COMPARISON OF CONSTRUCTION METHODS FOR BUILDING AN UNDERGROUND FREIGHT TRANSPORTATION IN TEXAS

by

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Abstract

COMPARISON OF CONSTRUCTION METHODS FOR BUILDING AN UNDERGROUND FREIGHT TRANSPORTATION IN TEXAS

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Freight transportation by trucks constitutes approximately 80% of total freight transportation in Texas and it is expected to approximately double by the year 2040. Social and environmental costs are adverse impacts of moving freights by trucks. Underground Freight Transportation (UFT) significantly reduces these negative impacts and is more sustainable method of freight transportation. UFT includes close-fitting vehicles carrying freight through underground pipelines or tunnels between terminals. The main objective of this research is to compare two construction methods: (1) tunneling using tunnel boring machine (TBM) and (2) tunneling using open-cut. To conduct this research, a comprehensive literature search on various construction technologies for building large diameter pipes or tunnels was conducted. Additionally, interviews with tunneling experts and stakeholder committee members were made, and a survey on comparison of tunneling vs. open-cut methods was performed. The result of this thesis shows that tunneling with TBM is more constructible, applicable and cost-effective than open-cut construction. This is due to several factors, such as, large tunnel size needed for UFT, difficulties in transportation and delivery of large precast diameter pipe sections for open-cut method, social and environmental impacts of open-cut, limitations in right-of-

way and natural and man-made obstacle, such as, bridges, rivers, existing utilities, difficult ground conditions, etc., as described in this thesis.

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Chapter 1

Introduction

The Texas transportation system is critical to the United States economy. Through 2030, the North American Free Trade Agreement (NAFTA) trade will increase by nearly 207 percent by tonnage. The number of trucks carrying NAFTA's freight will increase by 263 percent and the number of rail units will grow by 195 percent (TxDOT, 2007). This will have a profound impact on the Texas highway and rail systems. Also, Port of Houston is a first-ranked U.S. port in foreign tonnage and the sixth ranked US container port by total TEUs (Twenty-Foot Equivalent Unit)[1] in 2014[2]. Larger ships with higher capacity will arrive in the Port of Houston due to expansion of the Panama Canal (Tabesh et al, 2016).

The AASHTO report also points out that highway infrastructure alone will have a difficult time keeping up with this expanding freight volume demand. Between 1980 and 2006, traffic on the U.S. Interstate Highway system increased by 150 percent while Interstate capacity increased by only 15 percent. It also states that an average of 10,500 trucks per day travel the Interstate Highway System with some heavily used segments carrying over 50,000 trucks per 5 days. Texas is one of six states that, together, account for over 88 percent of the freight movement in the nation (AASHTO, 2010). Therefore, increasing the capacity of the freight transportation system is a must.

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[1] TEU stands for Twenty-Foot Equivalent Unit which can be used to measure a ship's cargo carrying capacity. The dimensions of one TEU are equal to that of a standard 20′ shipping container. 20 feet long, 8 feet tall. Usually 9-11 pallets are able to fit in one TEU. Two TEUs are equal to one FEU (forty-foot-equivalent unit). http://dedola.com/2011/10/what-is-a-teu/ (Accessed on December, 2015)

[2] http://www.portofhouston.com/business-development/trade-development-and-marketing/trade-statistics/ (Accessed on October 2015)

Underground Freight Transportation (UFT) system as the 5th mode of transportation (after highway, train, sea, and air), can be considered as a green alternative to increase freight transportation capacity and to make the current means of freight transportation more efficient, reliable, safe, secure, and environmentally friendly (Tabesh et al, 2016).

1.1 What is UFT?

Underground freight transportation (UFT) uses automated technology to carry individual freight vehicles through pipelines or tunnels (see Figure 1-1). During the operation, this system can carry freight into highly congested areas with minimum impacts on the surface.

Figure 1-1 Schematic of a UFT System (Winkelmans, 2009)

Freight transportation is a technology to transport most cargoes, normally transported by trucks, including construction materials (i.e., sand, gravel, and cement), goods in pallets and crates, boxes, etc., and even full-size (i.e., 40-ft-length) shipping containers. Tube freight transportation is a class of unmanned transportation systems in which close-fitting vehicles or trains of vehicles carry freight through tubes between terminals. Being able to use a part of the underground space of the existing right-of- way of highways, will greatly facilitate the construction of such tubes and reduce their construction costs. However, many questions must be answered through a rigorous study before freight tubes can be constructed along highways, and before they can become an integral part of the nation's future freight transportation system. UFT system layout is shown in Figure 1-2.

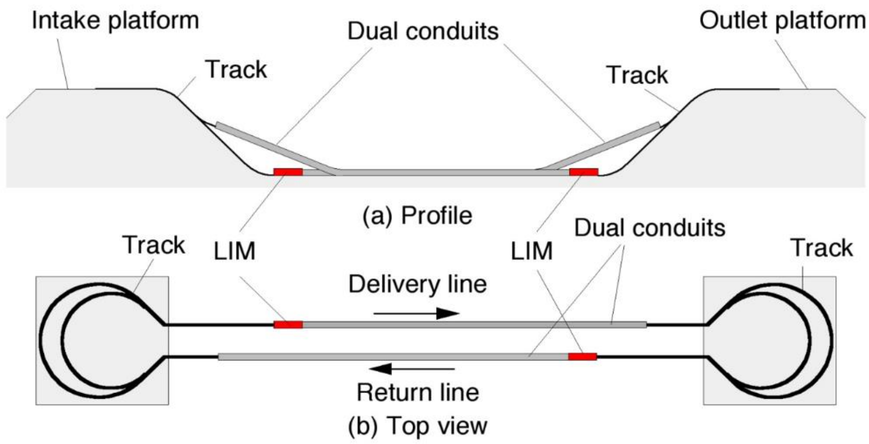


Figure 1-2 UFT System Layout (Liu, 2008)

The Center for Underground Infrastructure Research and Education (CUIRE) at UTA proposed an evaluation of UFT to transfer freight in Texas. As discussed, Texas is considered a state with high and increasing freight transportation needs. Underground Freight Transportation can be an appropriate solution to future freight transportation needs (Mousavipour, 2015). CUIRE study included 6 tasks as shown in Figure 1-3.

CUIRE proposed three routes (see Table 1-1 and Figures 1-4 through 1-6) and three cargo sizes (see Table 1-2 and Figure 1-7) and) to study UFT applicability.

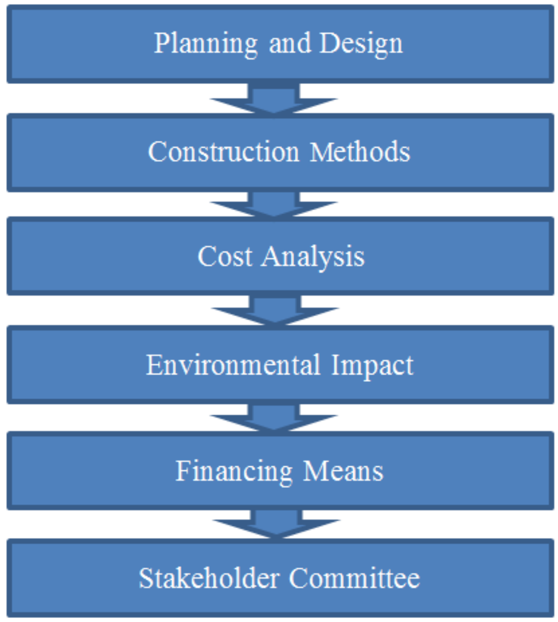


Figure 1-3 CUIRE UFT Research Approach

Table 1-1 Proposed UFT Routes in Texas (Tabesh et al, 2016)

Route	Cargo Size	Origin	Destination	Impacted Highways
1	Container	Port of Houston	Distribution Center in Dallas, TX	SH 210, IH 610, IH 45
2	Container	Port of Houston	Distribution Center in Houston, TX	SH 146
3	Container	U.S. Border at Laredo, TX	U.S.-Mexico Border at Mexico	IH 69W

This thesis focuses on the biggest size (standard shipping container) carrying the goods between Port of Houston to a proposed distribution center in Dallas.

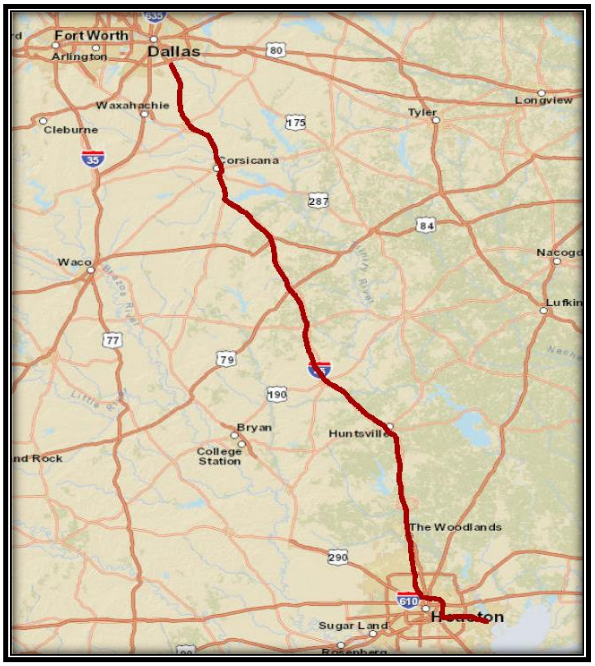


Figure 1-4 Route 1, Port of Houston to a Distribution Center in Dallas (Lancaster, TX)

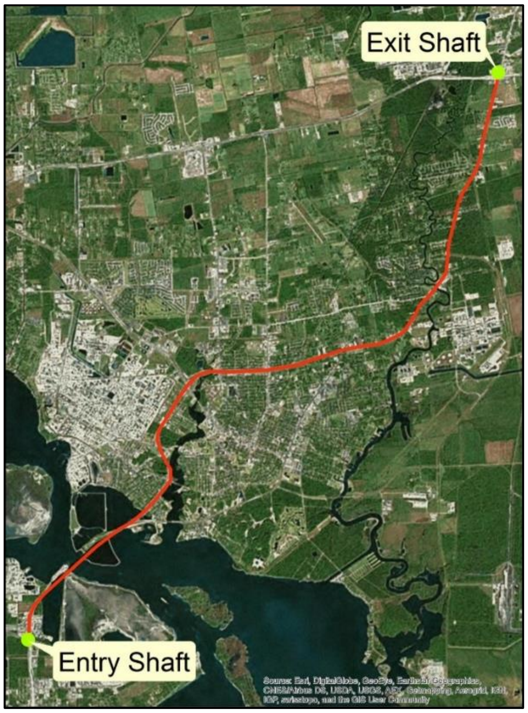


Figure 1-5 Route 2, Port of Houston to a Distribution Center Outside Houston

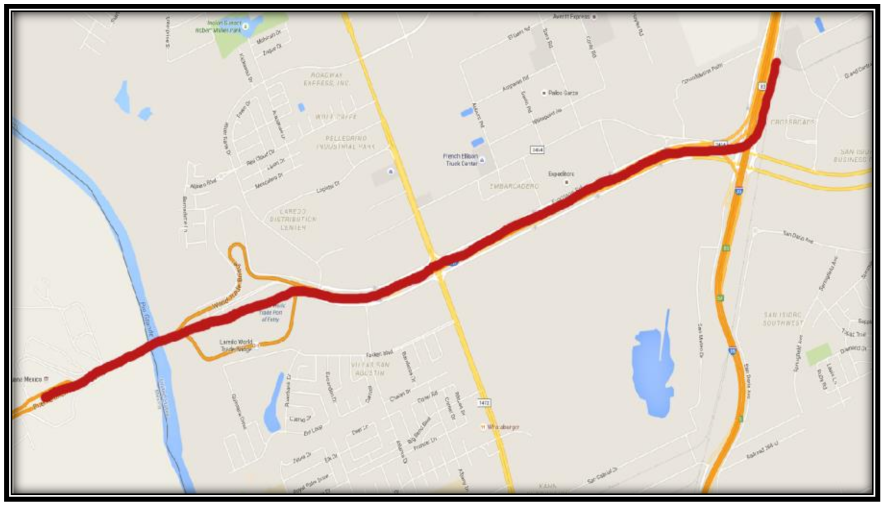


Figure 1-6 Route 3, The Border with Mexico at Laredo

Table 1-2 UFT Cargo Size (Tabesh et al, 2016)

Size	Cargo	Weight (lb)	External Diameter (ft) of Pipe with One Track
Small	Pallet	4,600	8.4
Middle	Crate	7,000	11.8
Large	Container	68,000	17

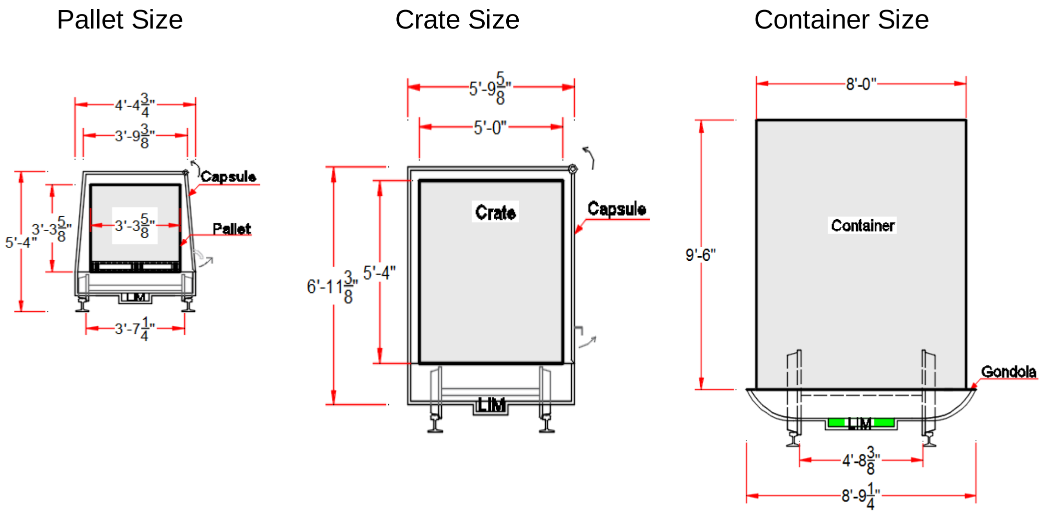
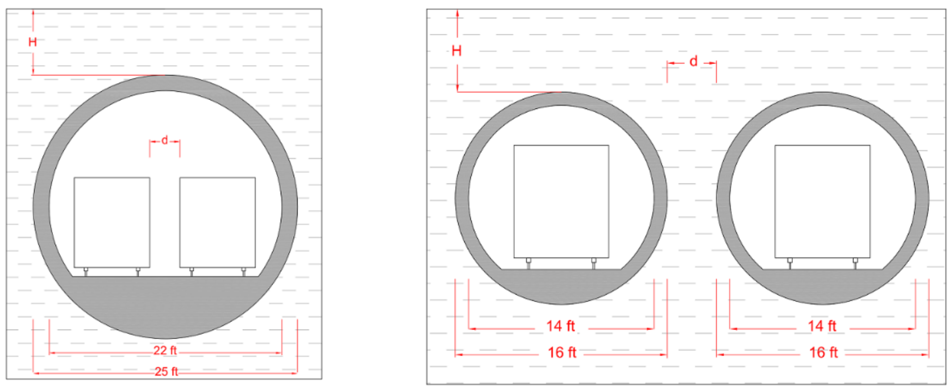


Figure 1-7 Proposed UFT Cargo Sizes

After analyzing the data from literature reviews, interviews with tunneling experts and stakeholder committee members and a survey that will be discussed in Chapter 4, two options were proposed for building the tunnels: (1) building tunnels with Tunnel Boring Machine (TBM), and (2) building tunnels with open-cut method as shown in Figure 1-8.



Type 1- Building Tunnels with TBM Method

Type 2- Building Tunnels with Open-cut Method

Figure 1-8 The Two Construction Options for Building Tunnels.

Due to the size of the cargos, difficulties in delivering and transportation the pipes and other obstacles, it was proposed to build a dual-track tunnel with 25 ft outside diameter using TBM and two single-track tunnels with 17-ft diameter each using open-cut method.

1.2 Background

UFT has been assessed twice in the past by the Federal Highway Administration (FHA). The first assessment was conducted in 1976 in a research project by Zandi (1976). This study examined various aspects of freight pipelines, and concluded that they are not only technically feasible but also economically promising in many situations. Furthermore, the study confirmed many advantages of pipeline freight that can transport over 70% of the freight transported by trucks.

The second assessment was conducted in 1994 by Dr. Lawrence Vance at the Department of Energy (DOE) Volpe National Transportation System Center (Vance and Mills, 1994). This assessment again concluded that underground freight transportation is technically feasible and has many merits. Its cost-effectiveness, on the other hand, must be determined on a case-by-case basis taking site-specific information into account such as freight volumes and construction costs. The authors also reported that using highway right-of-way (ROW), in unused underground areas along highways, can greatly enhance the economic feasibility of any pipeline freight project.

Finally, in 1998, ASCE (American Society of Civil Engineers) Task Committee on Freight Pipelines again assessed the state-of-the-art and future potential of various types of freight pipelines. The final report, published in 1998, concluded that "Freight pipelines are economical in many situations, reliable, automatic, environmentally friendly, energy efficient, and safe to people and the ecosystem. Advancements in pipeline technology and computer control systems have greatly facilitated the development and use of freight pipelines" (ASCE Task Committee, 1998).

