Stochastic Simulation of Construction Methods of Multi-purpose Utility Tunnels

Shayan Jorjam

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By: Shayan Jorjam

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Signed by the final Examining committee:

____Chair
Dr. Fuzhan Nasiri
____Examiner
Dr. Mazdak Nik Bakht
____Examiner
Dr. Fuzhan Nasiri
____Supervisor
Dr. Amin Hammad

Approved by Mazdak Nik Bakht

Graduate Program Director

Mourad Debbai

Dean of Faculty

Date 2022/05/03

ABSTRACT

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The traditional method of installing underground utilities, which is based on burying them under the roads, has been used for many decades. Repeated excavations related to this method cause many problems, which can significantly increase the actual costs as well as social costs. Multi-purpose Utility Tunnels (MUT) are a good alternative for buried utilities. Although MUTs are more expensive than the traditional method, social cost savings can make them more practical. Different factors should be investigated to determine if MUTs can be an economical and practical alternative. The construction method is one of the most important factors that should be carefully assessed to have a successful MUT project and reduce its impact on the surrounding area. Simulation can be used for investigating the different construction methods of MUTs. In this research, two stochastic discrete event simulation models depicting two MUT construction methods (i.e., microtunneling and cut-and-cover) are developed. The purpose of these models is to analyze the duration and cost of the MUT projects. Also, 4D simulation models of these methods are developed for constructability assessment of these projects. The conclusions of this research are as follows: (1) the duration of C&C method is more sensitive than microtunneling to the changes in tunnel diameter; (2) the cost of microtunneling method is more sensitive than C&C to changes in tunnel diameter; (3) in average, microtunneling is 52% more expensive and 66% faster than C&C; (4) the impact of the microtunneling on the surrounding area is less than the C&C.

Keywords: Discrete Event Simulation, Multi-purpose Utility Tunnel, Construction Methods, Microtunneling, Cut-and-Cover

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LIST OF ABBREVIATIONS

3D	Three Dimensional
4D	Four Dimensional
ABM	Agent-Based Modeling
AEC	Architecture, Engineering, and Construction
BIM	Building Information Modeling
C&C	Cut-and-Cover
CIPP	Cured In-Place Pipe
D&B	Drill and Blast
DES	Discrete Event Simulation
GIS	Geographic Information System
HDD	Horizontal Directional Drilling
HDPE	High-Density Polyethylene
PI	Plastic Index
PERT	Program Evaluation and Review Technique
MUT	Multi-purpose Utility Tunnel
MTBM	Micro Tunnel Boring Machine
SD	System Dynamics
TBM	Tunnel Boring Machine

CHAPTER 1: INTRODUCTION

1.1 Background

Utility networks are installed above and below the ground. The development of utilities above the ground, especially in urban areas has several disadvantages, such as presenting safety hazards, limiting urban spaces, and uglifying urban scenes. Therefore, it is more common in urban areas to place the utilities under the ground (Alaghbandrad, 2020)

Different reports have stated that the underground utilities in developed areas have reached or are nearing the end of their service lives resulting in the need of many repair and replacement projects (Gagnon et al., 2008). These projects have imposed many street closures and traffic disruptions, environmental pollution, etc., in urban areas (i.e., social cost) (Oum, 2018). As a solution, Multi-purpose Utility Tunnels (MUTs) offer a long-term, sustainable alternative by hosting utilities in a tunnel. MUTs are defined as "underground utilidors containing one or more utility systems, permitting the installation, maintenance, and removal of the system without making street cuts or excavations." (Canto-Perello and Curiel-Esparza, 2013).

The traditional method of installing underground utilities (e.g., water, sewer, gas pipes, and electrical cables) is based on burying them under the roads. MUTs are more expensive than conventional methods, but they could be more practical in dense areas due to social cost savings. To make MUTs as an affordable and efficient alternative, different factors, such as utility specifications, MUT location, and construction method should be investigated. The construction method is one of the most important factors that should be carefully assessed to have a successful MUT project (Thomas et al., 1990).

Construction methods of the MUTs can be classified in two main groups, which are Cut-and-Cover (C&C) methods (e.g., cast-in-place concrete method) (Clé de Sol, 2005; Ramírez Chasco et al., 2011) and trenchless methods (e.g., microtunneling method) (Byron et al., 2015). Different tunnel construction methods with their advantages and disadvantages are listed in Table 1.1.

Despite the high initial cost of the trenchless methods (e.g., drill and blast, Tunnel Boring Machine (TBM) and box jacking), avoiding excavation of streets and roads as well as low social costs make these methods more practical. Furthermore, using the C&C method is almost impossible or more expensive in dense areas, deep MUT projects or in some special geological conditions (e.g., hard rocks). For instance, there are more than 60 km of MUTs in Helsinki that are constructed using Drill-and-Blast (D&B) method (Vähäaho, 2016). The TBM, which is shown in Figure 1.1, was used in Warsaw to build a MUT under the Vistula river (Madryas et al., 2011). Also, a new utility tunnel is constructed in the campus of McGill University in downtown Montreal using D&B method, where because of the location of the McGill MUT (Figure 1.2), it was impossible to use the C&C method (Habimana et al., 2014). Therefore, it can be concluded that in dense areas the trenchless methods, such as microtunneling are more practical than other methods and can reduce the social costs of the project.

Table 1.1 Advantages and disadvantages of tunnel construction methods

Method	Advantages	Disadvantages	References
Cut & Cover	(a) Cheaper than other tunneling methods (b) Safe work progress in unstable weak ground (c) Small risk relative to other construction techniques	(a) Not suitable for very deep excavations (b) Cause interference with traffic and other urban activities (c) More dust and noise impact may arise	(Abdallah and Marzouk, 2013; Hubbard, 1984; Sharma, 2011)
Drill & Blast	(a) Very adaptable and flexible (b) Any shape of tunnel cross section is possible (c) Total investment cost is low (d) Tunnel shape can be changed along the drive length	(a) Safety is a serious issue (b) Advance rate of excavation is low (c) Low level of automation and mechanization of tasks	(Girmscheid and Schexnayder, 2002)
TBM	(a) Very high performance and low labor costs (b) High advance rate (especially in soft grounds) (c) Excellent cost efficiency and high automation level (d) Continuous operation (e) Less noise and disturbance to surrounding areas (f) Best option for constructing deep and long tunnels	(a) Limited flexibility in response to extreme geological conditions (b) High investment costs (c) Fixed circular geometry and tunnel diameter (d) Longer mobilization time and higher capital costs	(Abdallah and Marzouk, 2013; Girmscheid and Schexnayder, 2002)

Figure 1.1 TBM machine used in Warsaw for the installation of MUT under the Vistula River (Madryas et al., 2011)

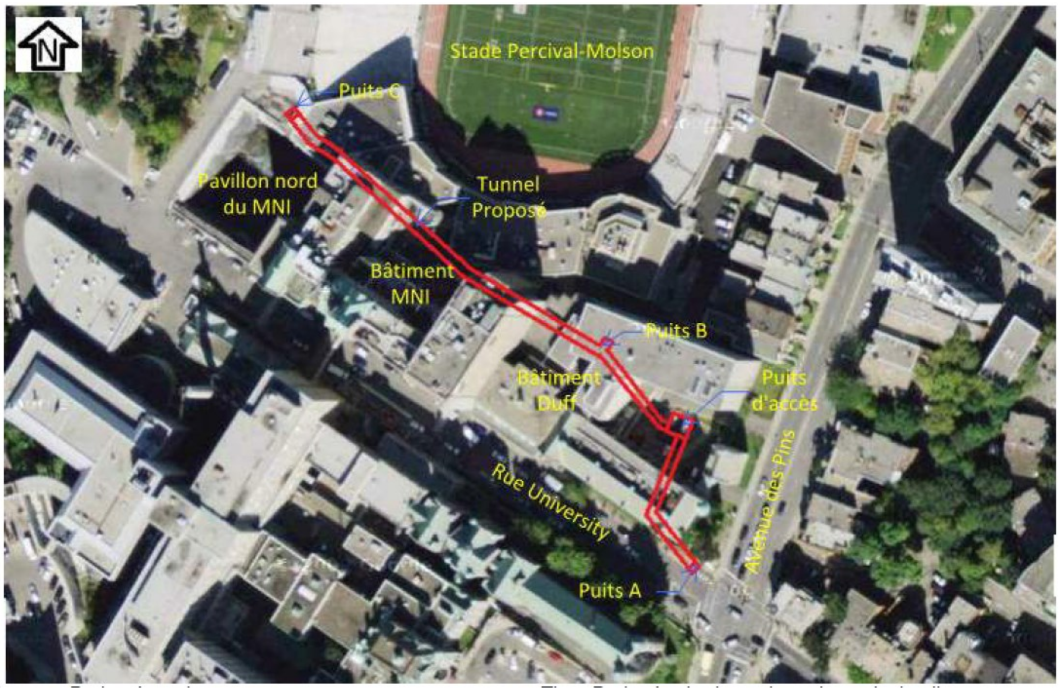


Figure 1.2 Location of the McGill MUT (Habimana et al., 2014)

Construction, like many other areas, can benefit greatly from scheduling and simulation techniques. Program Evaluation and Review Technique (PERT) is a network schedule analysis technique, which is used to estimate project duration when there is a high degree of uncertainty about the duration of induvial activities. In this method, the duration of each activity is determined as a deterministic value according to three possible scenarios, which are optimistic duration, most probable duration, and pessimistic duration (Forcael *et al.*, 2018). However, in PERT, the total duration of the project is determined as a deterministic value.

In the construction industry, simulation can be used for planning and resource allocation, risk analysis, site planning, and productivity measurements (AbouRizk et al., 1992; Mawlana et al., 2015). Discrete-Event-Simulation (DES) is one of the simulation methods, which models the operation of a system as a discrete sequence of events in time (Allen, 2011).

1.2 Problem Statement

Despite their advantages, most countries do not use MUTs extensively because of their high initial cost. One of the most important factors affecting the cost, productivity, and performance of construction projects is the construction method (Thomas et al., 1990). Therefore, choosing the appropriate construction method is vital to have a successful project. MUT construction methods can be divided in two main groups, which are C&C and trenchless methods. Trenchless methods are more expensive but avoiding excavation of streets and roads as well as low social costs and continuity of service can make these methods more practical especially in dense areas. Also, it should be mentioned that using C&C is almost impossible or more expensive in dense areas, deep MUT projects or in some special geological conditions like hard rocks. Therefore, it is important to simulate these two methods to be able to compare them in a quantitative way.

1.3 Research Objectives

The main aim of this research is comparing different construction methods based on DES to achieve the following objectives:

(1) Analyzing the durations and costs of the MUT construction projects according to different soil conditions and different sizes of the tunnel.
(2) Comparing different MUT construction methods based on DES.
(3) Constructability assessment of the MUT projects using 4D simulation including construction equipment.

1.4 Thesis Organization

The structure of this thesis is presented as follows:

Chapter 2 Literature review: This chapter reviews different aspects of MUT, such as classification, construction methods, benefits, and disadvantages. The use of simulation in construction and related works are also reviewed in this chapter.

Chapter 3 Proposed methodology: The overview of the proposed research approach and simulation models of MUT construction methods are presented in this chapter.

Chapter 4 Implementation and case study: The application of the proposed method in the case study for different MUT construction methods is done in this chapter.

Chapter 5 Conclusions and future work: The work done in this research is summarized in this chapter. The contributions of the research are discussed, and the future work is explained.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In this chapter, the classification, benefits, disadvantages, and construction methods of MUTs are discussed. A review of MUT projects around the world are presented afterwards. Then the use of simulation in tunnel construction and different simulation software are introduced. Also, related works in simulation of tunnel construction are presented.

2.2 Multi-purpose Utility Tunnels (MUTs)

In the following sections, the classifications, benefits, disadvantages, and construction methods of MUTs are briefly explained.

2.2.1 MUT Classification

As shown by Laistner and Laistner, (2012) in Figure 2.1, the history of MUTs started from the 19th century. Most of the MUTs in the 19th and 20th centuries were constructed using rectangular and semi-circular sections. In recent years, the use of circular sections, which lead to uniform distribution of forces and can reduce the damages caused by force concentration have become more popular in MUT construction (Alaghbandrad and Hammad, 2020).

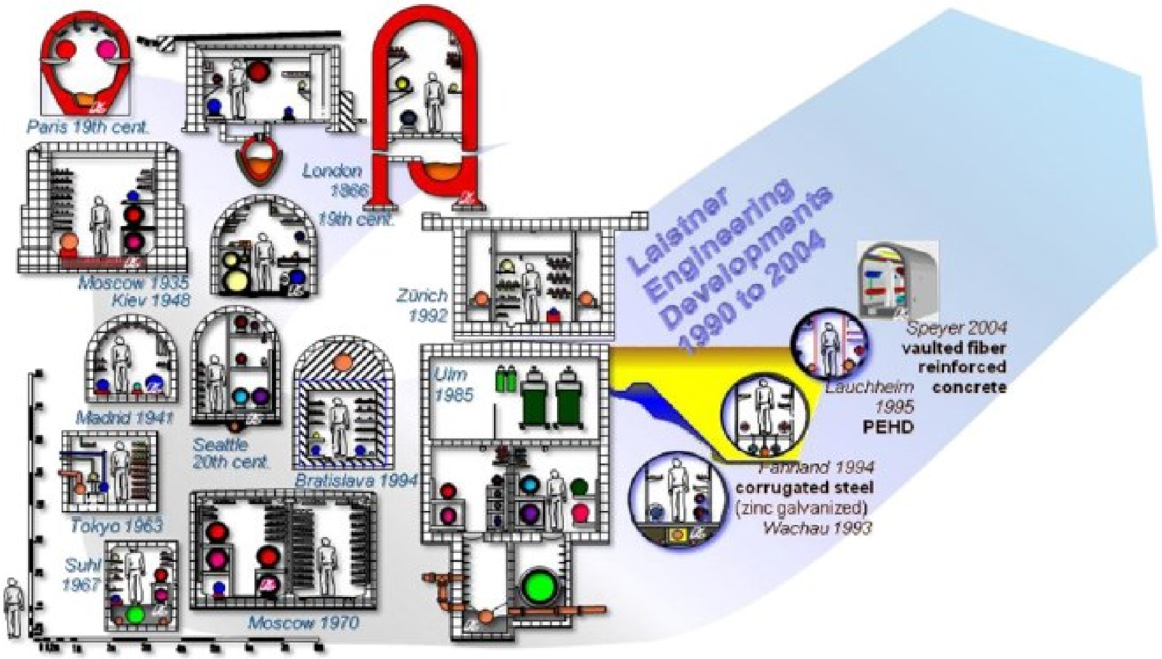


Figure 2.1 MUTs around the world from 1866 (Laistner and Laistner, 2012)

According to Rogers and Hunt (2006) MUTs can be classified based on different factors, such as depth, type, position of installation, shape, and material. As shown by Hunt et al. (2014) in Figure 2.2, according to the depth of the cover, MUT can be classified into three groups, which are flush-fitting (0.0 m), shallow (0.5–2 m), and deep (2–80 m). Also, MUTs can be defined as searchable, visitable, and compartmentalized based on their internal space and accessibility and can be placed under roads, metro lines, and pathways.

High-Density Polyethylene (HDPE), cast-in-place concrete, pre-cast concrete sections, steel, brick and mortar, and sprayed concrete are different materials, which can be used in MUT construction. MUTs have been constructed in different shapes, including rectangular, circular, trapezoid, etc.

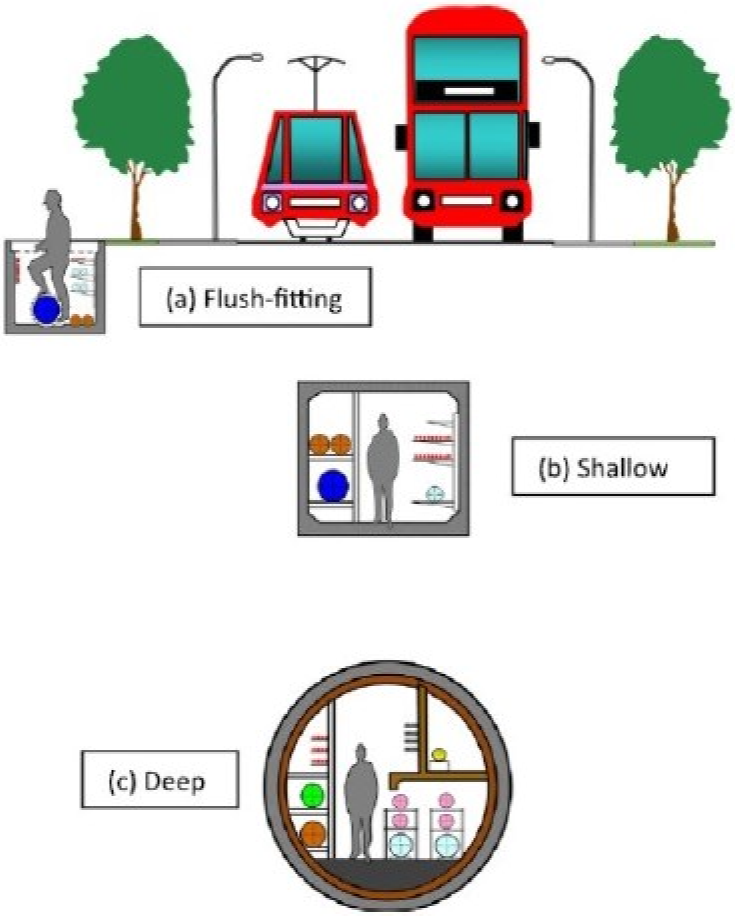


Figure 2.2 Different types of MUTs (Hunt et al., 2014)

2.2.2 MUT Benefits

Luo et al. (2020) categorized the benefits of MUT in two groups, which are the benefits for utility companies and municipalities, and benefits for utility users and citizens (i.e., social and environmental benefits). The main benefits of MUTs for municipalities and utility companies can be classified as follows (Luo et al., 2020):

(1) Reduction of construction costs: By using MUTs, the costs of excavation and reinstallation related to underground utilities will be greatly reduced during their lifecycle. (Cano-Hurtado and Canto-Perello, 1999; Rogers and Hunt, 2006; Canto-Perello and Curiel-Esparza, 2013). The amount of ground-level construction works, required equipment, machinery, and materials can be reduced since maintenance works can be

done inside the tunnel. Street closures due to construction will be minimized and normal traffic will continue. As a result, traffic control costs are reduced and local businesses and residents experience fewer disturbances (Gilchrist and Allouche, 2005; Hunt et al., 2014). Also, the number of accidental injury and death of workers related to the construction works are reduced during the lifecycle of utilities (Ormsby, 2009).

In addition, MUTs reduce the damages to detour roads, which may be used by vehicles during construction works, by avoiding the repeated excavations related to maintenance of utilities (Najafi and Kim, 2004).

(2) Improving inspection and maintenance of utilities: MUTs provide better access for inspection and assessment of underground utilities, which can reduce the failure of utilities and increase their life span (Canto-Perello and Curiel-Esparza, 2013; Hunt et al., 2014).

(3) Minimization of damage and corrosion of utilities: The buried utilities can be damaged during the excavations since their location cannot be easily identified. MUTs reduce the damages to the utilities and also protect them against corrosion by integrating them inside the tunnel (Canto-Perello and Curiel-Esparza, 2013).

(4) Future development and upgrade cost savings: MUTs reduce the costs related to upgrading and future development of the utilities by avoiding repeated excavations (Clé de Sol, 2005; Kang and Choi, 2015).

(5) Major reduction of labor accidental injury and death: Ground-level construction works can cause trench-relating death and serious injuries to workers. MUTs reduce these kind of damages to the workers by avoiding repeated excavations (Ormsby, 2009).

(6) Reduction of municipal revenue loss: Street closures related to conventional buried utilities can reduce the municipal revenue. For instance, the parking meter machines become deactivated during the construction works and no more income can be gained by them (Ormsby, 2009). Also, the sale tax revenue from the local businesses is reduced duo to less shopping form them during the construction works (Gilchrist and Allouche, 2005).

(7) More organized planning of underground space: MUTs enable the municipalities and utility companies to better organize the underground space by integrating all utilities in a tunnel (Sterling et al., 2012).

The social and environmental benefits of MUTs are generally related to the users of the utilities and all citizens, who are living or have a business near the location of the project. These benefits include:

(1) Major reduction of traffic congestion or detour road: The vehicles arrive to their destination with delay because of traffic congestion or detour roads related to the construction works. This delay wastes the time of the vehicle passengers and imposes on them delay cost (Gilchrist and Allouche, 2005; Ormsby, 2009b; Oum, 2018). Also, the operation costs of vehicles increase because of the extra operation time due to traffic congestion or detour roads (Clé de Sol, 2005; Ormsby, 2009b). In addition to the vehicle's passenger, pedestrians are also affected by delays because of construction works and losing time (Ormsby, 2009). Another cost is imposed to emergency vehicles (e.g., ambulance, firefighter vehicle, police) because of loss of time due to the road obstruction (Ormsby, 2009).

(2) Improved health, environment, and safety: Construction work for conventional buried utilities causes safety issues (e.g., accidental injuries or death) related to the falling into

the trenches or collapse of trenches. Also, road closures will delay the pass of emergency vehicles (Ormsby, 2009).

The noise and vibration of machinery in construction works of the conventional method (Jung and Sinha, 2007), dust propagation to the air from construction work, emission of toxic gases and underground water pollution (Gilchrist and Allouche, 2005) are other issues related to the health of people and environmental problem.

(3) Improved quality of utility services and customer satisfaction: Since the MUTs improve the inspection and maintenance of the utilities, the number of faults and breakdowns decreases, and the expected life span of the utilities increases. This helps the utility companies to provide a better quality of services with fewer service disruption and cheaper services cost (Cano-Hurtado and Canto-Perello, 1999; Canto-Perello and Curiel-Esparza, 2006). Customer satisfaction increases through the higher quality of services and fewer charges.
(4) Major reduction of local business loss: The customers of local businesses in the area of the construction work can be reduced, which can result in income loss. For instance, the businesses that provide delivery services will encounter delays because of traffic congestion and road closures (Ormsby, 2009).
(5) Major reduction of damage or closure of recreational facilities: Recreational facilities, such as parks and playgrounds are usually closed or damaged temporarily because of construction works, which has a negative impact on the users of these facilities (Ormsby, 2009).

2.2.3 MUT Disadvantages

The main disadvantages of MUTs can be classified as follows (Luo et al., 2020):

(1) High initial investment cost: It may not be possible for a single utility company to afford the initial investment for constructing an MUT (Rogers and Hunt, 2006) even by considering the possibility of renting the space of the tunnel to other utility companies (Hunt et al., 2014). Some conditions, such as deep excavation, waterproofing, and shoring are more likely in MUT construction, which may not be needed usually for conventional methods and add expenses to MUT projects (Najafi and Kim, 2004). In addition, the need for installing temporary bypass utilities for keeping the utilities in service and their diversion imposes an extra cost for MUT projects (McKim, 1997; Rogers and Hunt, 2006).
(2) Disruption of services: The disruption of services of utilities can be a critical problem in construction of MUTs. A high density of underground utilities needs deep MUTs to pass under them, in order to keep the services during the construction works (Cano-Hurtado and Canto-Perello, 1999; Hunt and Rogers, 2005).
(3) Compatibility and safety issue: Because of incompatibility, placing of some utilities close to each other may has a high risk (Cano-Hurtado and Canto-Perello, 1999; Hunt and Rogers, 2005). For instance, placing gas pipes and electricity cables close to each other imposes a potential risk of fire (Canto-Perello and Curiel-Esparza, 2001; Legrand et al., 2004).
(4) Security risks: MUTs integrate all utilities in a tunnel. Therefore, providing the security of MUTs from human attacks is an important issue. Limiting access doors and people

who have access to the MUT, using sensors, and surveillance systems are some solutions suggested for improving the security of MUTs (Canto-Perello and Curiel-Esparza, 2013).

(5) Coordination issues: Since MUTs integrate different utilities in a tunnel, installation, and maintenance of utilities in an MUT requires more coordination between the utility companies and municipalities. This coordination needs a very good level of management compared to conventional open-cut maintenance and installation works (Laistner and Laistner, 2012).

2.2.4 MUT Projects Around the World

According to Rogers and Hunt (2006), different names have been given to MUTs, such as ‘utilidors’ (USA), Common Service Tunnels in Singapore, Common Utility Tunnels in Malaysia, Common Utility Enclosures in Hong Kong, Common Utility Ducts in Taiwan and Multi-networks Gallery in France.

Luo et al. (2020) reviewed recent development and the history of MUTs in the world. The first MUT, which integrated sewer and water pipes was built in France in 1850 (Cano-Hurtado and Canto-Perello, 1999; Canto-Perello and Curiel-Esparza, 2001; Wang et al., 2018).

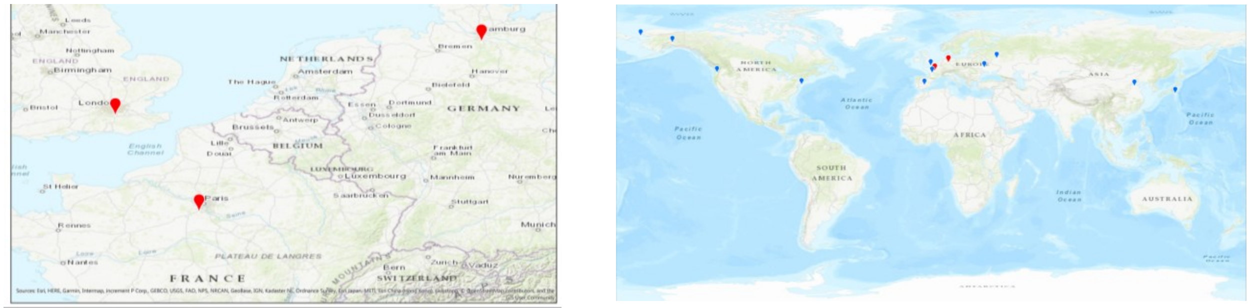
As shown in Figure 2.3(a), Germany is one of the countries that first implemented MUTs. There was a lag in MUT construction from 1893 to 1920. Between 1921 and 1960, several MUTs were built in North America, Asia, and Europe as shown in Figure 2.3(b). As shown in Figure 2.3(c), from 1961 to 1980, the construction of MUTs increased and about 30 MUTs were built. During this period, France built MUTs in different cities like Angers, Paris, Rouen, Lyon, etc. The number of MUTs, which were built in France was about 50% of the total number of MUTs in the world. Following the Utility Tunnel Law passed in 1963, Japan was able to build approximately 2000 km of utility tunnels in 80 Japanese cities (Wang et al., 2018). Countries like Belgium, Czech Republic, Germany, Switzerland, etc., were also involved in the construction of MUTs (Luo et al., 2020).

Between 1981 and 2000, the Czech Republic increased the constructions of MUTs. Japan also increased the construction of MUTs during this period, which was about 30% of the world MUTs. In addition, as shown in Figure 2.3(d), countries like Norway, Spain, China, and the USA also constructed different MUTs in this period. MUT construction has increased in Asia in the 21st century. Currently, as show in Figure 2.3(c), 80% of the MUTs in the world are being constructed in China. Countries like Israel, Malaysia, India, Qatar, Singapore, and Canada have also implemented MUTs. Most of the MUTs in the USA are constructed on university campuses, hospitals, private establishments, and military installations.

Among the countries in Europe, the Czech Republic, France, and Germany have the highest number of MUTs. MUTs are constructed in Europe as a solution to one or more challenges. For example, the Czech Republic built MUTs to reduce the impact of excavations in historical areas, France and the UK built MUTs to stop the spread of cholera (Luo et al., 2020).

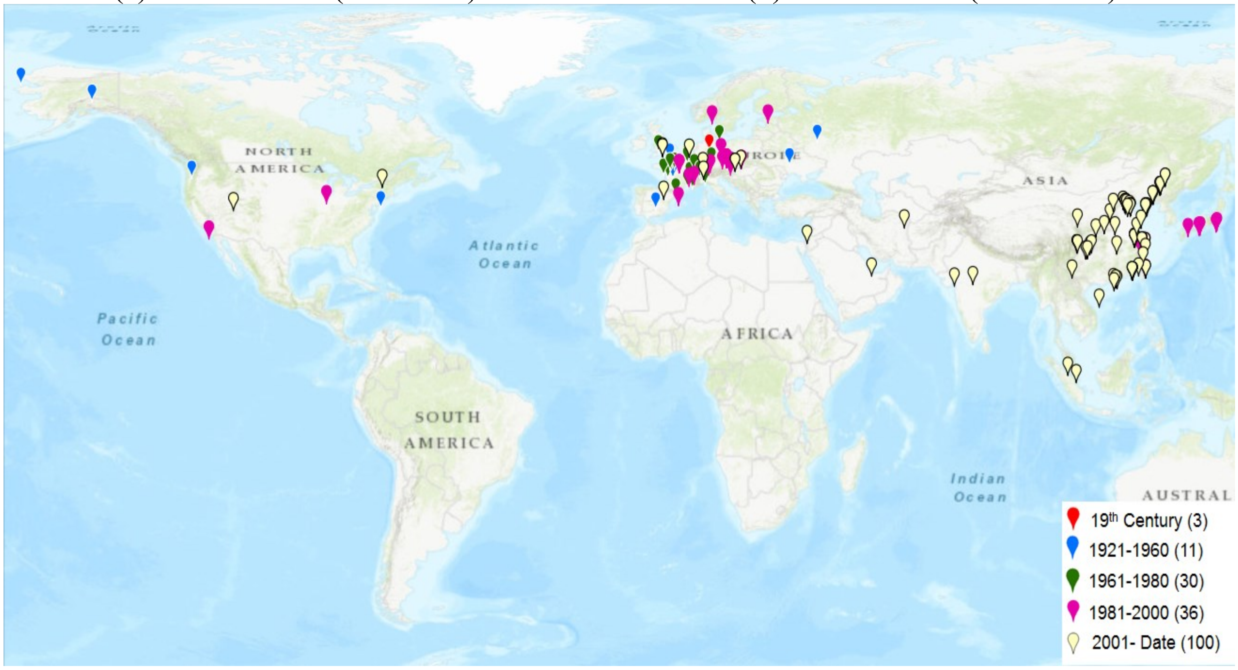
In North America, most of the MUTs are built in university campuses, hospitals, airports, and military installations (Laistner and Laistner, 2012) because these bodies own and operate their utility infrastructure and the coordination, security, funding, and operation of the utilities are easily overcome (Hunt et al., 2014). According to a survey by Kuhn et al., (2002) most states in the USA are interested in MUTs. However, very little work has been done, in the public sector, in recent years related to MUTs (Luo et al., 2020).

Many of the new MUT projects are in the Middle East oil countries like Qatar, Saudi Arabia, and Kuwait (Luo et al., 2020). China is one of the leading countries in building MUTs with a total length of about 500 km in major cities from 1994 to 2015, which is almost equal to the length of MUT in all other cities in the world. (Yang and Peng, 2016; Zhou et al., 2017). Yang and Peng (2016) reported that, 1000 km of MUTs are constructed in about 69 cities in China. Also, in 2015, 10 cities were selected in China for building MUT pilot projects, which has a total length of 389km. The government of China invested 45% of these projects and published a series of policies and guidelines for planning, financing, and solving technical issues of MUTs construction.



(a) 19th Century (3 MUTs) (b) 1921 to 1960 (11 MUTs)

(c) 1961 to 1980 (30 MUTs) (d) 1981 to 2000 (36 MUTS)



(e) 2001 to 2019 (100 MUTs)

Figure 2.3 Location of MUTs built at different time periods (Luo et al., 2020)

2.3 Process Simulation

Process simulation has been widely used in different fields, such as manufacturing, business, computer science and construction (Roberts and Dessouky, 1998; Banks et al., 2010). Shannon (1977) defined simulation as: "The process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system”.

There are three common types of simulation methodologies, which are Discrete-Event-Simulation (DES), System Dynamics (SD) and Agent-Based Modeling (ABM). The DES method is used to model a complex system’s operation as a sequential series of events. The SD method is used for high-level understanding and analyzing the behavior of a system over time (Dang, 2015). Individual agents are simulated in the ABM method, which is a class of computational models for simulating the behaviors and interactions of autonomous agents (Macal and North, 2006). In this research, the DES method is used to simulate the MUT construction methods because it is more suitable for simulating well-defined processes. In the following section a brief introduction of this method will be presented.

2.3.1 Discrete-Event-Simulation (DES)

DES is commonly used to model and evaluate construction sequences in simulation studies. In this method, workers, equipment, documents, tasks, etc., are represented by passive objects called entities. These entities move thorough the simulation model’s blocks, where they can be waiting in queues, processed, delayed, seizing and releasing resources, split and combined, etc. (Borshchev and Filippov, 2004).

The operation of a system is modelled by DES as a discrete sequence of events in time. Each occurrence occurs at a specific point in time and represents a change in the system’s state. Since no change in the system is anticipated between consecutive events, the simulation time will skip directly to the next event’s occurrence. DES models are developed by breaking down activities into tasks. The duration of each of these tasks can be either presented as a deterministic value or as a probabilistic distribution, such as the triangular distribution (Beck, 2008). Therefore, by using probabilistic distributions in DES models, the total duration of the project can be determined within a range of potential durations instead of a deterministic value.

2.3.2 4D Simulation

While DES focuses on the time dimension of project simulation, 3D models enable architects, engineers, and project managers in the Architecture, Engineering, and Construction (AEC) sector to visualize construction projects in the design phase and to detect clashes between components.

Hartmann et al. (2008) categorized the 3D/4D models application areas into seven groups: photorealistic renderings, virtual design revies, analyzing different design options, cost estimating, analyzing construction sequences, production of construction documents, and preparing the bid packages. Photorealistic renderings enable the AEC sector and the project stakeholders to visualize the facilities. The coordination between the stakeholders involved in the proposed design would improve when the project is simulated and visualized from the viewpoint of a person through 3D walkthroughs and movie clips (Whyte et al., 2000). 3D models are used by project designers to express design ideas to stakeholders and other designers in different industries. This coordination leads to the detection and resolution of any unforeseen clashes that may arise between the electrical, mechanical, and plumbing sectors’ designs (Hartmann et al., 2008). Also, 3D models can be used for: (1) analyzing and comparing different design options;

(2) analyzing the building operations; and (3) providing a bill of quantity and estimating the cost of the project (Hartmann et al., 2008).

However, 3D models do not offer scheduling or construction progress control to planners. A 4D simulation can be defined as a 3D model linked to the construction schedule (Koo and Fischer, 2000). Heesom and Mahdjoubi (2004) identified the applications of 4D models in the construction industry in three categories: product modeling and visualization, process modeling and visualization, and communication and collaboration. 4D models have been used to verify the accuracy of work sequences and schedules, assess site accessibility, and spatial-temporal conflicts (Hartmann et al., 2008).

2.3.3 Simulation in Tunnel Construction

In this section, the literature review about the use of process simulation for research and application in tunneling construction will be presented. Subsequently, the papers are summarized and compared with the current research in Table 2.1.

Touran and Asai (1987) developed several simulation models for investigation the effect of different variables on the tunnel advance rate. These variables include tunnel boring machine penetration rate, train travel time, the number of muck trains, the type of rock, and the rock stand-up time. Ruwanpura et al. (2001) presented the results generated from the special-purpose tunnelling simulation template using the historical data to test the template and analyze the potential construction processes. Zhou et al. (2009) developed a simulation system as an optimization tool for automating site layout problems and seeking a near optimum construction site layout for utility tunnel construction. Liu et al. (2010) estimated the penetration rate of the tunnel excavation with TBM based on the rock mass classification. Al-Bataineh et al. (2013) presented the use of simulation to plan tunnel construction of a project in Edmonton, Alberta, Canada. Nido et al. (1999), the research aimed to identify and analyze the different soil conditions and various resources that affect the productivity of microtunneling. Luo and Najafi (2007) enhanced CYCLONE simulation model based on the research by Nido et al. (1999). The purpose of this study was to evaluate the effect of the different soil conditions on productivity in microtunneling operations. Marzouk et al. (2010) developed a simulation module tool for planning microtunneling projects using computer simulation. Dang (2015) developed a simulation module to analyze the effect of the various resources and different soil components on productivity in microtunneling operations. