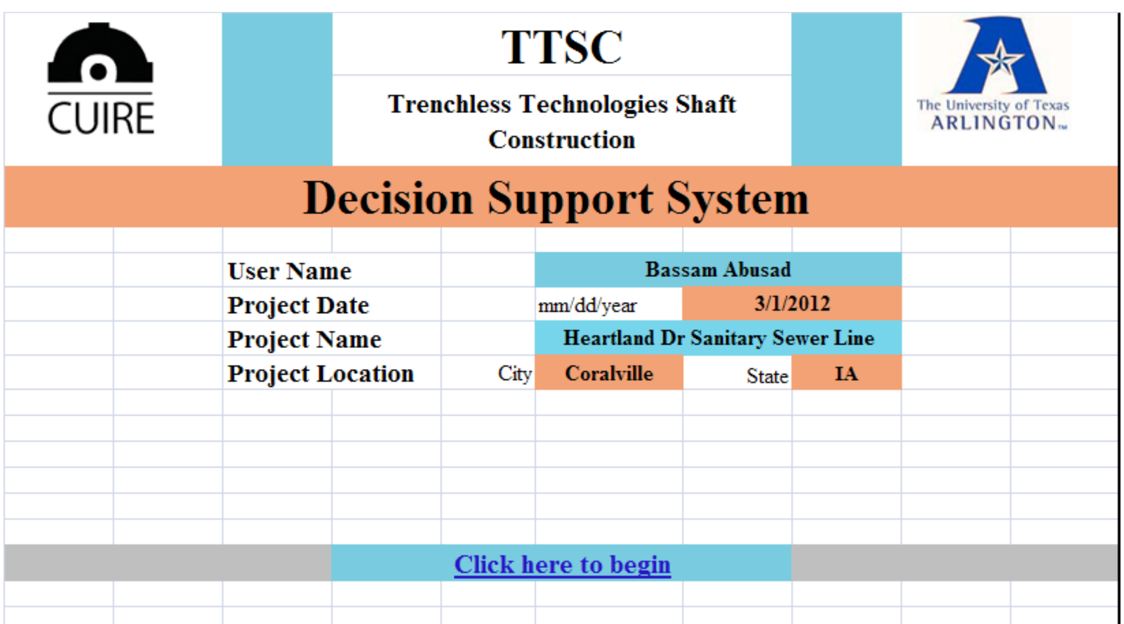


Figure 4.3: Validation # (1) Project Information

The second stage of the DSS is entering the type of Trenchless Construction Method (TCM) used for the project, from the drop down menu. Choosing a TCM is required for the DSS to continue with the evaluation. The DSS stage is illustrated in Figure 4.4.

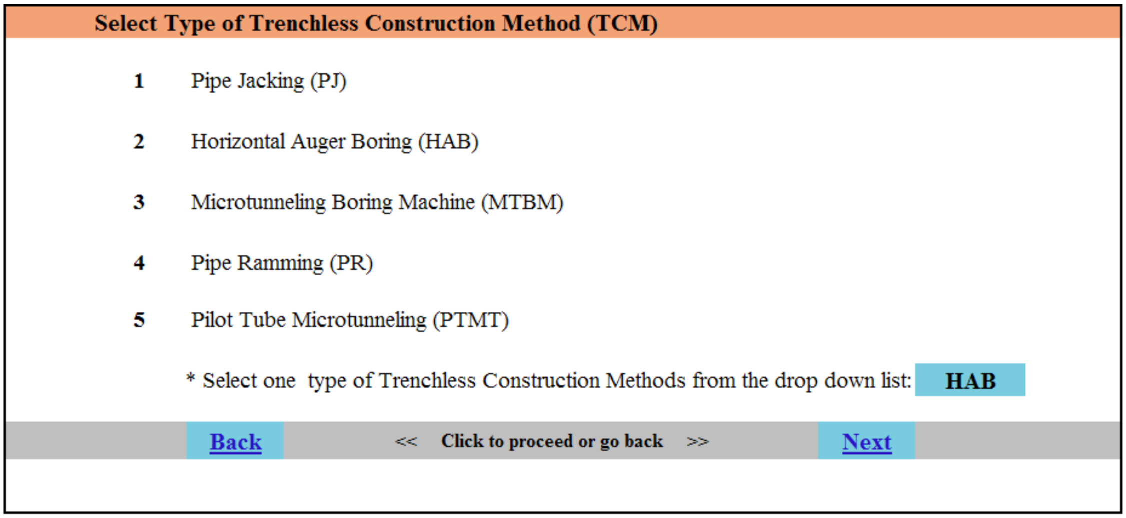


Figure 4.4: Validation # (1) Type of Trenchless Construction Method

The third stage of the DSS is entering the pipe information for the project. Since HAB was chosen as the TCM, when entering pipe information a pop up box will appear next to each field informing the user about the chosen TCM range. Data entry in every field of the pipe information sheet is required for the DSS to continue the evaluation. Since the projects depth is 10 ft, all of the wall support systems applicable at this stage. The pipe size entered was 16 inches, using 20 ft pipe segments, for a project length of 420 ft. From Table 3.3, for HAB the dimension for the entry shaft is 10 ft wide by 34 ft long. The shaft dimensions are presented in the project summary page. Figure 4.5 presents the data entry in the DSS.

The fourth stage of the DSS is entering the soil conditions for the project. The user must select the type of soil conditions from the drop down menu. Also the user must input the groundwater level depth if available. For sloping the DSS uses Table 3.6. For medium clay, the DSS will recommend a 1:1 slope. From Table 3.7 the DSS selects the rest of the wall support systems. For medium clay and no ground water, the only wall support system that is eliminated is sheet piling. The remaining systems will be listed in the project summary sheet. Figure 4.6 presents the soil condition data entry in the DSS.

The final stage of the DSS is the project summary page. After entering all the projects information, the DSS selects the applicable type of evaluation for the system results in the project summary page (see Figure 4.7). The DSS entry shaft dimensions are 10 ft x 32 ft with 1:1 slope as a shaft construction method. The actual entry shaft dimensions were 10 ft x 32 ft and used 1.5:1 slope. The DSS output was the minimum recommended dimensions and applicable types of wall support systems. It was the contractor's decision to alter the shaft construction methods and size the shaft.

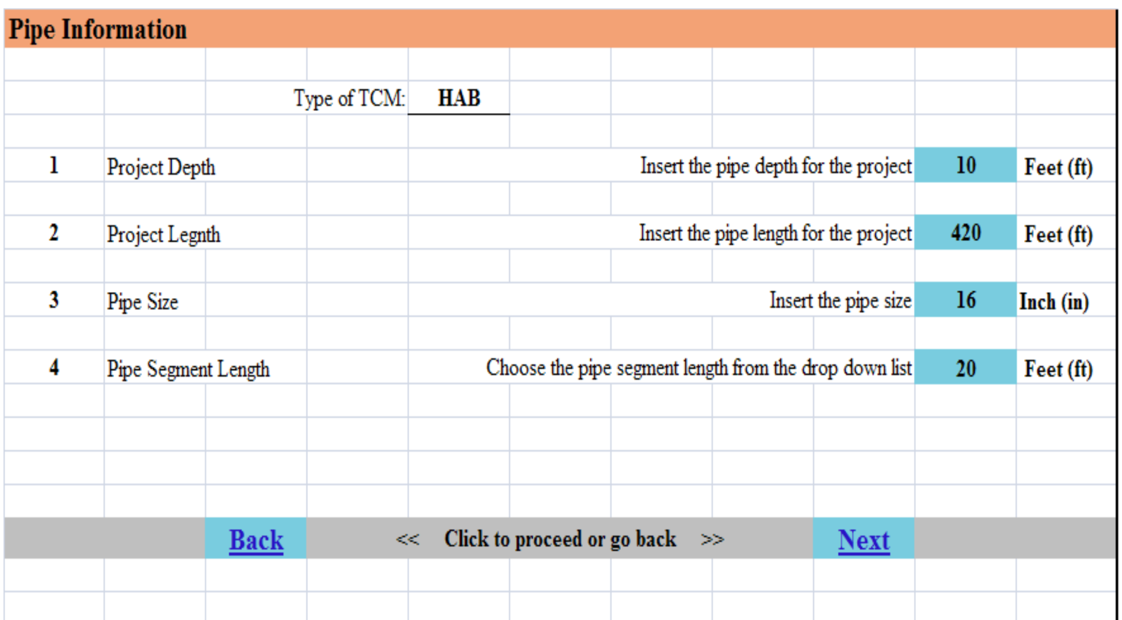


Figure 4.5: Validation # (1) Pipe Information

Soil Conditions

Choose the applicable types of soils at the project site, then insert the ground water level in feet (ft):

1	Sand
2	Clay
3	Boulders
4	Rocks

* Choose the applicable type of soil at the project site from the drop down list: **Clay**

* Choose the type of Clay at the project site: **Medium**

* **Ground Water Levels** Insert the ground water level depth in feet (ft) ____ **Feet (ft)**

Back << Click to proceed or go back >> **Next**

Figure 4.6: Validation # (1) Soil Conditions

CUIRE

TTSC

Trenchless Technologies Shaft Construction

The University of Texas ARLINGTON

Project Summary

User Name		**Bassam Abusasd**
Project Date	mm/dd/year	**3/1/2012**
Project Name		**Heartland Dr Sanitary Sewer Line**
Project Location	City **Coralville**	State **IA**

Type of TCM: **HAB**

Type of Entry Shaft wall Support System		**Depth (ft)**	**Length (ft)**	**Width (ft)**	**Discription**
1	Sloping	10	32	12	1:1 slope
2	2-Flange Steel Liner Plates	10	32	12	
3	Horizontal Metal Sheeting	10	32	12	
4	Trench Boxes	10	32	12	
5	Slide Railing System	10	32	12	
6	Soldier Piles	10	32	12	
7	Concrete Sinking Shafts	10	32	12	
8	Ground Freezing	10	32	12	

Notes

* For entry shafts deeper than 20 ft a liscense Civil or Structural Engineer stamp is required.

** follow OSHA rules and regulations for depth deeper than 4 ft

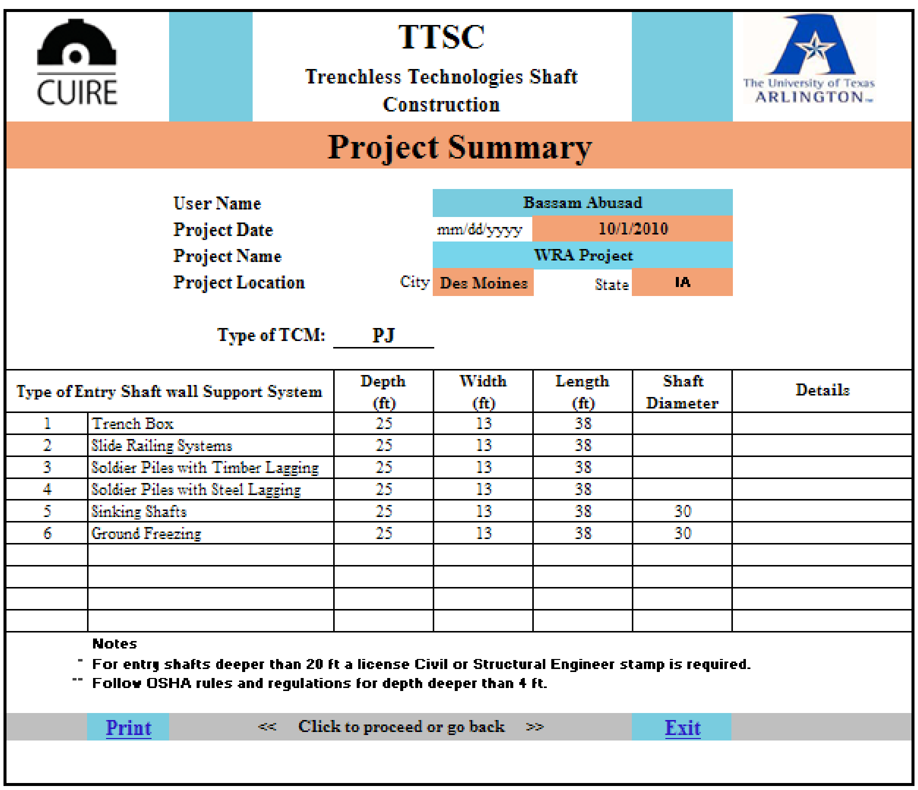
Print << Click to Print or Exit >> **Exit**

Figure 4.7: Validation # (1) Project Summary

4.3.2 DSS Validation 2: WRA Project

The project used a pipe jacking machine to install a pipe line in Des Moines, Iowa. Installing an 80-inch diameter, 20-ft pipe segments 25-ft deep. The project started in the beginning of October 2010 and ended November 2010. The project length was 330 ft long. The soil encountered was wet clay, with 10 – 12 ft ground water levels. The shaft size was 14 ft wide by 45 ft long, and used slide railings as the wall support system.

After entering the project's information in the DSS, the final results are displayed in the project summary sheet presented in Figure 4.8. The final recommendation from the DSS for the shaft size 13 ft wide by 38 ft long, and recommended several possible wall support systems which included trench boxes, slide railing, sheet piles, soldier piling, concrete sinking shafts, and ground freezing. Depending on cost, equipment and material availability, and time, the contractor may make a different decision. The actual wall support system used for this project was the slide railing system.



TTSC

Trenchless Technologies Shaft Construction

Project Summary

User Name: Bassam Abusad

Project Date: mm/dd/yyyy 10/1/2010

Project Name: WRA Project

Project Location: City Des Moines State IA

Type of TCM: PJ

Type of Entry Shaft wall Support System		Depth (ft)	Width (ft)	Length (ft)	Shaft Diameter	Details
1	Trench Box	25	13	38		
2	Slide Railing Systems	25	13	38		
3	Soldier Piles with Timber Lagging	25	13	38		
4	Soldier Piles with Steel Lagging	25	13	38		
5	Sinking Shafts	25	13	38	30	
6	Ground Freezing	25	13	38	30	

Notes

* For entry shafts deeper than 20 ft a license Civil or Structural Engineer stamp is required.

** Follow OSHA rules and regulations for depth deeper than 4 ft.

Print << Click to proceed or go back >> Exit

Figure 4.8: Validation # (2) Project Summary

4.4 Chapter Summary

This chapter presented the results of the industry survey. The survey results along with two case studies were used as a reality check for the decision support system (DSS).

CHAPTER 5

CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusions

Almost all Trenchless Construction Methods (TCMs) require an entry shaft, an exit shaft, and in some cases, an intermediate shaft except for the Horizontal Directional Drilling (HDD) method. The success of a TCM project that uses entry shafts heavily relies on the accuracy, stability, and durability of the entry shaft. Due to the major benefits of using trenchless technologies versus the open cut method, more and more TCM projects are on the way. With more upcoming TCM projects, the knowledge of how to prepare and understand a TCM project is very beneficial for decision makers, i.e., project owners and design engineers. To assist in sizing and selecting a wall support system for the entry shaft construction, a Decision Support System (DSS) was developed with this thesis. Before using the DSS, detailed surface and subsurface investigations are required. Depending on the depth of the project, geotechnical reports are needed to determine the underground soil types and conditions. Reviewing the Occupational Safety and Health Administration (OSHA) guidelines are necessary.

There is no single wall support system construction method that can be used for all entry shaft construction methods. Depth of installation, site conditions, and other constraints (i.e., system availability, costs, etc.) must be considered when selecting the wall support system. For entry shafts deeper than 5 ft, the construction of a wall support system is required by OSHA's rules and regulations. The use of the DSS will identify the different types of potential wall support systems that can be used for the project's entry shaft construction.

For panning purposes, and by knowing the size of the entry shaft and the different wall support system options that can be applied, the DSS users can compare available alternatives for their projects. The shaft sizing and wall support requirements may impact selection of trenchless construction method, an important decision that needs to be evaluated in early stage of project planning.

5.2 Limitations

This thesis was a first attempt in the area of shaft construction for trenchless construction methods. Important factors in selection of a specific shaft wall support system are cost and schedule. While the DSS will provide a number of methods that are technically possible, the cost and schedule will eliminate many of these methods and there will be one or two methods remaining. Due to time and resource limitation, it was not possible in this thesis to consider costs and schedule and provide a comparison of different shaft wall systems based on these important parameters. Additionally, the survey conducted provided limited information, as many contractors may consider their shaft construction method proprietary. However, with an extensive survey and use of methods such as AHP, a comprehensive DSS can be developed. Hopefully this research will develop an interest among future researchers to investigate this subject more in depth.

5.3 Recommendations for Future Research

Based on this study, the following recommendations for future research are proposed:

1. Considering cost and schedule for different shaft construction methods.
2. Including more parameters than presented in this thesis, in the selection of a specific shaft construction method.
3. Expanding the Decision Support System to output exit shaft construction methods.
4. Upgrading the Decision Support System and using the Analytical Hierarchy Process, to improve the selection of a shaft construction method.
5. Developing a Decision Support System for Trenchless Renewal Methods (TRMs).

6. Including load bearing capacity of different shaft construction methods, based on soil conditions and depth of watertable.

APPENDIX A

SURVEY QUESTIONNAIRE

Hello,

This questionnaire is part of a research study being conducted on developing a Decision Support System (DSS) for selecting shafts construction and support systems for trenchless construction methods. The purpose of this study is to gather different entry shaft construction methods and wall support systems used on different projects, and why those methods systems were used. The questions are designed to help me understand the link between project characteristics and project entry shaft construction method, so that hopefully I can come up with a system that will give a recommendation on selecting an entry shaft method and wall support system. In the future the decision system will assist decision makers during preliminary planning and budgeting and what to expect on a new trenchless construction project. Your input is very valuable for this research.

There are 18 questions asking about a trenchless construction project that you have completed and what type of wall support system you have used for the entry shaft construction. If you had completed more than one trenchless construction projects that had different wall support systems for the entry shafts, please feel free to submit 2 or 3 more projects at your convenience. At the end you can click the submit button, which will automatically save your input and attach it to your email ready to be sent. Or the manual method by saving the PDF files on your desktop and then attaching it to your email.

If you have any questions about this survey or research please contact Bassam Abusad (bassam.abusad@mavs.uta.edu) graduate student at the University of Texas at Arlington, Department of Civil Engineering at (214)502-4112, or research supervisor Dr. Mohammad Najafi P.E (najafi@uta.edu) Director, CUIRE, and professor at the University of Texas at Arlington, Department of Civil Engineering at (817) 272-0507

Thank you in advance for your help, we do appreciate your time.

Bassam Abusad

Graduate Student Department of Civil Engineering

The University of Texas
ARLINGTON

Project Overview				
1. Type of Work	Auger Boring ○	Microtunneling ○	Pipe Jacking ○	Pipe Ramming ○
2. Project Name				
3. Duration	Start Date		Finish Date	
4. Location	City		State	
5. Pipe Length (ft)	Pipe Size (in)		Pipe Segment Length (ft)	
6. Contact Person	Name	Phone	Email	
7. Total Construction Cost $		Entry Shaft Construction Cost $		
Site Conditions				
8. Site Access	○ Good Access		○ Poor Access	
9. Working Area	○ Open-Good Working Area		○ Tight-Poor Working Area	
10. Geotechnical Conditions	○ Rock	○ Cobble	○ Boulder	
	○ Wet Sand	○ Dry Sand	○ Wet Clay	
	○ Dry Clay	○ Other (Explain)		
11. Ground Water	○ Yes	○ No	If Yes, depth of ground water level?	
Entry Pit/Shaft Size				
12. Pit/Shaft Size	Entry Shaft (W x L x D) in (ft) or Diameter (in)?		Exit Shaft (W x L x D) in feet (ft)?	
13. Soil Excavation	List the different types of machines used to excavate the entry shaft?			
14. Shaft Duration	How long did it take to complete the excavation and wall support system for the entry shaft?			

If the entry shaft depth is > 5 ft then please continue answering the rest of the questions, if not then please skip to question 18

15. Please choose one entry shaft wall support method, If two explain why?

○ Sloped Walls	Sloped Walls Ratio (i.e. 3:1 slope)		
○ Sheeting	○ Metal Vertical	○ Metal Horizontal	
	○ Timber Vertical	○ Timber Horizontal	
○ Trench Box	What kind and size of box?		
○ Sheet Pile	What Kind and size of each sheet pile?		
○ Soldier Pile	○ Timber Planks	○ Metal Planks	○ Precast Concrete Planks
○ Shotcrete & Soil Nailing			
○ Slurry Wall			
○ Circular or Cylinder	○ Precast Concrete	○ Metal	
○ Other Methods			

16. Why did you choose that method in question 15? (i.e. cost, availability, time,)

17. Would you have done it another way?

18. Risk or Problems if any?

Submit

Instructions regarding each question

- Move cursor from cell to cell: Tab key (for reverse direction Shift Tab) or use mouse
- Mark the checkbox: click or spacebar

1. Type of work: mark one of the four different trenchless technologies used on your project
2. Name of the project
3. Duration of the project, when it started and when it was completed
4. Location of the project
5. Pipe length for the entire project, pipe diameter size, and each segment length
6. Insert your contact information
7. Total construction cost of the project, and the entry shaft construction cost that includes excavation and wall support system if used
8. Site access conditions
9. Working area conditions
10. Different Soil types that you encountered during construction of the entry shaft
11. Ground water level
12. Entry shaft size and exit shaft size
13. What machine or technique you used to excavate the entry shaft
14. How long did it take to complete excavation and constructing the wall support system if used
15. Choose the wall support method. If another method is used please explain in other methods
16. The reason you choose that method because of cost, availability, time, or any other reason
17. Would you have chosen a different method on the same project for another reason
18. Any risks or problems encountered during construction of the entry shaft and while working in it

When completed you can click the submit button, which will automatically save your input and attach it to your email ready to be sent. Or manually saving the PDF file on your desktop and then attaching it to your email. If you have any questions, please contact:

Bassam Abusad,
Graduate Student
Department of Civil Engineering
Phone: (214) 502-4112
E-mail: bassam.abusad@mavs.uta.edu

APPENDIX B

SURVEY RESPONSE LOG

Table B.1: Survey Response Log

Date Contacted	Company Name	Response
3/7/2012	1127 Construction Inc	No
3/7/2012	A.E. Bragger Construction	No
3/7/2012	Aaron Enterprises Inc	No
3/7/2012	AECON	No
3/7/2012	Alex E. Paris Contracting	No
3/8/2012	Angelica Boring Co	Yes
3/8/2012	Ansco & Associates	No
3/8/2012	Arrow Direction Boring	No
3/8/2012	B Frank Joy LLC	No
3/8/2012	Bullseye Backhoe Services	No
3/8/2012	Cantex Inc.	No
3/8/2012	Carson & Roverts Site Construction &Engineers	No
3/9/2012	CELTEK Inc.	No
3/9/2012	The Crossing Company Inc.	No
3/9/2012	Cruz Contractors LLC	No
3/9/2012	CSU Inc	No
3/9/2012	Daetech	Yes
3/13/2012	Daniel R .Shmoldt Enterprise	No
3/13/2012	Danielson Inc.	No
3/13/2012	Davis Horizontal Drilling	No
3/13/2012	ERS Constructors	No
3/13/2012	Fornea Road Boring	No
3/13/2012	G.L. Howard Inc.	No
3/13/2012	Gator Boring & Trenching	No
3/13/2012	Cleason Construction Co. Inc.	No
3/13/2012	Globe contractors Inc.	No
3/14/2012	Geotek Engineering	No
3/14/2012	Claude H. Nix Construction	Yes
3/15/2012	Hearn Co	No
3/15/2012	Hemlock Directional Drilling	No
3/15/2012	Henkels & McCoy Inc.	No
3/15/2012	Hewitt Power	No
3/15/2012	Hunter Excavation	No

Table B.1: Survey Response Log (continued)

Date Contacted	Company Name	Response
3/16/2012	Bore Master Inc.	No
3/16/2012	Bortech Co. Inc.	No
3/16/2012	Michels Corp	Yes
3/16/2012	Brannar Construction Company	No
3/17/2012	Western Trenchless	No
3/17/2012	Texas Sterling Construction Inc.	No
3/17/2012	Planetary Utilities	No
3/19/2012	Casey B Inc	No
3/19/2012	Kamloops Augering and Boring LTD	No
3/19/2012	Ken Thompson Inc.	No
3/19/2012	Ken's Road Boring	No
3/19/2012	Kinsel Industries Inc.	No
3/19/2012	Lawrimore Construction Inc.	No
3/19/2012	M & P Pipe Jacking Corp.	Yes
3/19/2012	Linde Corp.	No
3/21/2012	Miller The Driller	Yes
3/21/2012	Pacific Boring	Yes
3/21/2012	Scott Drilling Services	No
3/21/2012	Southwest Horizontal Drilling	No
3/21/2012	BRH Garver	Yes
3/21/2012	WRS Compass	No
3/21/2012	W.E. Close Develop	No
3/21/2012	SCCI Inc.	No
3/21/2012	Osborn Contractors	No
4/2/2012	Clay Pipeline, Inc.	No
4/2/2012	Midwest Mole Inc.	Yes
4/3/2012	Iowa Trenchless	Yes

APPENDIX C

USER MANUAL FOR THE TRENCHLESS TECHNOLOGIES SHAFT CONSTRUCTION (TTSC) DECISION SUPPORT SYSTEM

Getting Started

Double-click on the Decision Support System excel file called TTSC. The project information page will appear. The user must input his/her name, project date, project name, project city, and project state. Entering this information is not mandatory but helpful when saving the file for back up. When ready to continue, click the “Click here to begin” link.

Using the Decision Support System

1. The user has to choose one of the Trenchless Construction Methods (TCM) that is listed on that page. Click on the drop-down menu and choose one of the TCM for your project. When selecting the correct trenchless construction type, click “Next” to proceed.
2. The next page is the pipe information page. At the top of the page you will see your type of TCM, if that is incorrect, click the “Back” link to go back and modify your selection. The information on this page is very important. You must enter your project’s information in each field. When inserting data in every field, a pop up box will appear notifying you with the allowable ranges depending on your TCM. If you enter a number not within the allowable range, an error message will pop up. Be aware of the units that are either in feet (ft) or in inches (in.). When entering all the information in all of the fields, the user can click “Next” to proceed, or “Back” for any modifications.
3. The following page is the soil condition page. The user must select one of the soils listed in the page from the drop-down menu. When selecting a type of soil, the user must select a soil classification from the drop-down menu below. Entering the ground water level is necessary if known. If left blank, than the depth will automatically be “zero” which means there is no water level within the shafts depth. Click “Next” to continue or “Back” to modify the previous entry.

4. The final page is the project summary page. Here the project information, type of TCM and a list of shaft construction methods appear if applicable. The user can click “Exit” to exit the DSS, or “Print” to print the project summary page.

Notes

Since the DSS is an excel file. The user can manually operate the system by clicking the bottom tabs, and the top tool bars. This method is not recommended, because missing important information will give wrong results.

APPENDIX D

ACRONYMS AND ABBREVIATIONS

Table D.1: List of Abbreviations

ASCE	American Society of Civil Engineers
CFA	Continuous Auger Flight
CM	Compaction Method
DIP	Ductile Iron Pipe
DSS	Decision Support System
GRP	Glassfiber Reinforced Polyester
TT	Trenchless Technology
HAB	Horizontal Auger Boring
HDD	Horizontal Directional Drilling
MTBM	Microtunnel Boring Machine
OSH	Occupational Safety and Health Service New Zealand
OSHA	Occupational Safety and Health Administration
PCP	Polymer Concrete Pipe
PJ	Pipe Jacking
PTMT	Pilot Tube Microtunneling
PR	Pipe Ramming
PVC	Poly-vinyl-chloride
RCP	Reinforced Concrete Pipe
TCMs	Trenchless Construction Methods
TRMs	Trenchless Renewal Methods
VCP	Vitrified Clay Pipe

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BIOGRAPHICAL INFORMATION

Bassam Abusad graduated with a Bachelor of Science in Architecture from the University of Texas at Arlington in 2005. After graduation, he worked as a drafter at Kahn's and Associates in Plano, Texas. Then he worked for Double Diamond as a project manager in Dallas, Texas, supervising construction of three luxury golf course resorts. With the great motivation and enthusiasm for developing higher-level skills and knowledge in the construction industry, he decided to pursue a Master of Science in Civil Engineering with a focus in Construction Engineering and Management at the University of Texas at Arlington. He continued to maintain a strong academic standing during his studies, having the great opportunity to work on his research with Dr. Mohammad Najafi. His research interests are trenchless technology, and are focused on developing Decision Support Systems (DSS) for shaft construction methods.