It is a general perception that in rural areas, the open-cut method is the most economical way of laying pipes. While this concept is generally true, there are other considerations that may make open-cut difficult or impossible. For example, the UFT concept assumes that the pipe will be buried only a few feet underground (Liu, 2004), but large pipe diameters will increase trench depth to 27 ft that requires a wider trench at the surface and huge amount of soil excavation and backfill. Additionally, trenchless technologies are more environmentally friendly, and they result in less carbon footprint, enhancing safety and productivity (Najafi and Gokhale, 2005).

In 2004, Liu and Najafi completed a project to assess the feasibility of using various sizes of PCP for underground freight transportation in New York City (Liu, 2004). The study, sponsored by the New York State Energy Research and Development Authority, examined six different potential applications of PCP including: (1) tunnel construction, (2) transporting municipal solid waste, (3) transporting mail and parcels, (4) delivering goods on pallets, (5) dispatching containers from seaports to an inland inspection/transfer station, and (6) ferrying trucks at the food market at Hunts Point. Results of this study showed that all six of the aforementioned applications are technically feasible, and will bring significant benefits to New York City in terms of enhanced transportation safety and security, and reduction in air pollution and traffic jams caused by trucks. The first five of the six applications are also found to be economically attractive (cost-effective), see Table 1-3.

Table 1-3. Comparison of Costs in 2012 dollars[3]

Cost	Tunneling Costs	Open-trench Costs	Open-trench Costs with PCCP (Two Trenches)	Open-trench Costs with PCCP (One Trench)
Total Cost $	$166,167,650	$25,687,700	$88,774,500	$ 87,408,750
$/ Foot	$10,471	$1,622	$5,691	$ 5,520
$/ M	$34,326	$5,318	$18,666	$18,097

The social cost of construction includes inconvenience to the general public and damage to existing structures. Social costs are becoming more important due to growing public awareness and the need to conserve and protect our environment (Tabesh et al, 2016). The social costs include:

- Damage to roads and detour roads
- Damage to adjacent utilities and structures
- Noise, vibration, and dust

[3] Unpublished Report by Udupa and Najafi (2012)

- Air pollution and environmental impacts
- Vehicle traffic disruption
- Business and trade loss
- Site safety and pedestrian safety
- Citizen complaint

1.3 Objectives

The main objectives of this thesis are:

- To identify construction technologies for building a large diameter tunnels.
- To show that several important parameters dictate the decision for selecting a construction method between open-cut and specific trenchless, such as, social and environmental factors, availability of surface space, site and ground conditions, and specific project parameters.

1.4 Need Statement

As it is evident from literature search, not much research has been done on building large diameter pipes, tubes or tunnels to transport freight. Based on the previous discussion, in the next 3 decades, United States expects a growth in the economy as well as expansion in the population which will lead to a an increase in the demand of goods and thus an increase in its transportation. The following sections present growth impacts on Texas and its transportation system.

1.4.1 Freight Transportation Growth

According to TxDOT (2007), NAFTA truck tonnage on Texas highways will increase by 207 percent from 2003 through 2030. Truck tonnage will grow by 251 percent while rail tonnage is estimated to increase 118 percent (see Figure 1-9). This data is assumed to change linearly, so truck tonnage will increase by 150 percent from 2015 through 2030 and rail tonnage will grow 109 percent. The number of trucks carrying

NAFTA goods will increase by 158 percent. NAFTA truck VMT (vehicle miles traveled) will grow by more than 200 percent from 2015 through 2030 (TxDOT, 2007). Moreover, it is estimated that Texas handles approximately 80% of all NAFTA trade from Mexico. The truck VMT due to NAFTA is projected to more than quadruple by 2030 (TxDOT, 2007).

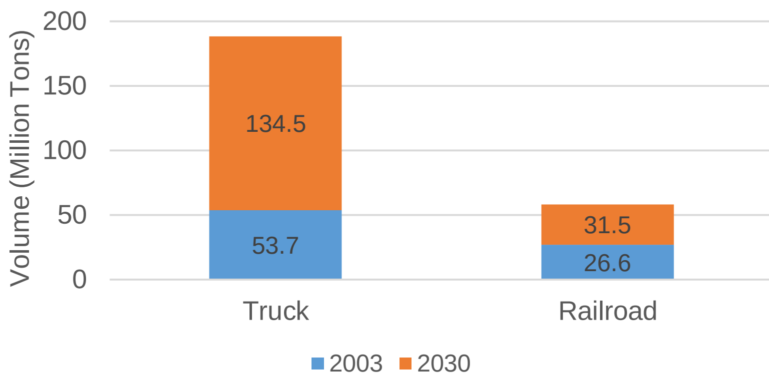


Figure 1-9 NAFTA Growth

Source: Texas NAFTA Study Update by TxDOT

In 2012, as shown in Figure 1-10, more than 13 billion tons of freight across America’s highways were transferred by aproximately 10 million trucks. These trucks are main causes of congestion on 4,500 of the most crowded highway miles in the US (U.S. Department of Transportation, 2015).

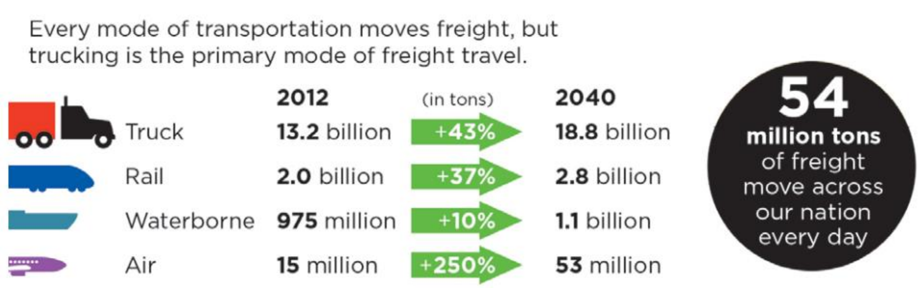


Figure 1-10 Modes of Transportation Distribution

Source: U.S. Department of Transportation, 2015

Additionally, Table 1-4 compares the averageannual daily truck traffic (AADTT) of the most congested highways in Texas in 2013 and 2033.

Table 1-4 High Congested Routes in DFW

Source: Derived from Statewide Planning Map

http://www.txdot.gov/apps/statewide_mapping/StatewidePlanningMap.html

Route	From	To	Length (mile)	AADTT * (2013)	AADTT * (2033)
IH-20	US-377	US-175	52	15,769	22,114
IH-30	IH-35W	IH-635	42	11,458	16,040
IH-35E	IH-20	US-380	50	12,198	17,078
IH-35W	IH-20	US-380	45	10,501	14,701
IH-635	SH-121	IH-20	38	17,655	24,716
US-75	IH-30	US-380	32	13,635	19,088

* AADTT: Average Annual Daily Truck Traffic

1.4.2 Panama Canal Expansion

As it is shown in Figure 1-11, Houston, Texas is the third largest port in the U.S with $168.3 annual worth of import and export.

The expansion of the Panama Canal will allow transit by ships of up to 12,600 TEU compared to the current approximate maximum of around 4,500 TEU (TranSystems, 2009). as shown in Figure 1-12, The larger size container vessels have many impacts on Port operation. Because of lack of land adjacent to the Port of Houston[4], larger ships must spend more time in the Port' hence, demands include more

[4]http://www.marad.dot.gov/wp-content/uploads/pdf/Panama_Canal_Phase_I_Report_-_20Nov2013.pdf (Page 51), (Accessed on November, 2015)

efficient container-hauling to avoid delays. Additionally, there will be more traffic congestion in the Port due to higher flow of containers between the berth and the yard[5].

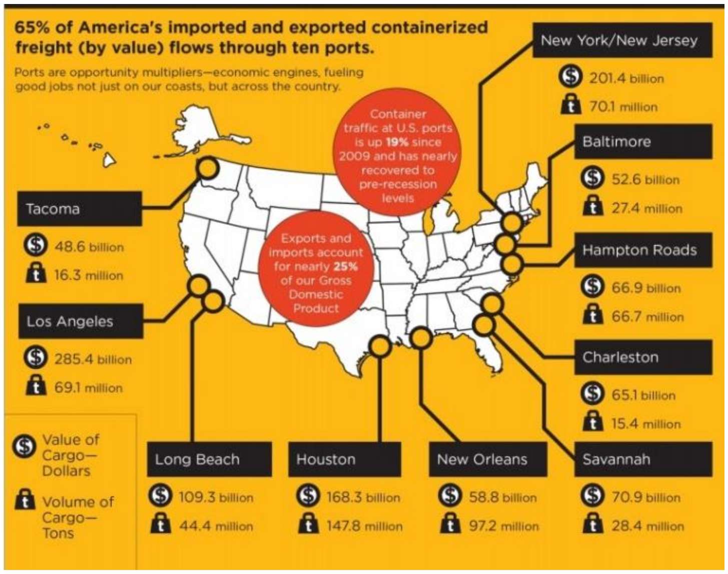


Figure 1-11 Top 10 U.S. Ports in 2014 by Cargo Value

Source: U.S. Department of Transportation, 2015

Panama Canal is expected to be done by the widening and deepening process by 2016. This change will enable larger ocean-going vessels (see Figure 1-12), known as "post-Panamax" ships. Hence, container ship freight volume is expected to increase at Gulf and East Coast ports, since 64 percent of the vessels are destined for or originate in US.

Panama Canal expansion will become crucial for ports since new generation of vessels offload larger volumes of containers in shorter period of time (U.S. Department of Transportation, 2015).

[5] http://www.worldshipping.org/industry-issues/transportation-infrastructure/Observations_on_Port_Congestion_Vessel_Size_and_VSA_May_28_2015.pdf (Accessed on December, 2015)

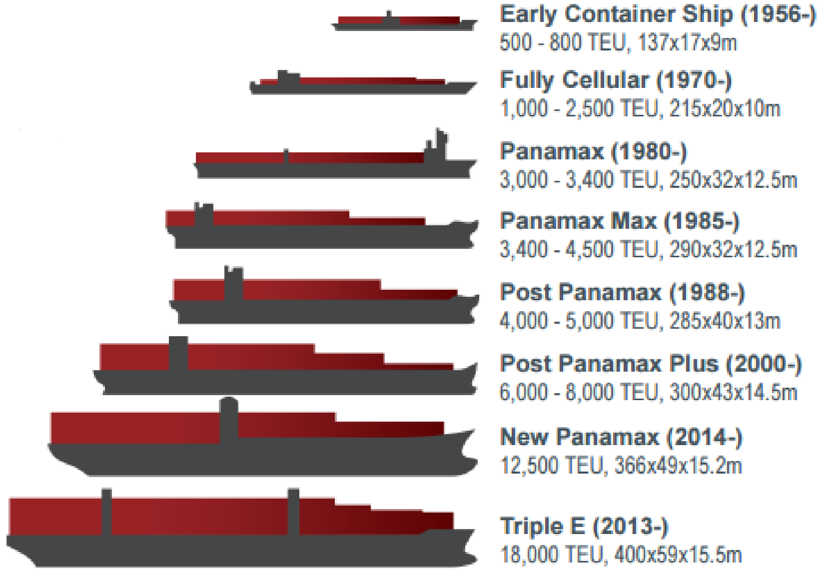


Figure 1-12 Large Ocean-going Vessels

Source: Freight Movement in Texas by TxDOT

A three percent annual growth in total volumes transiting the canal is expected to occur by the Panama Canal Authority (ACP) in 2025. There will be an additional 6.6 million tons of cargo arriving and 15.5 million tons exporting in the amount of transportation in Texas ports (U.S. Department of Transportation, 2015).

1.5 Methodology

As it is shown in Figure 1-13, in this project, after defining the problem which is finding the most applicable construction method for building large diameters tunnels of UFT, some literature reviews will be performed. Research sources will include: academic data base sources, books, journals, reports and other online publications.

Based on data collection from literatures and case studies, conducting a survey from the experts in tunneling industry, discussions at the stakeholder committee meetings and some interviews, open-cut and tunneling with TBM were chosen as the most applicable methods for building UFT.

In conclusion, by analyzing the results, duo to the size of tunnels, transportation and delivery of the pipes, social and environmental impacts, limitation in right-of-way and the obstacles (e.g., bridges, rivers, utilities relocation, soil condition, underground water, possibility of settlement at the surface, etc.), tunneling with TBM is more applicable than open-cut and pipe jacking.

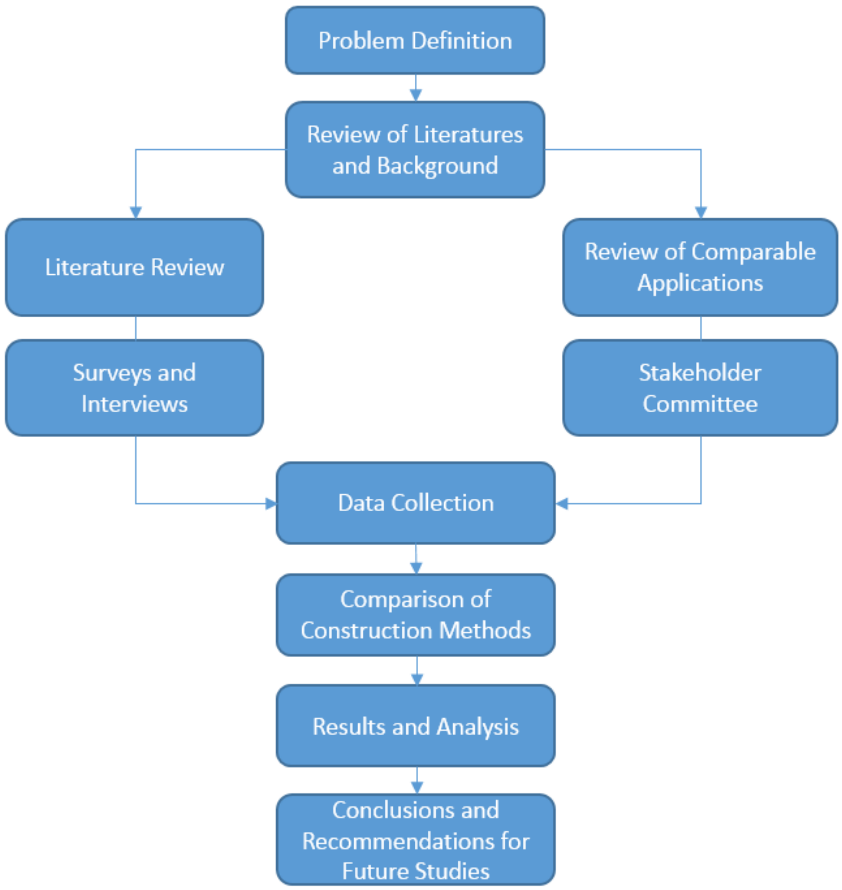


Figure 1-13 Methodology

1.6 Expected Results

It is expected that due to the size of the tunnels, transportation and delivery of the pipes, social and environmental impacts, limitation in right-of-way and the obstacles (e.g., bridges, rivers, utilities relocation, soil condition, underground water, possibility of settlement at the surface, etc.), tunneling with TBM will be more applicable than open-cut.

1.7 Chapter Summary

This chapter presented the concept of underground freight transportation (UFT). Expected growth in freight transportation was presented. Also, objectives, methodology, need statement and expected outcome of this thesis were described.

Chapter 2

Literature Review

In chapter 1, UFT system was introduced as the 5th mode of transportation (after highway, train, sea, and air) that uses an automated technology to carry individual freight vehicles through pipelines. For building a large diameter tunnel, there is a need to analyze the applicability, constructability and productivity of each tunnel construction method.

In this chapter the major aspects of tunneling with tunnel boring machines and open-cut will be discussed. Additionally, pipe jacking method will be briefly introduced in this chapter.

2.1 Large Diameter Tunnel Construction

In this thesis three major tunneling technologies is studied with a focus on tunneling and open-cut method.

2.1.1 Building Large Diameter Tunnels Using Trenchless Technologies

Installation of new pipelines by trenchless technology is commonly divided into two installation categories: worker-entry and non-worker-entry (Figure 2-1). For the success of trenchless construction projects, selection of appropriate equipment and tools are critical. Such factors as site restrictions, design requirements (pipe strength), existing underground utilities, above ground structures, obstructions on the installation path, soil conditions, drive/reception shafts' distances, required accuracy, as well as costs are all important. In this thesis, several primary factors were identified to select the appropriate trenchless methods. These factors include pipe diameter, surface access, obstructions, soil conditions, required working space, drive length, depth of installation, and construction productivity. Based on the characteristic of each of trenchless construction method and project requirements, only worker-entry methods of pipe jacking (PJ) and tunneling (TL) can be used. The other methods, horizontal auger boring (HAB), pipe ramming (PR), and pilot tube (PT) are eliminated due to diameter limit and length of dive limitations. Micro Tunneling (MT) is eliminated due to higher cost and type of application which is more suited for gravity flow. Between pipe jacking and tunneling, pipe jacking is eliminated due to its limited drive lengths, high jacking force requirement due to large pipe size. The size of pipe (17 and 25 ft) makes delivery and installation very difficult. Therefore, tunneling is selected for this project. Najafi (2013) provides capabilities and limitations of trenchless construction methods as shown in Figure 2-1.

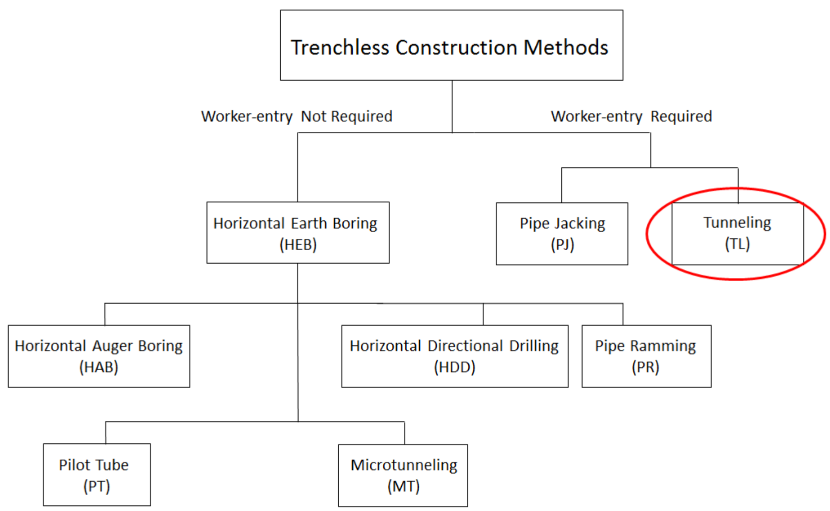


Figure 2-1 Trenchless Construction Methods for New Installation of Underground Pipelines (Adapted from Najafi, 2013)

2.1.1.1 Conventional Tunneling

According to definition of International Tunneling Association (ITA, 2009), the conventional tunneling technology is construction of underground openings of any shape with a cyclic construction process of excavation, installing the pipes, and placement of temporary support elements.

In excavation, drilling, blasting or mechanical excavators are normally used. Špačková considered excavation method, round length, excavation sequencing and support measures all as construction method depending on the geotechnical conditions and cross-section area of the tunnel (Špačková, 2012).

The critical factor for the selection is the stand-up time of the unsupported opening. To give an example, a tunnel constructed in very good ground conditions with long stability of unsupported opening can be excavated full face with round length of several feet and it requires only simple support. On the other hand, in difficult ground conditions, a finer sequencing, shorter round length and demanding support measures must be applied.

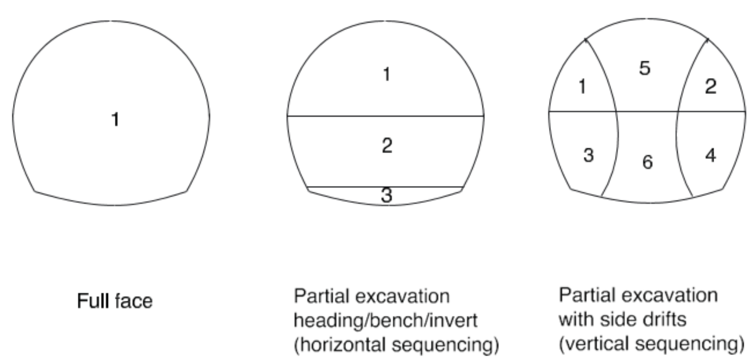


Figure 2-2: Typical Excavation Sequencing Types in Conventional Tunneling

Source: ITA, 2009

The conventional tunneling allows adjusting the construction process based on observations of the ground behavior, which are continuously carried out during the construction. The technology is therefore especially suitable for tunnels with highly variable geotechnical conditions, tunnel with variable shapes of tunnel cross-sections and for short tunnels, where utilization of expensive TBM would not be economically justifiable (Špačková, 2012).

The geotechnical monitoring is an essential part of the construction process. It enables to check the structural behavior with respect to the safety and serviceability criteria, to optimize the construction process and to control the impact of construction on the adjacent structures. The monitored parameters are usually the deformations (displacements, strains, changes in inclination or curvature), stresses and forces on structural elements, piezo metric levels and temperatures. A picture of tunnel construction by means of conventional tunneling with partial excavation is shown in Figure 2-3.

Figure 2-3: Conventional Tunneling in Dobrovskeho Tunnel, Brno, Czech Republic

(Špačková, 2012)

2.2.2.1 Tunnel Boring Machine (TBM)

International Tunneling Association defines mechanized tunneling as tunneling techniques, in which excavation is performed mechanically by means of teeth, picks or disks. The machinery used for the excavation is commonly called Tunnel Boring Machine (TBM). An example of TBM is shown in Figure 2-4. Diameter of the tunnel excavated with TBM can range from three ft (done with micro-TBMs) to 60 ft.

The application of TBM has several advantages compared to conventional tunneling methods. The excavation is generally faster, the deformations of the ground and surface are smaller, which is beneficial for the existing structures. However, the TBM can only excavate a round tube. Thus, must be in most cases combined with other construction methods for construction of access tunnels, technological rooms etc. It is also only suitable for longer tunnels, where the initial investment into the TBM purchase is reasonable.

The essential parts of the machine include the following items (ITA, 2001):

- Rotary cutter head for cutting the ground
- Hydraulic jacks to maintain a forward pressure on the cutting head
- Muck discharging equipment to remove the excavated muck
- Segment election equipment at the rear end of the machine
- Grouting equipment to fill the voids behind the segments, which is created by the over-excavation.

Different types of TBMs are designed for drilling in soft grounds and hard rocks. An overview is given in Figure 2-5.

Figure 2-4 TBM Used for Excavation of Underground Line Extension in Prague

Available at: http://stavitel.ihned.cz/

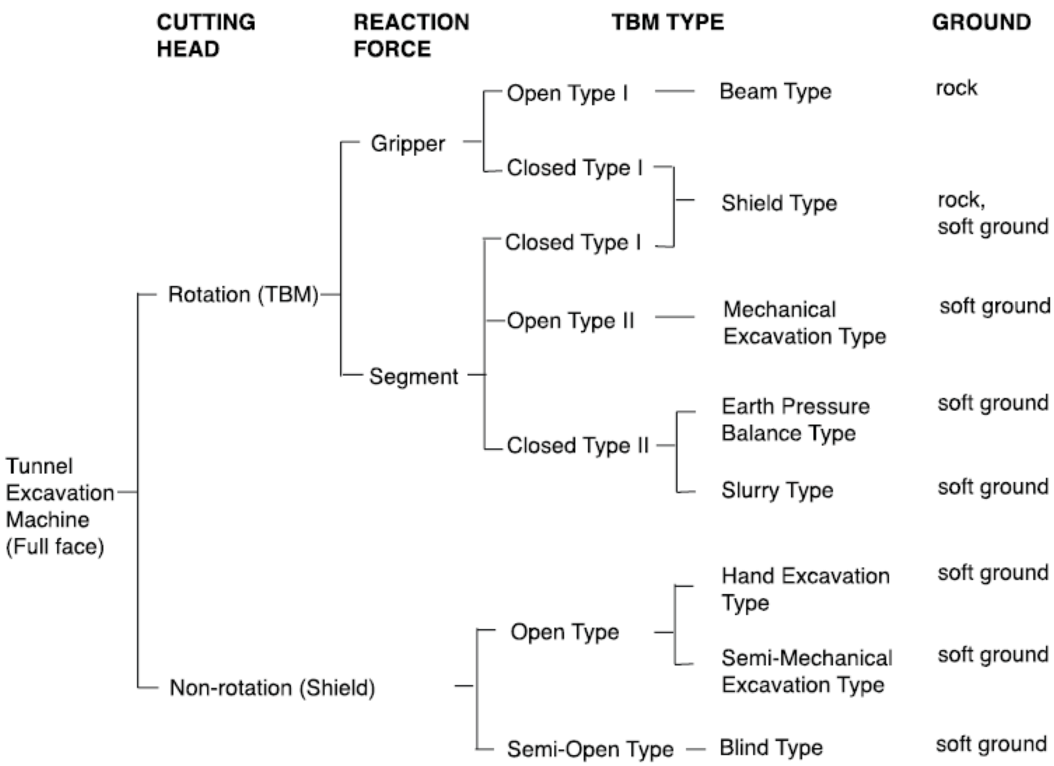


Figure 2-5 Types of Tunnel Excavation Machines (ITA, 2001)

2.2.2.2 Tunnel Boring Machine Technologies

The Tunnel Boring Machine (TBM) was introduced in 1975. The transport and evacuation of the excavated mucks and the mounting of the reinforced concrete lining was done using this machine. Since then, the technology has developed widely. For instance for three ft tunnel, the technology comprises of:

1. The excavation phase and the TBM advance.
2. The pre-casted concrete segmental lining is erected.
3. Soil grouting and water proofing works outside the lining ring.

Tunneling construction involves three main processes, namely excavation, dirt removal and tunnel support (Ruwanpura, 2001). The construction of a tunnel (using TBM) begins with the excavation and liner support of the vertical shaft. In the construction of a tunnel using TBM the following operations can be distinguished:

- Excavation and support of the undercut area
- Excavation of the tunnel and tail tunnel
- Disposal of dirt from the tunnel face
- Hoisting dirt to ground level
- Lining the tunnel
- Extending the services and rail tracks
- Excavation and support of the removal shaft.

Two types of tunneling boring machines are used in the tunneling construction practice, namely the open-face and closed-face shielded machines. Both methods are used in different circumstances. The open- face boring machines are used when excavating stable soils. When the soil conditions become less stable, because the soil consists of for example silt or sand, closed-face shielded machines are used. Important properties in the excavation processes using TBM are the excavation rate and stroke length of the tunneling boring machine. The excavation rate is dependent on the soil conditions and TBM horsepower. The stroke length determines how often the TBM will need to be reset.

Dirt handling involves the transportation and disposal of spoil from the tunnel face to the shaft, from where it is transported to the surface. Different methods are used to haul the spoil from the tunnel face to the shaft; examples are trains and belt conveyors. Using trains to haul spoil has many advantages. First of all it is compatible with most excavating and loading methods, and can be used in almost all sizes of tunnels. Another advantage is that besides hauling of spoil, also laborers and support liners can be transported using trains. Depending on the tunnel diameter, a single or double-track system can be used.

Belt conveyors on the other hand have the advantage of providing a continuous spoil removal system. The spoil that is hauled to the shaft of the tunnel using trains and /or belt conveyors subsequently has to be lifted up to the surface. Hoisting dirt can be done using different methods, these are: with a skip, a clamshell bucket, a crane, a gantry or a derrick hoist. The working shaft is also used to transport construction material and personnel (Ruwanpura, 2001).

Two important tunnel support systems consist of rib-and- lagging and concrete segments. The rib-and-lagging support system is used as a primary lining system. When tunneling excavation is finished, cast-in-place concrete is placed as final lining. Pre-cast concrete segment lining acts as primary and final lining. The segments are installed inside the shield of the TBM, and expanded against the soil as it leaves the shield (Ruwanpura, 2001). For tunneling by TBM there are also other primary support systems used, namely: steel sets, rock reinforcement systems, and shotcrete (Likhitruangsilp, 2003).

2.1.2 Open-cut Tunneling

Open-cut involves trenching or digging and then installing the pipeline on a suitable bedding material and then backfilling (Najafi and Gokhale, 2005). Figure 2-6 illustrates a typical pipeline installation. Open-cut construction for the UFT project will be considered as an option for pipeline installations at locations where there will be minimal disturbance to the traffic, public and environment. Typically, in rural areas, open-cut method is more feasible and economical as adequate space will be available in medians, side aprons as well as there will be less number of roadways crossing the right-of-way as compared to urban areas. But, in open-cut method, a part of construction efforts and resources are spent on detour of roads, managing traffic flow, trench excavation, shoring, dewatering in certain cases, backfilling and compacting, bypass pumping, and reinstating the surface (Najafi and Gokhale, 2005). Hence, for routes in urban areas, such as the proposed route of DFW airport to any of the major distribution centers, trenchless technology methods (pipe jacking and utility tunneling) will be the only feasible solutions.

Figure 2-6. Typical Pipeline Installation (Photo by Dr. Najafi)

Open-cut is the most commonly used underground construction method. This is essentially an open excavation in which the structure is supported by retaining walls while it is being built and then backfill placed above the completed facility.

Structures buried at relatively shallow depths are generally well suited for open-cut techniques, off ring a fairly low-cost excavation approach. The major drawback of open-cut method is the large work area required. When construction space is limited, as is often the case in congested urban areas, less disruptive construction techniques are often necessary. The designer must make a decision based not only on construction costs, but also on the relative merits of other types of construction, such as tunneling, which can greatly reduce surface traffic interference.

The open-cut tunnels are constructed directly from the surface. The construction consists of excavating a trench or a cut, installing of temporary walls to support the sides of the excavation, roofing the tunnel and covering it with fill material. The costs of the excavation increase significantly with the depth of the tunnel, the method is thus suitable for construction of shallow tunnels. The method is often used for the construction of beginning and end parts of the bored tunnels as shown in Figure 2-7. The major limitations of an open-cut construction are its disturbing impact on the surroundings and the need of extensive traffic disruptions.

Figure 2-7 Blanka Tunnel in Prague, Czech Republic,

a Section Constructed with Open-cut Method

(Špačková, 2012)

In constructing tunnels using the open-cut method, the shape of tunnel will usually be rectangular. The followings are the basic technologies for open-cut tunneling:

1. Reinforced concrete walls with steel struts, pre-stressed tie-backs or self-supported.

2. The ground water in the soil is lowered by introducing the water well or similar systems.

2.1.3 Pipe Jacking

Pipe jacking is a technique for installing underground pipelines, ducts and culverts. Powerful hydraulic jacks are used to push specially designed pipes through the ground behind a shield at the same time as excavation is taking place within the shield. The method provides a flexible, structural, watertight, finished pipeline as the tunnel is excavated. Figure 2-8 shows the components of pipe jacking operation.

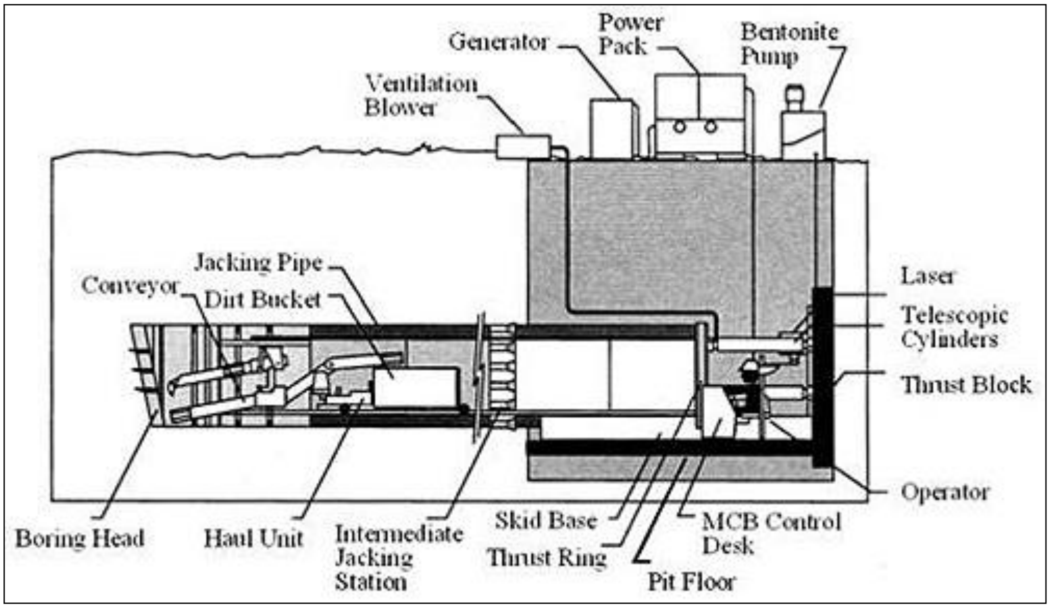


Figure 2-8 Typical Components of a Pipe Jacking Operation

(Najafi and Gokhale, 2005)

There is no theoretical limit to the length of individual pipe jacks although practical engineering considerations and economics may impose restrictions. Drives of several hundred feet either in a straight line or to a radius or a series of radii are readily achievable. A range of mechanical and remote control excavation systems are available. Pipes in the range one ft to 10 ft, can be installed by employing the appropriate system. Construction tolerances are comparable with other tunneling methods, and the pipe jacking method generally requires less over break than alternative systems. It provides ground support and reduces potential ground movement. Mechanical excavation methods are similar to those employed in other forms of tunneling. Shields, excavation and face support can be provided for a wide variety of ground conditions.

To install a pipeline using this technique, the basic procedure can be described as follows:

1. Excavate and prepare the drive shaft.

2. Set up the thrust wall, jacking frame and the hydraulic jacks and adjust to the proposed design line and grade.
3. A thrust wall is constructed to provide a reaction against which to jack. In poor ground, piling or other special arrangements may have to be employed to increase the reaction capability of the thrust wall. Where there is insufficient depth to construct a normal thrust wall, for example through embankments, the jacking reaction has to be resisted by means of a structural framework having adequate restraint provided by means of piles, ground anchors or other such methods for transferring horizontal loads.
4. Install the laser guidance system in the drive shaft. During the tunneling operation, the operator continuously checks the mark on the steering head and the laser point. If the operator detects a deviation, the steering head is articulated to correct the alignment. The initial alignment of the pipe jack is obtained by accurately positioning guide rails within the thrust pit on which the pipes are laid. To maintain accuracy of alignment during pipe jacking, it is necessary to use a steerable shield, which must be frequently checked for line and level from a fixed reference. For short or simple pipe jacks, these checks can be carried out using traditional surveying equipment. Rapid excavation and remote control techniques require sophisticated electronic guidance systems using a combination of lasers and screen based computer techniques.
5. Lower the tunnel boring machine (TBM) into the drive shaft and set on the guide rails.
6. To ensure that the jacking forces are distributed around the circumference of a pipe being jacked, a thrust ring is used to transfer the loads. The thrust ring is a frame that main cylinders push against to advance the boring head and the pipe.

The ring provides a 360° surface against the pipe to minimize the point loads and reduce the chance of pipe breakage. The jacks are interconnected hydraulically to ensure that the thrust from each is the same.

7. Advance the shield or TBM through the prepared opening in the shaft support structure. Begin the excavation and spoil removal process. Continue excavation, spoil removal, and forward advancement until the shield or the TBM is installed. The control panel outside the boring machine controls the movement of the jacking machine, whereas the control levers inside the boring machine control the tunneling operation.
8. Retract the jacks and push plate to provide a space for the pipe segment. The number of jacks used may vary because of the pipe size, the strength of the jacking pipes, the length to be installed and the anticipated frictional resistance.
9. Place the first pipe segment on the jacking tracks.
10. Mate the push plate to pipe and pipe to the shield or TBM.
11. Initiate forward advancement, excavation, and spoil removal. There are five main spoil transportation methods that include:
    a) Wheeled carts or skips
    b) Belt conveyor
    c) Slurry system,
    d) Auger system, and
    e) Vacuum extraction system
12. Repeat pipe jacking cycles until the complete pipeline is installed.
13. Remove the shield or the TBM from the reception shaft.
14. Remove the jacking equipment, IJS, and tracks from the drive shaft.
15. Restore the site as required.

When the pipe jack or microtunneling is carried out below the water table it is usual to incorporate a headwall and seal assembly within each thrust and reception pit. The use of these items prevents ingress of ground water and associated ground loss, and retains annular lubricants.

2.2 Chapter Summary

In this chapter the major aspects of tunneling with Tunnel Boring Machines and open-cut were discussed. In general, for long tunnels, the TBM method of tunneling will be more economical as it causes less disruption to the surface compared open-cut method. The major issue with open-cut method is its need for a large surface availability which in most cases is not available and almost impossible in urban areas.

Chapter 3

Case Studies

3.1 GRID Logistics

3.1.1 GRID Logistics Concept

GRID Logistics, Inc. (GLI) is not only proposing a system to optimize port productivity and connectivity to inland markets, but also providing a model for sustainable infrastructure in major port complexes around the world. This system will extremely reduce port-related emissions and traffic congestion, and, yield substantial acreage for real estate development. The freight pipeline, shown for an example application in Southern California in Figure 3-1, is the conduit for increasing container throughput for regional deliveries without requiring additional freeway construction or expansion to accommodate increased trucking.

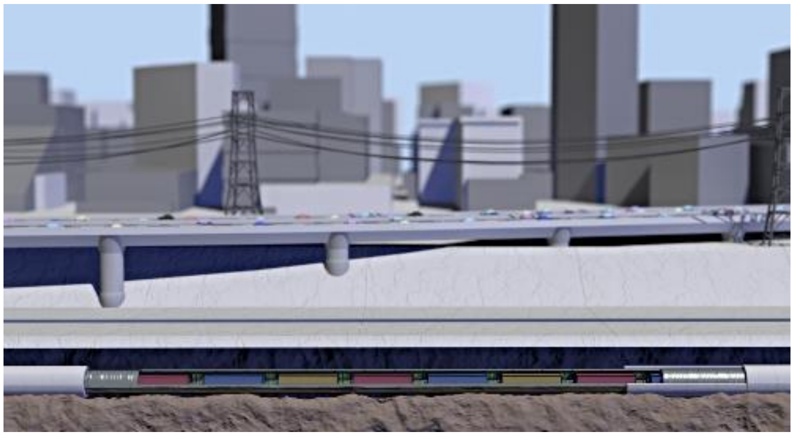


Figure 3-1 Grid Freight Pipeline Side-View

Available at: http://www.gridinc.biz/

Figure 3-2 shows a proposed pipeline route that would link the SuperDock™[6] with seven inland feeder terminals, shown as green dots, located near freight distribution warehouses, shown as blue dots. The 15-foot-diameter, underground pipeline will provide single direction circulation of vehicles traveling between the SuperDock™ and inland feeder terminals. Containers would intersect with the surface at the feeder terminals, for "last mile' delivery only by trucking to and from the warehouses. The freight pipeline will serve locally designated cargo currently transported via truck drayage. Since the freight pipeline will only serve unmanned vehicles, it will not require the lighting, ventilation, and similar full-scale life support systems applicable to subways. Hence, its base construction cost is comparable to that of large storm drains, with the addition of powered rail and life support systems only as required for maintenance.

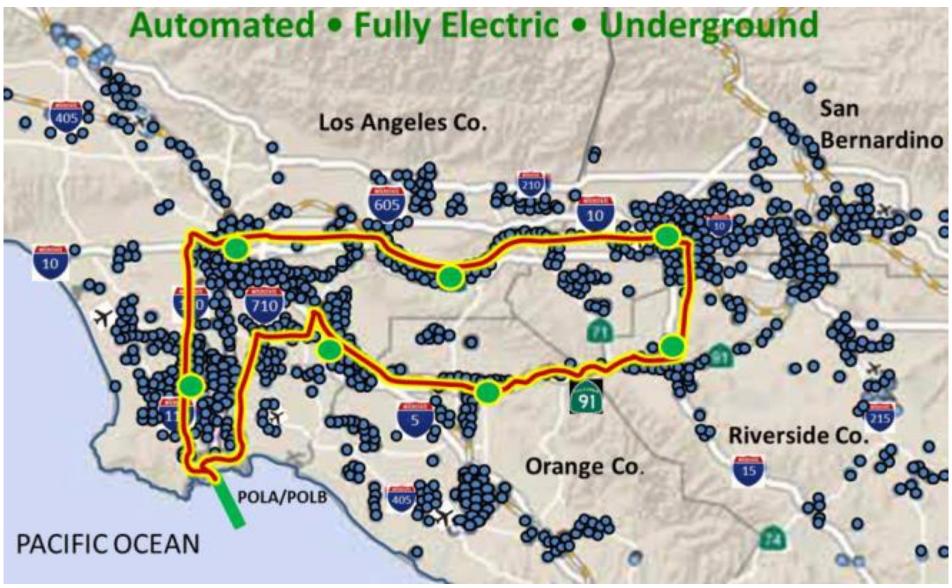


Figure 3-2 GRID Project Map for Los Angeles Area (Grid Logistics)

Available at: http://www.gridinc.biz/

[6] The SuperDock™ is a vertically-integrated ship-to-train container transfer, storage, and sorting module that can free up to half the land currently used in port facilities from cranes, trucks, and storage and make it available for development.

3.1.2 Inland Feeder Terminals

Inland feeder terminals (Figure 3-3) are proposed along the pipeline at strategic locations, near existing freight consolidation warehouses, factories, or other sources or destinations of goods. These terminals will allow local truck access to containers flowing in the freight pipeline between the feeder terminals and the SuperDock^{TM}. The feeder terminals will transfer containers between the pipeline and trucks, and are designed to be similar to the SuperDock^{TM} with vertical storage. Truck travel zones will be generally limited to a reasonably short radius around each feeder terminal, repurposing the trucks to last-mile deliveries within local distribution zones. This ultimately allows the trucker to complete more deliveries per day, rather than traveling to and from a port complex for one inland container delivery, expending fuel and contributing to freeway congestion.

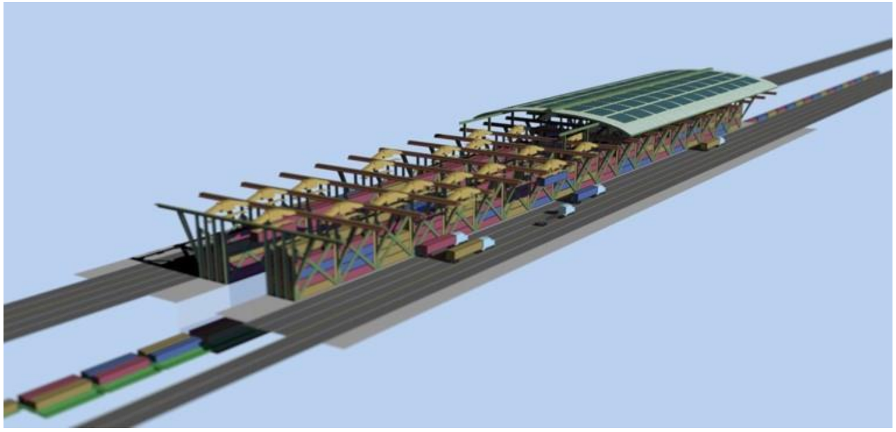


Figure 3-3 Grid Feeder Terminal (Grid Logistics)

Available at: http://www.gridinc.biz/

3.2 Freight Shuttle

3.2.1 Freight Shuttle System Concept

The Freight Shuttle System (FSS) concept was initiated at the Texas A&M Transportation Institute (TTI) for the purposes of finding a low-emissions alternative to moving freight and relieving congestion created by trucks in heavy freight corridors. The

Freight Shuttle moves truck trailers up to 53 ft, domestic intermodal containers up to 53 ft, and all sizes of ocean shipping containers. FSS works with electric powered transporters on elevated guideways in the medians of highways, other sides of rights-of-way and private properties over distances of up to 500 miles. Fully automated, the electrically powered shuttle transporters travel unimpeded along a dedicated guideway above traffic. This provides additional security for the freight and avoids interaction with existing traffic, possibly adding capacity to existing transportation infrastructure. As an electrically powered transportation technology, it will create very small amount of emissions within existing highway rights-of-way where it is operated, and the potential emissions that may have been created by a hydrocarbon based transport are mitigated.

The guideway-vehicle combination comprises the elements necessary for an electrically-powered linear induction motor—with the stator positioned as a vertical element in the center of the guideway and the motor windings positioned on either side of the stator as opposing linear motors on each shuttle vehicle. The shuttle vehicle is positioned across and straddles the vertical guideway in a manner that prevents decoupling from the guideway. The system is further characterized by steel wheels operating on a continuous steel running surface. The guideway's track surface consists of a reinforced concrete structure of sufficient thickness and width to support fully-loaded intermodal containers. The guideway can be elevated or installed alongside existing roadways or other facilities, thereby utilizing existing highway or other rights-of-way.

The overall system is designed to operate as a continuously circulating conveyor of containers or truck trailers over distances ranging from a few miles up to 500 miles. I-35 corridor may be an ideal location for a first phase of a FSS in Texas. Ultimately, a multi-segment system could connect Laredo, San Antonio, Austin, and Dallas/Fort Worth, in addition to potentially linking these areas to the major Texas ports. Removing trucks from this corridor of statewide economic significance would not only reduce congestion in some of the most constrained areas of the Texas transportation system, but also help mitigate the detrimental effects that trucking has had on some of the cities located along this corridor. Dallas, San Antonio, and Austin have been identified as experiencing some level of unhealthy air quality (TxDOT).

3.3 Cargo Cap

3.3.1 Cargo Cap Concept

CargoCap is a concept for an underground transportation system based on automatically driven vehicles in pipelines. Each capsule carries two euro-pallets (2.6 ft x 3.9 ft x 3.4 ft) at a nearly constant velocity of 22mph. The euro-pallet is a standardized freight carrier that has proved itself in practice. Because of the loading with only two euro-pallets into each capsule, a high loading and distribution flexibility is ensured. If more goods have to be delivered to one destination, simply more vehicles run in combination. Flexible, fully automated and loading and unloading stations make the turnover fast and competitive.

CargoCap is considered for freight transport in congested urban areas on the local and long-distance traffic sector up to 90 miles. The vehicles call at many stations in an extensive underground transportation pipe network 24 hours a day. At their final destination one or more vehicles arrange themselves automatically into the station to be reloaded or unloaded. Because of underground transportation pipes, CargoCap is independent, unaffected and uninfluenced by other transports, traffic routes and traffic jams. In operation CargoCap does not impair the environment neither with noise or exhaust fumes.

The great advantage of CargoCap is the fast and uncomplicated extensibility of the transportation pipe network. If the demand for transport increases, the underground transportation network simply grows with it. Thus CargoCap is able to support the economic development and the increase of the competitive ability of business locations effectively beneath far reaching advantages for the environment and benefits for security.

3.3.2 Cargo Cap Construction Method

Because of using pipe jacking and the relatively small diameter of the transportation pipes, the CargoCap-pipes can be laid in public space next to or under existing infrastructure facilities without problems. That could be sewers, gas-, water- and district heating pipes, pipelines, electric cables for data and energy transfer as well as underground railway and road tunnels.

Figure 3-4. View of a Starting Shaft in Pipe Jacking method

Available at: http://www.cargocap.com/

CargoCap is able to expand unrestrictedly because of underground line alignment. Additional transportation pipes increase the transport capacity depending on demand.

3.3.3 Cargo Cap Technology

In CargoCap, the vehicles are designed aerodynamically and trailing wheels take on the function of bearing, lateral guide rollers keep the Vehicles on track.

The drive is provided electrically by the wheels. In this connection three-phase asynchronous motors supplied by frequency converters come into operation. This concept is marked by a robust construction, low energy consumption, low initial costs as well as a long life with a low need for maintenance. In addition, the chosen drive concept provides optimum traction in connection with high operation security.

In connection with the individual control of the vehicles the small distance of 7 ft requires a novel branching system which makes it possible to discharge the single vehicles out of a collective without speed reduction. Thus a constant flow of transport is ensured.

In this connection the vehicle steers the process of turning off. The switches themselves are complete passive elements. The driving direction is chosen by the vehicle before entering the branching area according to the final destination programmed inside the on-board computer.

3.3.4 Cargo Cap Operating Safety

An elementary criterion of CargoCap represents the operating safety. The vehicles possess, beneath the electric service breaking device, a second independent brake unit. The equipment with several engines ensures that in case of a defect the way can be continued with reduced performance at least to the next station. In addition, the fronts of the vehicles are equipped with collision units which allow pushing broken down vehicles out of the pipeline or tunnel.

Table 3-1. CargoCap Characteristics

Derived from http://www.cargocap.com/

Characteristics	Value	Unit	Characteristics	Value	Unit
Net Weight	1,767	lb	Wheel Diameter	7.87	in.
Max. Payload	4,410	lb	Wheel Base	9.3	ft
Max. Speed	25	mph	Length of the vehicle	11.5	ft
Speed	22	mph	Supply Voltage	500	Volts
Max. Acceleration	3.3	ft/s^2	Duration Power	3.4	kW
Track Gauge	31.5	in.	Top Performance	35	kW

3.3.5 Sustainability

During the construction of the mechanic as well as the electric components it was emphasized that inevitable wear and tear always occurs on the vehicle but not on the track. So wearing parts can be replaced easier, faster and cheaper.

3.3.6 Control Technique

An essential aspect of CargoCap is the fully automated operation management. This applies to the control of the tracks, vehicles, shunting and load turnover as well as the various safety controls. The operational control system is integrated into a logistic structure, so the customer is able to follow the movement of the goods at any time.

The concept of control and the information processing shows a distributed architecture. It includes specific computers together with sensor technology, actuators and communication interfaces for various tasks.

The interaction of all components requires a safe exchange of information. For that CargoCap possesses a partly cable-based and a partly radio-based communication network.

3.4 Chapter Summary

Table 3-2 shows the specifications of the case studies reviewed in chapter 3.

Table 3-2 Case Studies

Name	Cargo's Sizes	Pipe Diameter (ft)	Propulsion System	Speed (mph)	Proposed Length (miles)	Constructi on Method	Proposed Location	Studied by
Freight Shuttle System	Container	N/A	LIM	N/P	Up to 500	Bridge and Deck	I-35 from Laredo Border to DFW	TTI
GRID Logistics	Container	15	LIM	N/P	Up to 137	TBM	Southern California	GRID Logistics, Inc.
Cargo Cap	Euro-Pallet	6.5	LIM	22.3	Up to 90	MTBM/Pipe Jacking	Germany	CargoCap GmbH
CUIRE UFT	Container	25	LIM	45	Up to 500	TBM/Open-cut	Port of Houston to Dallas	CUIRE / UTA
CUIRE UFT	Crate	17.4	LIM	45	Up to 25	TBM	DFW Airport to Distribution Center	CUIRE / UTA
CUIRE UFT	Pallet	13	LIM	45	Up to 25	TBM/Pipe Jacking	Port of Houston to Distribution Center	CUIRE / UTA

Chapter 4

Survey and Interview

4.1 Survey

4.1.1 Survey with Tunneling Experts

To supplement the literature research, a survey was conducted with several tunneling design and construction as well as transportation planning and engineering firms in U.S. and also out of U.S. (countries such as, Germany, France, China, Netherlands, and Italy) to find their comments and expertise in tunneling and open-cut tunnel construction. The survey gathered valuable technical information on key elements of UFT.

The survey consisted of three parts. First part is the respondent contact information. Second part focuses on the tunneling with TBM. Third part is tunneling with open-cut. The Survey included multiple choice, essay and rank questions. Under each question a comment box was designed so the respondents can provide their feedback. The survey was sent to more than 70 individuals in various tunnel construction fields of expertise such as engineering and design, planning, contracting, operating and regulating in and out of U.S and total number of 38 responses were received. Appendix B includes questionnaire. Figure 4-1 shows the number of respondents from each country.

Multiple choice questions were analyzed and presented in a table and a chart format. In ranking questions, to be able to make comparison among provided options, weights were assigned to the options based on their degree of desirability. For instance in the question which asked for ranking the obstacles in TBM or open-cut method, the option which ranked the 1st, received weight of 6 and the option that was ranked as the least favorable received the weight of 1. Then weighted average was calculated for each alternative. The option that received the highest weighted average score was determined as the most desirable answer. Ranking questions results are presented in a table and a pie chart format. The results of the survey are as follows. Additionally, the definitions are listed in Appendix A.

Figure 4-1 Number of Respondents from Each Country

Since the respondents might have more experience either in tunneling or open-cut method, they could fill the survey partially. Therefore, the number of respondents for every question is different. In survey analysis section, this number is specified for each question.

1. Have you been involved in planning, design or construction of pipe jacking /tunnels and/or pipeline construction using open-cut methods?

Table 4-1 Number of Respondents Involved in Tunnel Construction

Based on 38 Respondents

Answers	No. of Responses	Percentage (%)
Yes	35	92
No	3	8

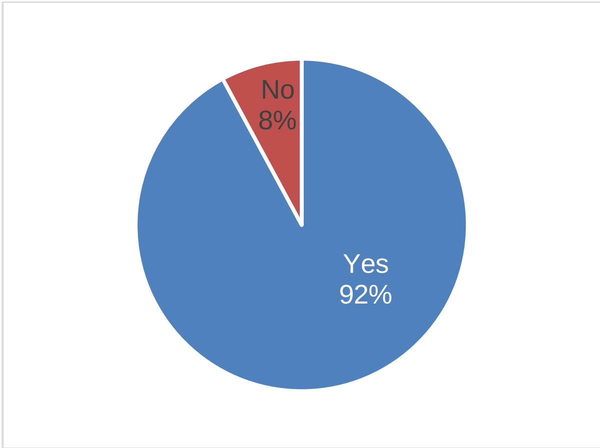


Figure 4-2 Number of Respondents Involved in Tunnel Construction

Based on 38 Respondents

As it is shown in Figure 4-2, since this survey was asked from the tunnel industry firms, almost all of the respondents are involved in tunnel design or construction and only 8% of them did not have any experience in this fields. Therefore, survey analysis was restrained to 35 respondents only.

2. Please specify your type of involvement with pipe jacking/tunnels and/or pipeline construction using open-cut methods.

Table 4-2 Type of Respondents Affiliations

Based on 35 Respondents

Affiliations	No. of Responses	Percentage (%)
Planning	19	54
Engineering	12	34
Contracting	2	6
Regulating	2	6
Operating	0	0

Based on Table 4-2 and Figure 4-3, on overall distribution, the highest number of affiliations served with planning and design of tunnel projects in and out of U.S., that is 19 and the second highest is engineering followed by contracting and regulating.

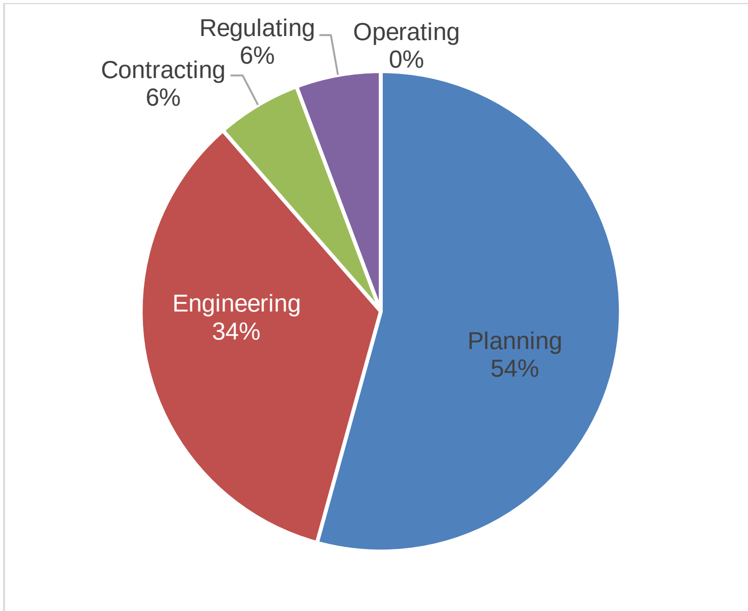


Figure 4-3 Type of Respondents Affiliation

Based on 35 Respondents

3. For the following, please rank *Obstacles* in TBM method from **1 (the least)** to **6 (the most)**?

Table 4-3 Obstacles in TBM Method

Based on 35 Respondents

Obstacles	Ranking Score	Percentage (%)
Bridges (Piles, Foundations, Piers, etc.)	96	24
Rivers	76	19
Underground Water	60	15
Possibility of Settlement at the surface	58	15
Utilities Relocation	56	14
Soil Condition	52	13

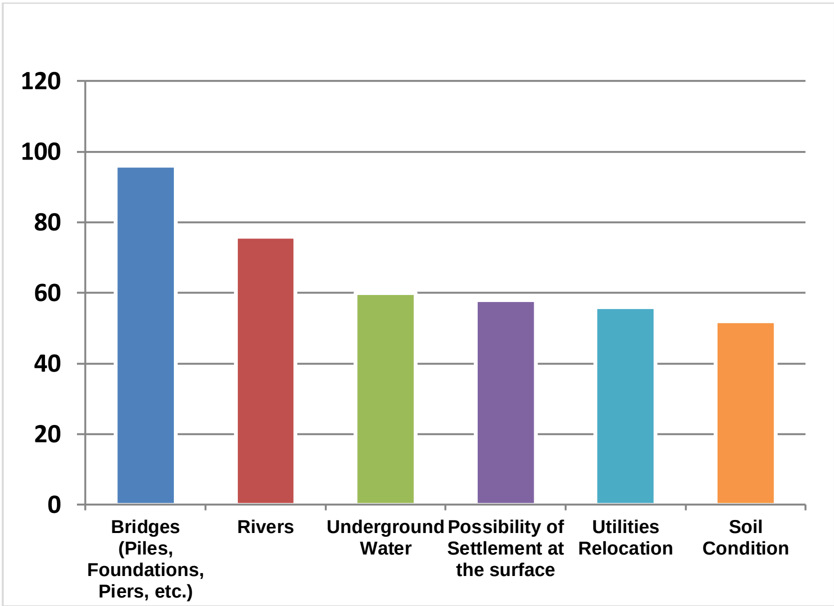


Figure 4-4 Obstacles in TBM Method

Based on 35 Respondents

As it is shown in Table 4-3 and Figure 4-4, bridges piles, foundation and piers are the obstacles that can highly impact on tunnel construction in TBM method. The second obstacle is river which can cause difficulties on TBM operation and tunnel construction followed by underground water, settlement at the surface, utilities relocation and soil condition.

4. Which of the following has *more impact* on **Productivity** of *TBM method*? Please rank from **1 (the lowest impact)** to **13 (the highest impact).**

Table 4-4 and Figure 4-5 show that in TBM method, mobilization/demobilization and ROW space are the most important parameters that effect on productivity of the tunnel project and soil condition and TBM excavation have the least impact on the productivity.

Table 4-4 Parameters Impact on Productivity of TBM Method

Based on 33 Respondents

Parameters	Ranking Score	Percentage (%)
Soil Condition	240	13
Spoil Removal	202	11
TBM Excavation	202	11
Groundwater	176	10
TBM Maintenance	170	10
Availability and Delivery of Segmental Linings	158	9
Availability of Disposal Sites	120	7
Mobilization/demobilization	102	6
Access Shaft Construction	100	6
Entry/Exit Shaft	94	5
TBM Manufacturing of the Project	92	5
Social and Environmental Impacts	76	4
Right-of-way Space	54	3

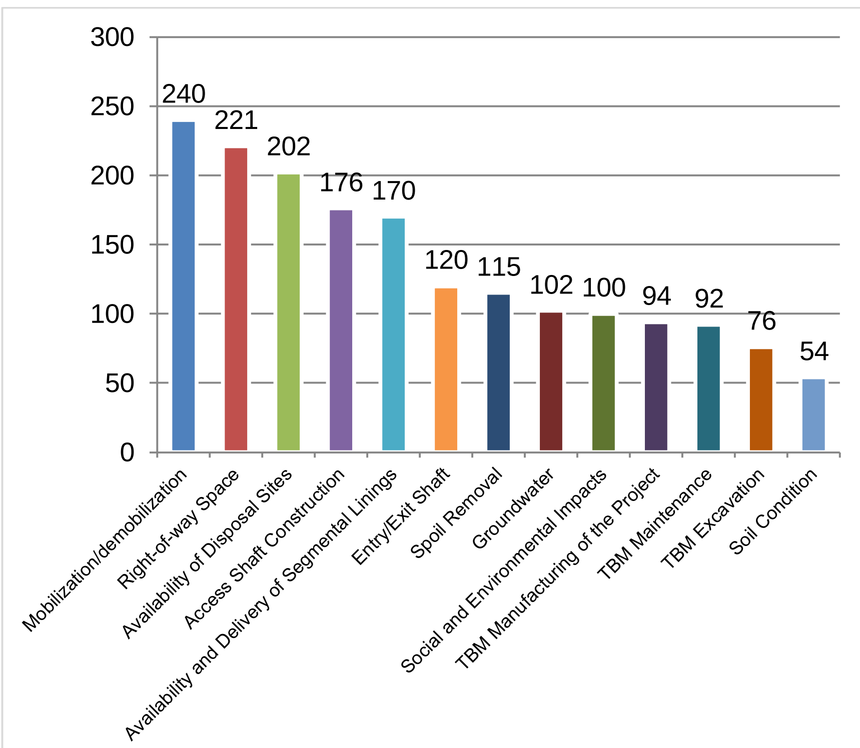


Figure 4-5 Parameters Impact on Productivity of TBM Method

Based on 33 Respondents

5. Which of the following has *more impact* on **Constructability** *TBM method*?

Please rank from **1 (the lowest impact)** to **13 (the highest impact).**

Table 4-5 Parameters which has Impact on Constructability

of TBM Method, Based on 33 Respondents

Parameters	Ranking Score	Percentage (%)
Soil Conditions	258	14
Spoil Removal	184	10
Groundwater	174	10
Availability of Disposal Sites	152	9
TBM Excavation	146	8
TBM Maintenance	138	8
Availability and Delivery of Segmental Linings	134	7
Entry/Exit Shaft	132	7
Access Shaft Construction	124	7
Right-of-way Space	106	6
Mobilization/demobilization	84	5
Social and Environmental Impacts	82	5
TBM Manufacturing of the Project	80	4

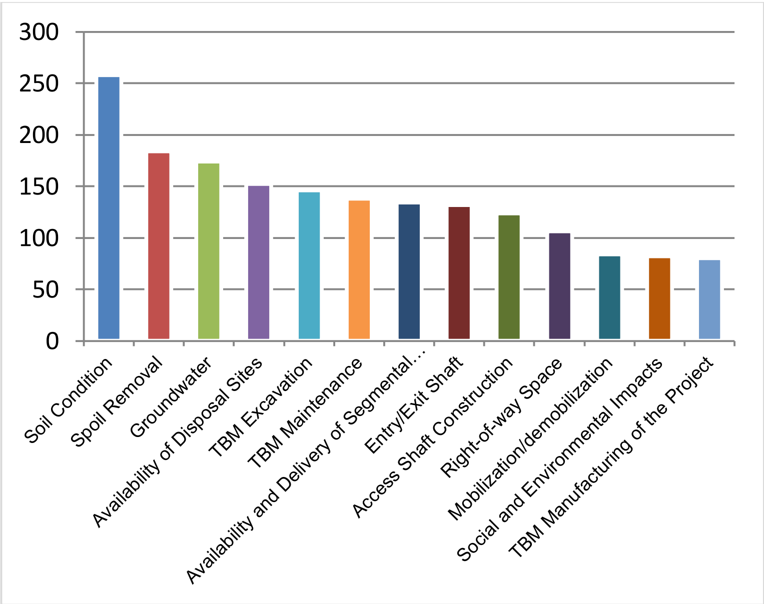


Figure 4-6 Parameters Impact on Constructability of TBM Method

Based on 33 Respondents

Table 4-5 and Figure 4-6 presented that soil condition has significantly the most impact on constructability of TBM method. Moreover, spoil removal followed by groundwater and availability of disposal site are the parameters that impact on the constructability of a tunnel project using TBM method.

6. What is the *minimum Depth to top of the tunnel* using TBM method?

Table 4-6 Depth to the Top of the Tunnel Using TBM Method

Based on 29 Respondents

Min. Depth to Top of Tunnel	No. of Responses	Percentage (%)
20 ft	24	83
20 – 40 ft	5	17
40 – 60 ft	0	0
More than 60 ft	0	0

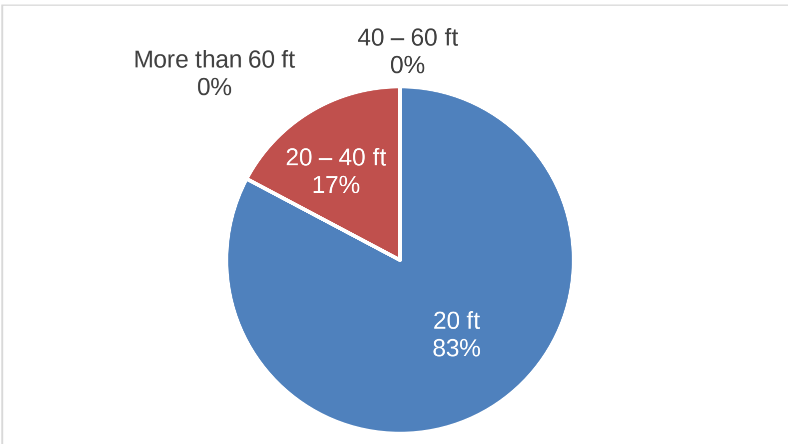


Figure 4-7 Depth to the Top of the Tunnel Using TBM Method

Based on 29 Respondents

As it is presented in Figure 4-7On this question, one of the experts in tunneling industry had a comment that "generally, the rule of thumb suggests the depth of the tunnel (from surface to centerline of tunnel) to be 2/3 times the diameter." Additionally, most of the respondents chose minimum depth of 20 ft to the top of tunnel and 17%

believed that 20 ft depth is not adequate for a 25 ft diameter tunnel and it should be between 20 ft and 40 ft.

7. What is the *maximum Slope* for *TBM operation*?

Table 4-7 Maximum Slope for TBM Operation

Based on 20 Respondents

Maximum Slope	No. of Responses	Percentage (%)
10° - 20°	10	50
20° - 30°	7	35
Less than 5°	2	10
5° - 10°	1	5
More than 30°	0	0

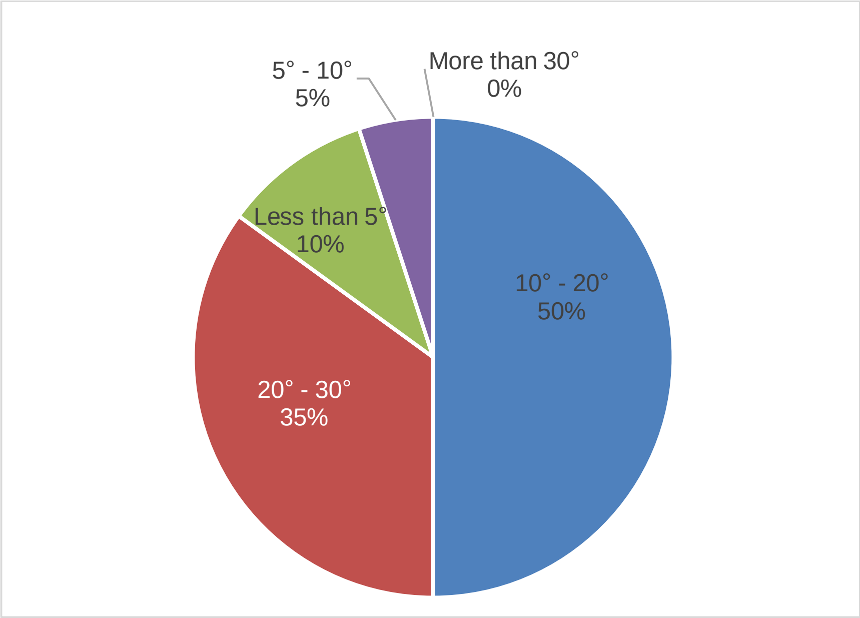


Figure 4-8 Maximum Slope for TBM Operation

Based on 20 Respondents

Figure 4-8 and Table 4-7 illustrate the slope for TBM operation. About 50 % of the respondents were satisfied with 10° – 20 °, whereas 35% of the experts chose 20° to 30° followed by less than 5° and 5° to 10 °.

8. What is the *suitable maximum Distance* between *Access Shafts*?

Table 4-8 Maximum Distance between Access Shafts

Based on 23 Respondents

Max. Distance between Access Shafts	No. of Responses	Percentage (%)
1 – 1.5 mile	19	82
0.5 - 1 mile	4	18
Less than 0.5 mile	0	0
More than 1.5 mile	0	0

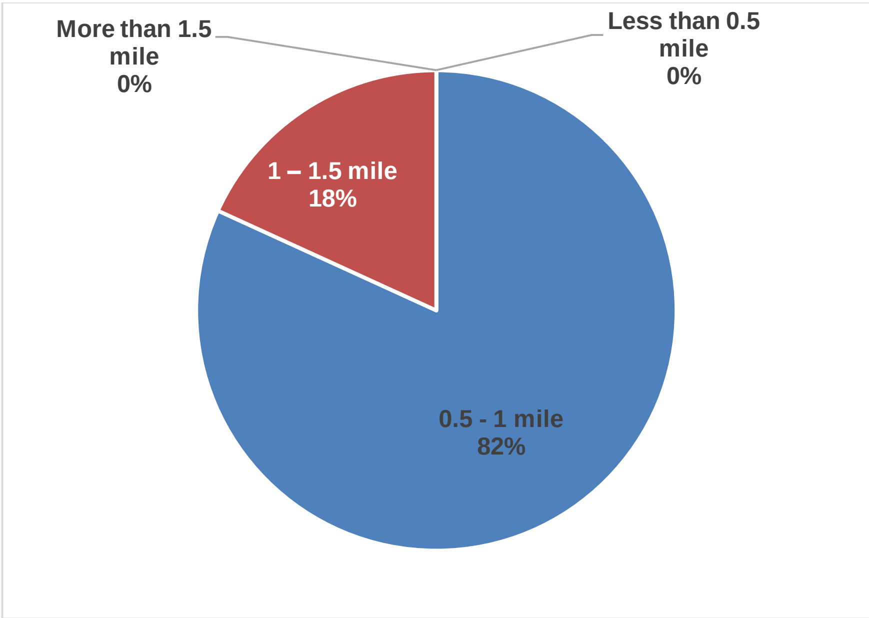


Figure 4-9 Maximum Distance between Access Shafts

Based on 23 Respondents

Based on Figure 4-9 and Table 4-10, most of the respondents suggested 0.5 to 1mile distance between access shafts and only 18% believe that it should be between 1 and 1.5 miles.

9. What is the *maximum Distance* for one *TBM operation*?

Table 4-9 Maximum Distance for one TBM Operation

(Between Entry and Exit Shafts)

Based on 18 Respondents

Max. Distance	No. of Responses	Percentage (%)
15 – 20 mile	6	33
20 – 25 mile	6	33
Other*	6	33
Less than 10 mile	0	0
10 - 15 mile	0	0

* Respondents added different distances.

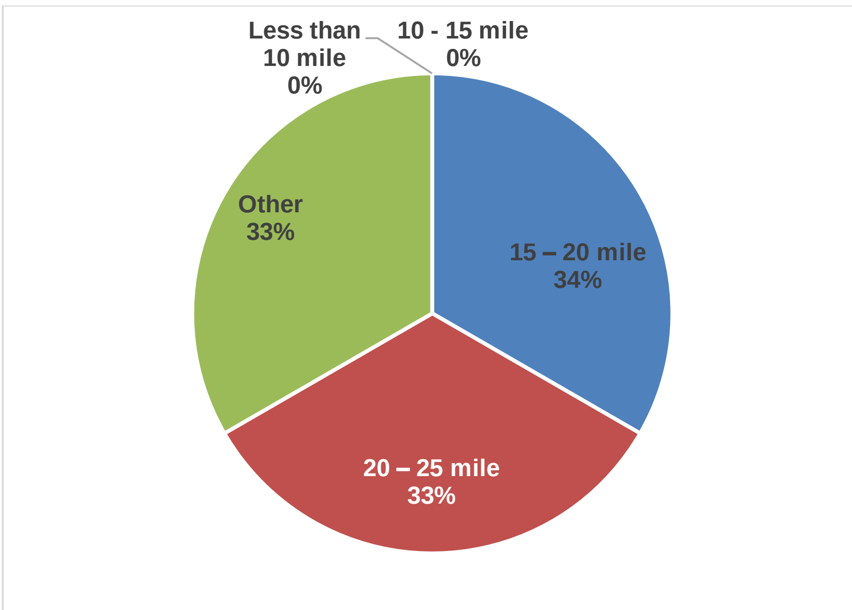


Figure 4-10 Maximum Distance for one TBM Operation

Based on 18 Respondents

As it is shown in Table 4-9 and Figure 4-10, the percentages of three options for the distance for one TBM operation are equal. It shows that the respondents did not have enough knowledge about this issue and these answers are disqualified for analysis.

10. What is the *approximate Advance Rate* of constructing tunnels using *TBM*?

Table 4-10 Advance Rate of Constructing Tunnels Using TBM

Based on 25 Respondents

Advance Rate	No. of Responses	Percentage (%)
100 - 150 ft/day	13	50
More than 150 ft/day	8	33
50 - 100 ft/day	4	17
Less than 50 ft/day	0	0

Table 4-10 and Figure 4-11 show 52% of the respondents believe that the approximate advance rate for building a tunnel with TBM method is between 100 and 150 ft/day. Interestingly, the result presents that 83% of the experts chose the advanced rate of more than 100 ft/day in this question.

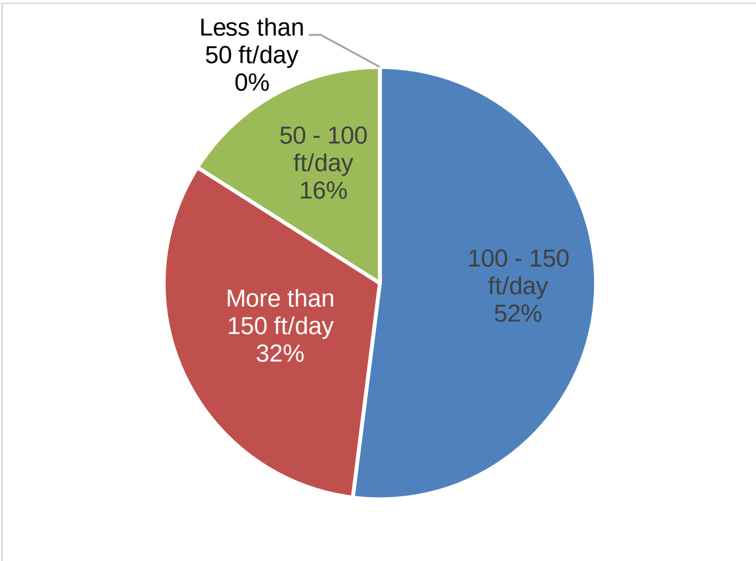


Figure 4-11 Advance Rate of Constructing Tunnels Using TBM

Based on 25 Respondents

11. For the following, please rank *Obstacles* in *Open-cut method* from **1 (the least)** to **6 (the most)**?

Table 4-11 Obstacles in Open-cut Method

Based on 31 Respondents

Obstacles	Ranking Score	Percentage (%)
Rivers	124	25
Bridges (Piles, Foundations, Piers, etc.)	94	19
Utilities Relocation	90	18
Underground Water	82	16
Soil Conditions	70	14
Possibility of Settlement at the Surface	38	8

Table 4-11 and Figure 4-12 present that rivers could be major obstacles for building the tunnel using open-cut method. Moreover, bridges, utilities relocation and underground water are some problems that the project might be faced during the construction.

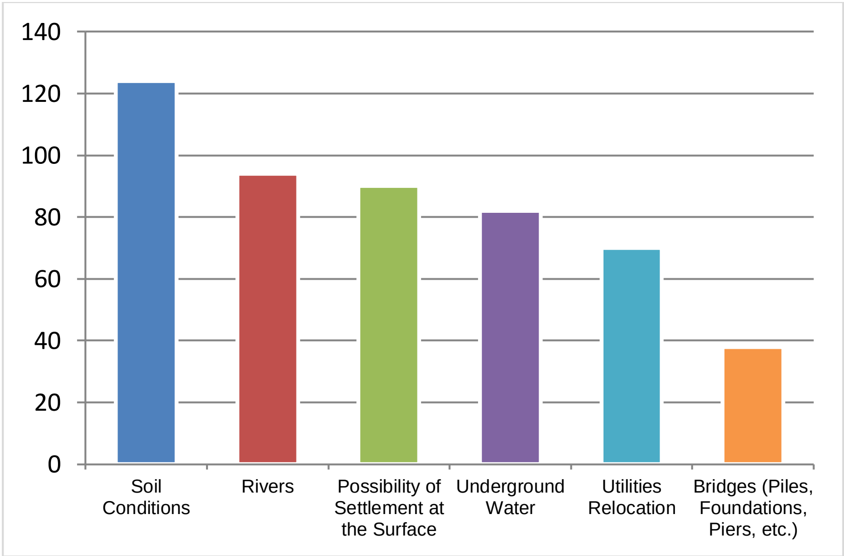


Figure 4-12 Obstacles in Open-cut Method

Based on 31 Respondents

12. Which of the following has *more impact* on **Productivity** of *Open-cut method*?

Please rank from **1 (the lowest impact)** to **12 (the highest impact).**

Table 4-12 Parameters Impact on Productivity of Open-cut Method

Based on 31 Respondents

Parameters	Ranking Score	Percentage (%)
Right-of-way Space	228	12
Groundwater	210	11
Spoil Removal	204	11
Soil Condition	200	11
Support System	164	9
Availability of Disposal Sites	144	8
Installation and Handling the Pipes	140	7
Social and Environmental Impacts	128	7
Availability of the Pipes	126	7
Transportation and Delivery of the Pipe	124	7
Pipe Joints	114	6
Mobilization/demobilization	72	4

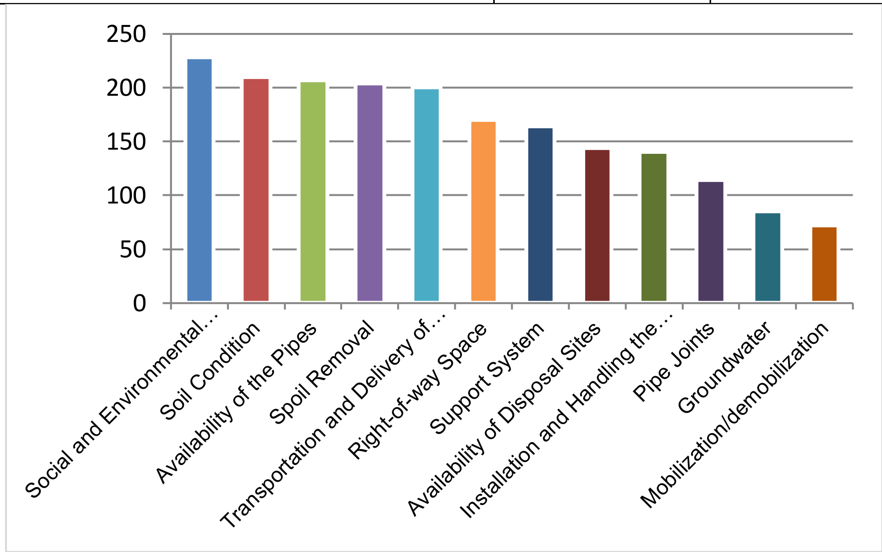


Figure 4-13 Parameters Impact on Productivity of Open-cut Method

Based on 31 Respondents

Figure 4-12 and Table 4-13 illustrate that the social and environmental impacts such as, detour roads, vibration, air and noise pollution are the most problems that impact on the productivity of open-cut method followed by soil condition, availability of the pipes and spoil removal.

13. Which of the following has *more impact* on **<u>Constructability</u>** of *<u>Open-cut method</u>*? Please rank from **1 (the lowest impact)** to **12 (the highest impact).**

Table 4-13 Parameters Impact on Constructability of Open-cut Method Based on 31 Respondents

Parameters	Ranking Score	Percentage (%)
Right-of-way Space	226	13
Soil Condition	210	12
Availability of the Pipes	204	12
Transportation and Delivery of the Pipe	172	10
Spoil Removal	170	10
Social and Environmental Impacts	136	8
Availability of Disposal Sites	130	7
Groundwater	116	7
Support System	116	7
Installation and Handling the Pipes	102	6
Mobilization/demobilization	84	5
Pipe Joints	76	4

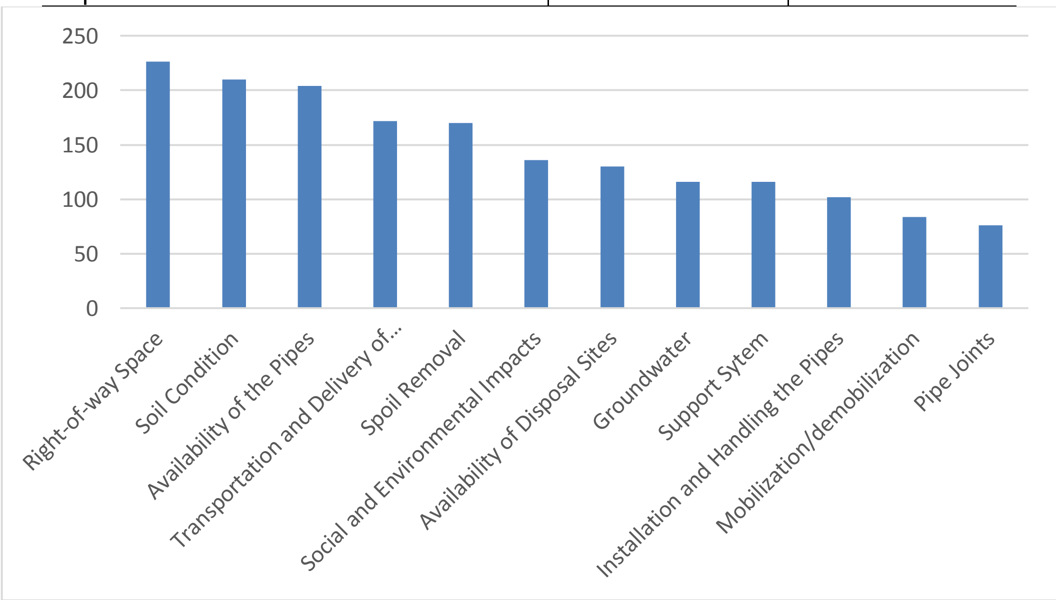


Figure 4-14 Parameters Impact on Constructability of Open-cut Method Based on 31 Respondents

Figure 4-13 and Table 4-14 show that ROW is the major problem that this project would be faced in constructability aspect. Moreover, as the large pipes are approximate 17 ft diameter, availability, transportation and delivery of the pipes are difficult.

14. What is the *minimum Depth to top of the Open-cut method*?

Table 4-14 Depth to the Top of Tunnel

Based on 23 Respondents

Min. Depth to the Top of Tunnel	No. of Responses	Percentage (%)
5 ft -10 ft	15	65
10 ft - 20 ft	5	22
Less than 5 ft	3	13
More than 20 ft	0	0

Table 4-14 and Figure 4-15 show that 65% of the respondents believe that the most appropriate depth to the top of the 17 ft diameter tunnel could be between 5 and 10 ft.

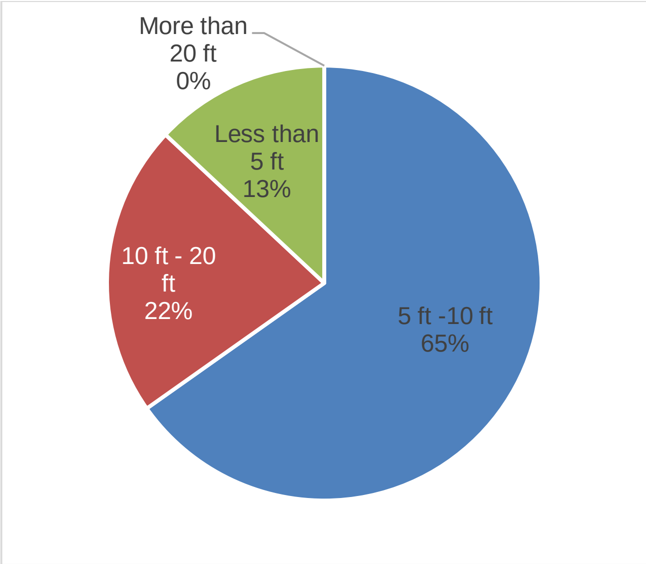


Figure 4-15 Depth to the Top of Tunnel

Based on 23 Respondents

15. What is the *Approximate Advance Rate* of Open-cut method?

Table 4-15 Advance Rate of Open-cut Method

Based on 19 Respondents

Advance Rate	No. of Responses	Percentage (%)
Less than 50 ft/day	11	65
50 - 100 ft/day	5	23
More than 150 ft/day	2	12
50 - 100 ft/day	0	0

Table 4-15 and Figure 4-16 present that the advanced rate of open-cut method is less than 50 ft/day. To compare this question with question 11, it is concluded that although, the assembly of a TBM may take 3 months but TBM is preferable in this aspect as it has a faster advanced rate.

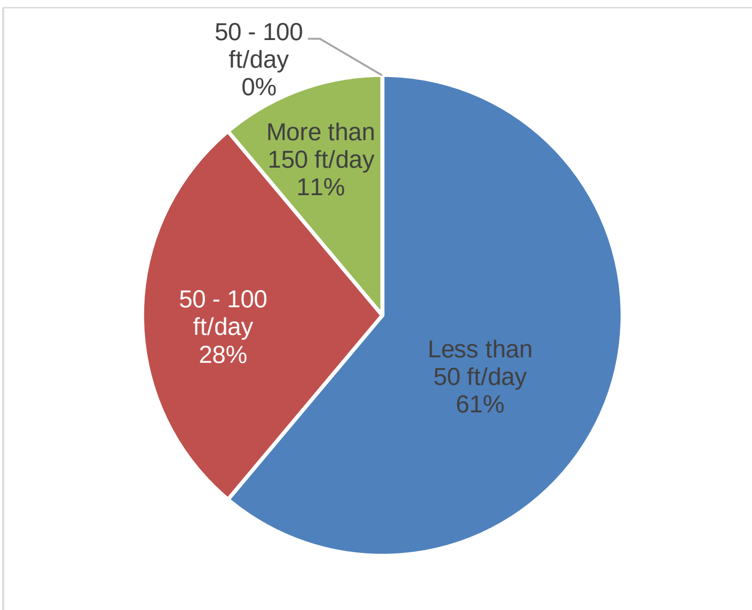


Figure 4-16 Advance Rate of Open-cut Method

Based on 19 Respondents

16. Which of the following is most *Constructible* and *Cost Effectiveness* option for pipe embedment? Please rank from **1 (the least)** to **5 (the most).**

Table 4-16 Constructible Options for Pipe Embedment

Based on 18 Respondents

Embedment Material	Ranking Score	Percentage (%)
Flowable fill (CLSM) with aggregate	78	25
Flowable fill (CLSM) with native soil	70	22
Aggregate (select materials)	66	21
Mix of native soil and cement	58	19
Native soil	40	13

Table 4-16 and Figure 4-17 show that flowable fill (CLSM) with aggregate and flowable fill (CLSM) with native soil are the most appropriate materials for pipe embedment in constructability aspect.

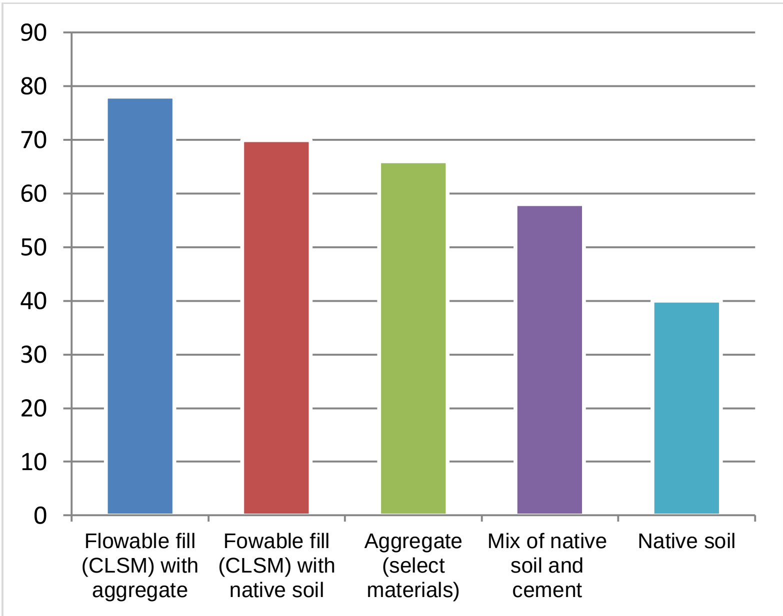


Figure 4-17 Constructible Options for Pipe Embedment

Based on 18 Respondents

Table 4-17 Effective Options for Pipe Embedment

Based on 18 Respondents

Embedment Material	Ranking Scores	Percentage (%)
Native soil	100	33
Aggregate (select materials)	66	33
Mix of native soil and cement	64	21
Flowable fill (CLSM) with native soil	46	15
Flowable fill (CLSM) with aggregate	28	9

Table 4-17 and Figure 4-18 show that native soil and aggregate (select materials) are the most appropriate materials for pipe embedment in cost effectiveness aspect.

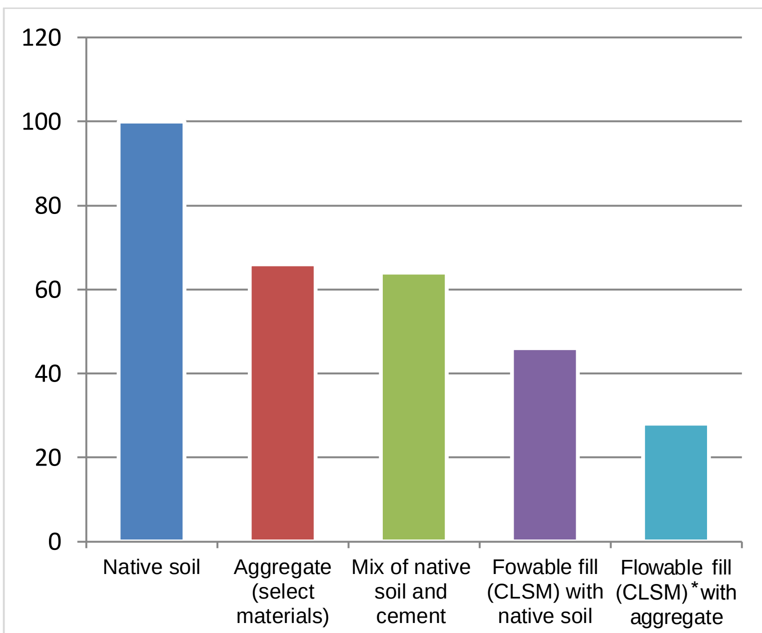


Figure 4-18 Effective Options for Pipe Embedment

Based on 18 Respondents

17. What types of pipe material are most *Efficient* and *Cost Effective for large diameter open-cut tunnel construction*? Please rank from **1 (the least)** to **6 (the most).**

Table 4-18 Efficient Types of Pipe Material

Based on 17 Respondents

Pipe Material	Ranking Score	Percentage (%)
Prestressed Concrete Cylinder Pipe (PCCP)	58	21
Reinforced Concrete Pipe (RCP)	56	20
Reinforced Concrete Cylinder Pipe (RCCP)	54	20
Steel Pipe	50	18
Glassfiber Reinforced Pipe (GRP)	36	13
Bar-wrapped Concrete Cylinder Pipe	22	8

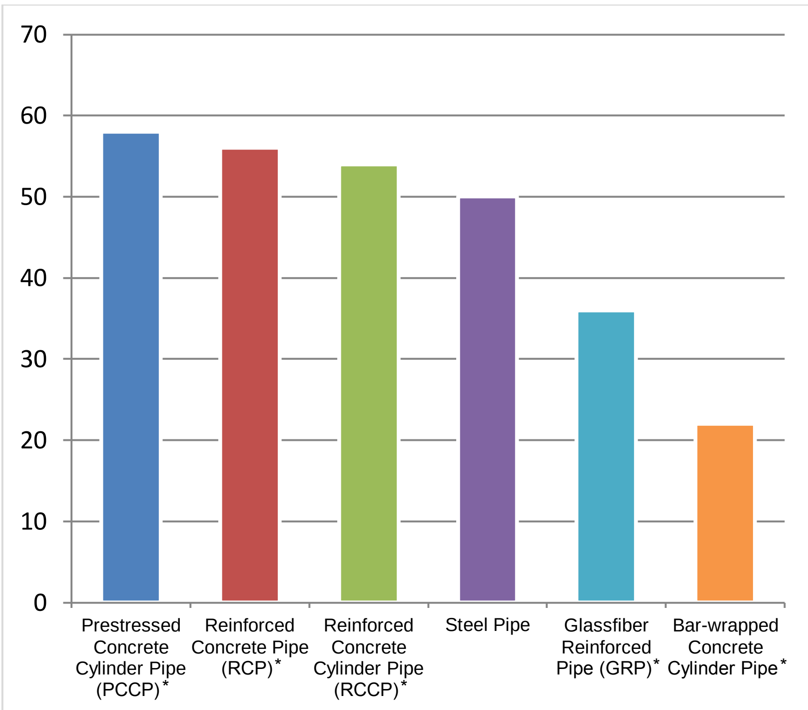


Figure 4-19 Efficient Types of Pipe Material

Based on 17 Respondents

Table 4-19 Cost Effective Types of Material for Pipe Embedment

Based on 17 Respondents

Pipe Material	Ranking Score	Percentage (%)
Steel Pipe	52	22
Reinforced Concrete Pipe (RCP)	48	20
Reinforced Concrete Cylinder Pipe (RCCP)	42	18
Prestressed Concrete Cylinder Pipe (PCCP)	40	17
Glassfiber Reinforced Pipe (GRP)	34	14
Bar-wrapped Concrete Cylinder Pipe	20	9

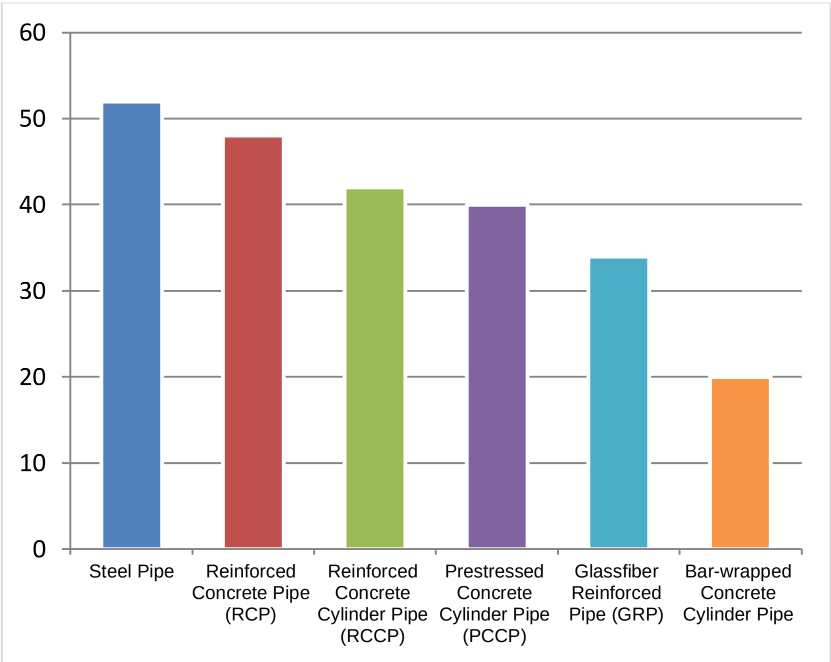


Figure 4-20 Cost Effective Types of Material for Pipe Embedment

Based on 17 Respondents

4.1.2 Survey with Stakeholder Committee Members

Under Task 6 of the UFT project, a Stakeholders Committee was formed not only to provide guidance and advice to the project but also to enable members of the Committee to consider using underground freight tubes in the future for the benefit of their organizations. Figure 4-22 shows the categorization of the attendees by type of the organizations.

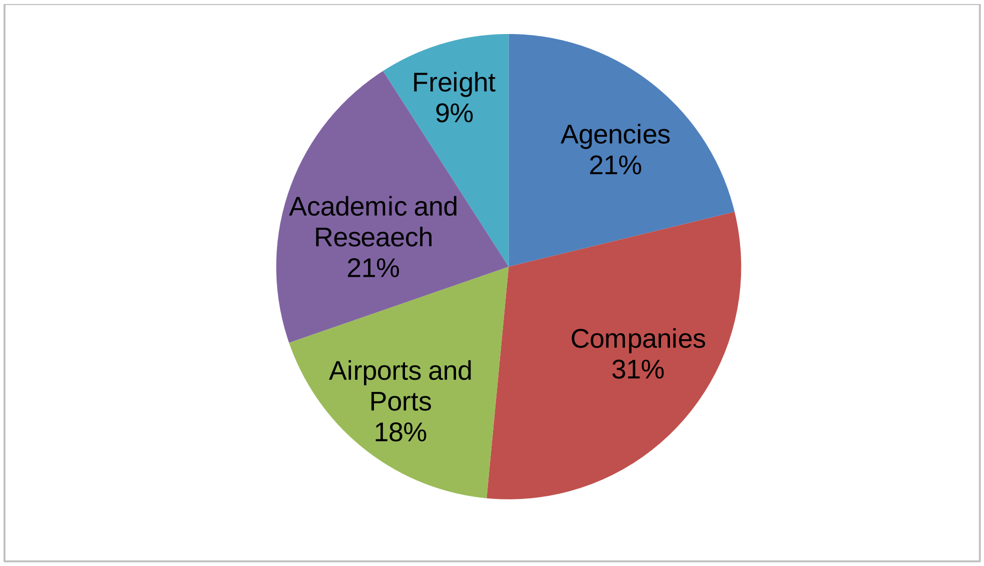


Figure 4-21 Attendees (Categorized by Type of the Organization)

At one of the meetings, the Stakeholders were asked to complete a survey and share their ideas about UFT. In general, the proposed routes, size of freight, and project challenges.

The survey had 14 questions about ranking different routes and freight sizes, financial means, constructability and feasibility of UFT project. Additionally, members were asked to provide strengths and weaknesses of each presentation as well as rating the stakeholder meeting in general. The only questions that is related to this thesis is the following:

1. What size UFT is most effective with 1 to 3, with 1 being the least and 3 being the most?

Table 4-20 Effective Size of UFT

Based on 13 Respondents

UFT Cargo Size	Ranking Score	Percentage (%)
Large	31	49
Medium	21	35
Small	10	16

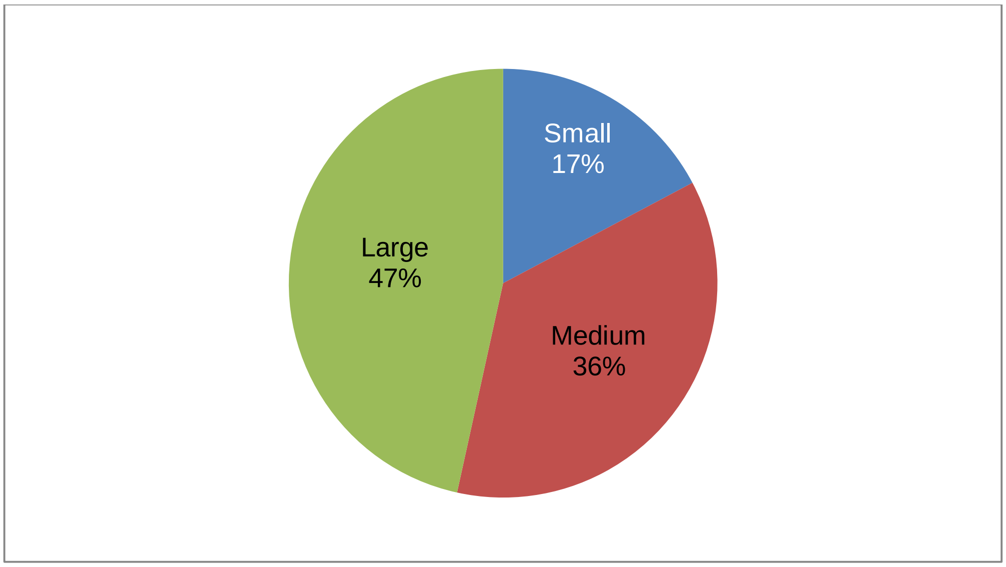


Figure 4-22 Effective Size of UFT

Based on 13 Respondents

4.2 Interviews

On March 20 through 24, No-Dig Show conference was held in Dallas. No-Dig Show is the must-attend conference for underground infrastructure professionals and the largest trenchless technology conference in North America, where professionals attend to learn new techniques that will save money and improve infrastructure. At this conference, there was an opportunity to interview with some TBM manufacturers. Many inquiries were made about TBM operation and TBM tunneling methods. Since not much information is available in literature on large diameter tunneling, the information received from this interview helped with this research. Interestingly, all companies had similar answers to the questions from the interview. The result of question/answer of the interviews with the experts from large companies across the world such as Akkerman (located in Brownsdale, Minnesota), Herrenknecht (located in Germany), and Forterra (Located in Grand Prairie, Texas) are as following:

Comparison of one 25 ft diameter twin-track tunnel vs. two single-track tunnels

- One twin-track tunnel is much cheaper than two single-track tunnel due to:
  - Smaller crew size
  - Less material (Pipe or Segment) is required.
  - Higher productivity with lower number of MTBM

Comparison of Pipe vs. Segment

- For both tunnel type, segment is better option.
- Quality of segment is higher than pipe.
- Segment transportation is cheaper and easier than pipe.
- We can have up to 45^{o} curve with segment.
- Pipe jacking distance is limited due to friction and jacking force.
- Less number of shaft with segment.

The maximum distance for one TBM operation?

- Depends on soil conditions
- If you consist on groundwater, EPB is used.
- After 10 – 15 miles, it needs service;
- Consider transporting segments, soil out, access shafts and etc.

Different Type of MTBM

- Slurry MTBM is good when we encounter with water table.

- Otherwise, we can use EPB MTBM or Conventional MTBM.
- Cost of tunneling with slurry MTBM is 1.5-2 times higher than other MTBMs.
- For all three different kind of MTBM, we can use pipe jacking and segment.

Assembly time of MTBM: 1-2 weeks

- Order time of MTBM:
  - 2-3 months for Conventional MTBM
  - 6 months for Slurry MTBM and EPB
  - It should be ordered a year ahead
- Minimum depth of pipe
  - Slurry method: 2D
  - Conventional method (Pipe Jacking): 1D
  - EPB: 1D

Advance rate of tunneling

- Depends on soil conditions;
- For same project, it was 200-250 m/week ~ 100 ft/day;
- Soil condition is very important and we should have enough capacity behind to take the soil out.

Can we say the advance rate for small size is more than big size?

- No. The same advance rate for both size.

Safe distance between two single-track tunnels

- It depends on geotechnical information, maybe one tunnel, sometimes it could be 1 ft.
- Diameter for loose soil – 3 feet clay soil

What are the mobilization requirements for tunneling?

- Crane, power, accessibility

What is the maximum slope for TBM operation?

- 45º

Auxiliary equipment do we need for TBM operation

- Crane and usual construction equipment

Social/environmental impact of tunnel construction

- Just the shaft area
- TBM has a power cable.

4.3 Chapter Summary

This chapter presented tunneling industry experts tunneling method with TBM rather than with open-cut. The survey results showed that, overall, 86% of the questions in part 2 (construction with TBM method) were responded. However, in part 3 (construction with open-cut method) only 45% of the questions were addressed. The results showed that, either there is a lack of knowledge in open-cut method for building a large diameter tunnels or it is preferable to build the tunnels by TBM method.

Based on the analysis that was mentioned above, the followings are the major points that were concluded from my multiple interviews and surveys with industry leaders in tunneling sector:

- One dual-track tunnel is more cost effective than two single-track tunnel
- Based on soil condition, advance rate of TBM would be 100 ft/Day
- Advance rate is more dependent on soil conditions than size of tunnel.
- Tunnel segment transportation is much cheaper than pipe section for open-cut method of tunneling
- Pipe jacking is not feasible for this project due the size of tunnel (25 ft)

- A crew of 10 people per TBM is required electricity consumption of TBM is 1MWh
- TBM assembly takes 3 months
- There is no noise and air pollution during tunneling
- 1 to 2 times diameter of the tunnel is the minimum required depth for tunneling

Table 4-21 shows the comparison between open-cut and tunneling methods as it was concluded from above analysis.

Table 4-21 Comparison between Open-cut and Tunneling

Open-cut	Tunneling
The distance from ground surface to top of the pipe is 7 to 10 ft.	The distance from ground surface to top of the tunnel can be 20 to 50 ft.
26-ft pipe size is not economical due to high volume of excavation and material hauling;therefore, 17-ft pipe was selected for Open-cut method.	Both 17 ft and 26 ft tunnels are possible.
More space is required for soil handing and backfill operations.	Only soil for the tunnel bore is excavated and handled.
Some extra soil can be used as a berm over the tunnel alignment.	Some extra soil can be used as a berm over the tunnel alignment.
Only applicable to “two single-track” tunnels.	Applicable for both “one twin-track” and “two single-track” tunnels.
Flowable fill can be used for bedding and haunching. Flowable fill aggregate may consist of native soils at some locations.	Entry/exit and access shafts are required.
Construction below watertable will be difficult.	Tunneling can be performed in different geological conditions along the alignment mainly consist of cohesive soils, and local shale and limestone (known as Austin Chalk).
Production rate might be higher by working on different location at the same section.	The average advance rate of 120 ft per day (20-hour work-days) per section is assumed to be a reasonable value.

Chapter 5

Conclusions and Recommendation for Future Research

This thesis used literature review, surveys and interviews to compare the tunneling and open-cut methods for construction of an underground structure. Using this methodology, different pros and cons of each method was found and since the scope of this thesis was on large diameter tunnels, there is not much information about.

The high cost of TBM machines are usually over- emphasized and sometimes that appears to be the reason that open-cut tunneling projects in more favor, but interestingly, there was no feedback received from the surveys and interview pointing out the high cost of TBM as an issue according to industry leaders. This thesis concluded that for large diameter tunnels, the tunneling construction method is a better option for the following reasons:

1. Much less disruption to ground surface
2. Less issues with underground utilities
3. Better productivity
4. Safer work environment
5. Better applicability and constructability, especially in urban areas

This thesis here concluded that tunneling method is a much more viable option based on the results received from interviews and surveys.

There are many research areas of underground freight transportation for further research, such as:

1. Development of a model for construction cost of TBM bored tunnels
2. Financing needs to be evaluated
3. Benefit- cost analysis and rate of return for such infrastructure projects
4. Construction delivery methods

Chapter 6

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Appendix A

Definitions

Bar-wrapped Concrete Cylinder Pipe: Consists of a steel cylinder lined with cement mortar, then helically wrapped with a mild steel bar and coated with dense cement mortar.

Flowable Fill (CLSM): A self-compacting low strength (60 to 100 psi) concrete with a flowable consistency that can be used as pipe embedment material as an alternative to compacted granular fill.

Glassfiber Reinforced Pipe (GRP): This pipe is made with glassfiber reinforcements, thermosetting resins, and other additives, such as small aggregates, catalysts, hardeners, accelerators, and so on.

Open-cut: A traditional method for installing and/or replacing pipeline infrastructure system using open trench construction.

Pipe Jacking: A method of laying underground pipelines by assembling the pipes at the foot of an entry shaft and pushing them through the ground while excavating at the face of tunnel.

Prestressed Concrete Cylinder Pipe (PCCP): A composite pipe of concrete core inside the cylinder, and embedded cylinder, with the concrete core cast both inside and outside the cylinder.

Reinforced Concrete Cylinder Pipe (RCCP): This is similar to RCP, but includes a steel cylinder embedded in the pipe wall.

Reinforced Concrete Pipe (RCP): Pipes with steel reinforcement in its densely compacted concrete wall.

TBM: Tunnel Boring Machine is used to mechanically excavate tunnels with a circular cross section through a variety of soil and rock strata.

Tunneling: This method follows the same process as pipe jacking, except that tunneling method uses a temporary support structure while simultaneously excavate at the face of tunnel. After completion of tunnel, the pipe sections are installed inside the tunnel and the annular space is grouted.

UFT: Automated technology to transport individual freight vehicles through underground pipelines.

Appendix B

Survey

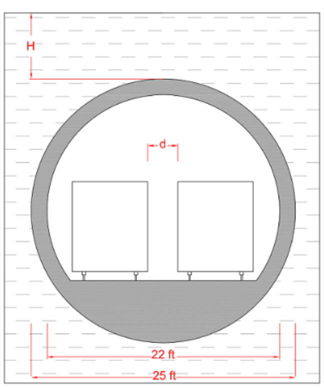
Comparison of Open-cut and Tunneling Methods for

Building Large Diameter Tunnels

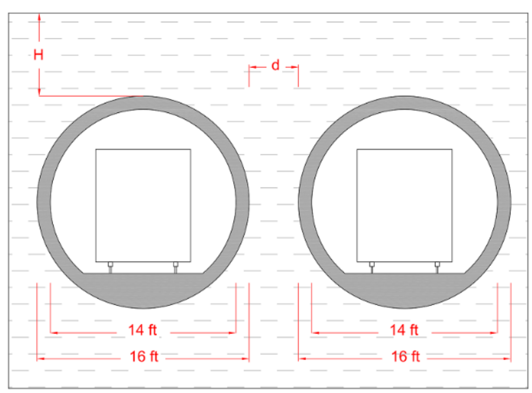
My name is Niloofar Rezaei. I am a graduate student at the University of Texas at Arlington working on my Master of Science (M.S.) degree in Civil Engineering with focus in Construction Engineering and Management under supervision of Dr. Mohammad Najafi, a Professor and Director of the Center for Underground Infrastructure Research and Education (CUIRE). I am planning to graduate in May 2016; therefore, I would appreciate if you can submit the completed survey by Friday, April 8th, 2016.

One of the CUIRE research project is feasibility of using Underground Freight Transportation (UFT) in Texas. As part of my thesis, I am sending you this survey to collect industry understanding and perceptions of different construction methods <u>for building the large diameter tunnels</u> for UFT.

The project considers building a 250-mile UFT tunnel to transport shipping containers from Port of Houston to a distribution center South of Dallas on I-45 Right-of-Way. There are two options for tunnel construction, using TBM /Tunneling method and using open-cut method according to the following figures.



Type 1- Building Tunnels with TBM method



Type 2- Building Tunnels with Open-cut method

This survey consists of three parts. First part is your contact information. Second part focuses on the tunneling with TBM . Third part is tunneling with open-cut. If you are not able to complete, all three parts, please submit the part you have experience with. Words with an "*" are defined on the last page.

I appreciate your assistance in completing this survey and your participation will be kept confidential, however, unless you notify us otherwise, we will acknowledge your help in completing this survey.

Part 1 – Contact Information

Name: ______________________________ Title: __________________

Company: ____

Address: ____

City: __________________ State: _______________ Zip code: ___________

Phone: __________________ Email: ______________________________

All above information will remain confidential.

1. Have you been involved in planning, design or construction of pipe jacking /tunnels and/or pipeline construction using open-cut methods?

   ☐ Yes

   ☐ No

If yes, continue with the survey, if No, please submit the form now.

2. Please specify your type of involvement with pipe jacking/tunnels and/or pipeline construction using open-cut methods.

   ☐ Engineering

   ☐ Planning

   ☐ Regulating

   ☐ Contracting

☐ Operating

☐ *Other, please specify* ______________________

Part 2 – Tunnel Construction Using TBM

1. For the following, please rank *Obstacles* in TBM method from **1 (the least)** to **6 (the most)**?

   ☐ Bridges (piles, foundations, piers, etc.)

   ☐ Rivers

   ☐ Utilities Relocation

   ☐ Soil Conditions

   ☐ Underground water

   ☐ Possibility of settlement at the surface

   Comments:

2. Which of the following has *more impact* on **Productivity** of *TBM method*? Please rank from **1 (the lowest impact)** to **13 (the highest impact).**

   ☐ Spoil removal

   ☐ Right-of-way space

   ☐ Soil conditions

   ☐ Groundwater

   ☐ TBM maintenance

   ☐ Availability of disposal sites

   ☐ Availability and delivery of segmental linings

   ☐ Access shaft construction

- [ ] Entry/exit shaft construction
- [ ] TBM excavation
- [ ] Mobilization/demobilization of the project
- [ ] TBM manufacturing and delivery
- [ ] Social and environmental impacts (i.e., detour roads)

Comments:

3. Which of the following has *more impact* on **<u>Constructability</u>** *<u>TBM method</u>*?

Please rank from **<u>1</u> (the lowest impact)** to **<u>13</u> (the highest impact).**

- [ ] Spoil removal
- [ ] Right-of-way space
- [ ] Soil conditions
- [ ] Groundwater
- [ ] TBM maintenance
- [ ] Availability of disposal sites
- [ ] Availability and delivery of segmental linings
- [ ] Access shaft construction
- [ ] Entry/exit shaft construction
- [ ] TBM excavation
- [ ] Mobilization/demobilization of the project
- [ ] TBM manufacturing and delivery
- [ ] Social and environmental impacts (i.e., detour over roads)

4. What is the *minimum Depth to top of the tunnel*, considering the following soil conditions?

Expansive Clay Soil	Limestone	Austin Chalk
☐ 20 ft	☐ 20 ft	☐ 20 ft
☐ 20 – 40 ft	☐ 20 – 40 ft	☐ 20 – 40 ft
☐ 40 – 60 ft	☐ 40 – 60 ft	☐ 40 – 60 ft
☐ More than 60 ft	☐ More than 60 ft	☐ More than 60 ft
☐ *Others*	☐ *Others*	☐ *Others*

5. What is the *approximate Tunneling Speed*, considering the following soil conditions?

Expansive Clay Soil	Limestone	Austin Chalk
☐ Less than 80 ft/day	☐ Less than 80 ft/day	☐ Less than 80 ft/day
☐ 80 – 100 ft/day	☐ 80 – 100 ft/day	☐ 80 – 100 ft/day
☐ 100 – 120 ft/day	☐ 100 – 120 ft/day	☐ 100 – 120 ft/day
☐ More than 120 ft/day	☐ More than 120 ft/day	☐ More than 120 ft/day
☐ *Others*	☐ *Others*	☐ *Others*

6. What is the *maximum Slope* for *TBM operation*, considering the following soil conditions?

Expansive Clay Soil	Limestone	Austin Chalk
☐ Less than 5°	☐ Less than 5°	☐ Less than 5°
☐ 5° - 10°	☐ 5° - 10°	☐ 5° - 10°
☐ 10° - 20°	☐ 10° - 20°	☐ 10° - 20°
☐ 20° - 30°	☐ 20° - 30°	☐ 20° - 30°
☐ More than 30°	☐ More than 30°	☐ More than 30°
☐ *Others*	☐ *Others*	☐ *Others*

7. What is the *suitable maximum Distance* between *Access Shafts*, considering the following soil conditions?

Expansive Clay Soil	Limestone	Austin Chalk
☐ Less than 0.5 mile	☐ Less than 0.5 mile	☐ Less than 0.5 mile
☐ 0.5 - 1 mile	☐ 0.5 - 1 mile	☐ 0.5 - 1 mile
☐ 1 – 1.5 mile	☐ 1 – 1.5 mile	☐ 1 – 1.5 mile
☐ More than 1.5 mile	☐ More than 1.5 mile	☐ More than 1.5 mile
☐ *Others*	☐ *Others*	☐ *Others*

8. What is the *maximum Distance* for one *TBM operation*, considering the following soil conditions?

Expansive Clay Soil	Limestone	Austin Chalk
☐ Less than 10 mile	☐ Less than 10 mile	☐ Less than 10 mile
☐ 10 - 15 mile	☐ 10 - 15 mile	☐ 10 - 15 mile
☐ 15 – 20 mile	☐ 15 – 20 mile	☐ 15 – 20 mile
☐ 20 – 25 mile	☐ 20 – 25 mile	☐ 20 – 25 mile
☐ *Others*	☐ *Others*	☐ *Others*

9. What is the *approximate Advance Rate* of constructing tunnels using *TBM*, considering following soil conditions?

Expansive Clay Soil	Limestone	Austin Chalk
☐ Less than 50 ft/day	☐ Less than 50 ft/day	☐ Less than 50 ft/day
☐ 50 - 100 ft/day	☐ 50 - 100 ft/day	☐ 50 - 100 ft/day
☐ 50 - 150 ft/day	☐ 50 - 150 ft/day	☐ 50 - 150 ft/day
☐ More than 150 ft/day	☐ More than 150 ft/day	☐ More than 150 ft/day
☐ *Others*	☐ *Others*	☐ *Others*

Part 3 – Tunnel Construction Using Open-cut Method

1. For the following, please rank *Obstacles* in *Open-cut method* from **1 (the least)** to **6 (the most)**?

- [ ] Bridges (piles, foundations, piers, etc.)
- [ ] Rivers
- [ ] Utilities Relocation
- [ ] Soil Conditions
- [ ] Underground water
- [ ] Possibility of settlement at the surface

Comments:

1. Which of the following has *more impact* on **Productivity** of *Open-cut method*?

Please rank from **1 (the lowest impact)** to **12 (the highest impact).**

- [ ] Spoil removal
- [ ] Right-of-way space
- [ ] Soil conditions
- [ ] Groundwater
- [ ] Support System
- [ ] Availability of spoil disposal sites
- [ ] Availability of the pipes
- [ ] Transportation and delivery of the pipe
- [ ] Installation and handling of the pipes
- [ ] Mobilization/demobilization of the project

☐ Pipe joints

☐ Social and environmental impact (i.e., detour roads, vibration, air and noise pollution, etc.)

Comments:

2. Which of the following has *more impact* on **Constructability** of *Open-cut method*? Please rank from **1 (the lowest impact)** to **12 (the highest impact).**

☐ Spoil removal

☐ Right-of-way space

☐ Soil conditions

☐ Groundwater

☐ Support System

☐ Availability of spoil disposal sites

☐ Availability of the pipes

☐ Transportation and delivery of the pipe

☐ Installation and handling of the pipes

☐ Mobilization/demobilization of the project

☐ Pipe joints

☐ Social and environmental impact (i.e., detour roads, vibration, air and noise pollution, etc.)

Comments:

3. What is the *minimum Depth to top of the* *Open-cut method*, considering the following soil conditions?

Expansive Clay Soil	Limestone	Austin Chalk
☐ Less than 5 ft	☐ Less than 5 ft	☐ Less than 5 ft
☐ 5 ft -10 ft	☐ 5 ft -10 ft	☐ 5 ft -10 ft
☐ 10 ft - 20 ft	☐ 10 ft - 20 ft	☐ 10 ft - 20 ft
☐ More than 20 ft	☐ More than 20 ft	☐ More than 20 ft
☐ *Others*	☐ *Others*	☐ *Others*

4. What is the *Approximate Advance Rate* of *Open-cut method*, considering the following soil conditions?

Expansive Clay Soil	Limestone	Austin Chalk
☐ Less than 50 ft/day	☐ Less than 50 ft/day	☐ Less than 50 ft/day
☐ 50 - 100 ft/day	☐ 50 - 100 ft/day	☐ 50 - 100 ft/day
☐ 100 - 150 ft/day	☐ 100 - 150 ft/day	☐ 100 - 150 ft/day
☐ More than 150 ft/day	☐ More than 150 ft/day	☐ More than 150 ft/day
☐ *Others*	☐ *Others*	☐ *Others*

5. Which of the following is most *Constructible* and *Cost Effectiveness* option for pipe embedment? Please rank from **1 (the least)** to **5 (the most).**

Constructability	Cost Effectiveness
__ Native soil	__ Native soil
__ Aggregate (select materials)	__ Aggregate (select materials)
__ Mix of native soil and cement	__ Mix of native soil and cement
__ Flowable fill (CLSM) with aggregate	__ Flowable fill (CLSM) with aggregate
__ Flowable fill (CLSM) with native soil	__ Flowable fill (CLSM) with native soil

Comments:

6. What types of pipe material are most *Efficient* and *Cost Effective for large diameter open-cut tunnel construction*? Please rank from **1 (the least)** to **6 (the most).**

Efficient	Cost Effective
__ Prestressed Concrete Cylinder Pipe (PCCP)	__ Prestressed Concrete Cylinder Pipe (PCCP)
__ Reinforced Concrete Pipe (RCP)	__ Reinforced Concrete Pipe (RCP)
__ Reinforced Concrete Cylinder Pipe (RCCP)	__ Reinforced Concrete Cylinder Pipe (RCCP)
__ Glassfiber Reinforced Pipe (GRP)	__ Glassfiber Reinforced Pipe (GRP)
__ Bar-wrapped Concrete Cylinder Pipe	__ Bar-wrapped Concrete Cylinder Pipe
__ Steel Pipe	__ Steel Pipe

Appendix C

List of Acronyms

AADTT	Average Annual Daily Truck Traffic
ACP	Panama Canal Authority
ASCE	American Society of Civil Engineers
CLSM	Controlled Low-Strength Material
CUIRE	The Center for Underground Infrastructure Research and Education
DFW	Dallas/Fort Worth
DOE	Department of Energy
FHA	Federal Highway Administration
FSS	Freight Shuttle System
ft	feet
GLI	GRID Logistics
GRP	Glassfiber Reinforced Pipe
in.	inch
kW	Kilo Watt
mph	mile per hour
MTBM	Micro Tunneling Boring Machine
NAFTA	the North American Free Trade Agreement
PCCP	Prestressed Concrete Cylinder Pipe
PJ	Pipe Jacking
RCCP	Reinforced Concrete Cylinder Pipe
RCP	Reinforced Concrete Pipe
ROW	Right-of-way
TBM	Tunnel Boring Machine
TEUs	Twenty-Foot Equivalent Unit
TTI	The Texas A&M Transportation Institute

TxDOT	Texas Department of Transportation
UFT	Underground Freight Transportation
UTA	The University of Texas at Arlington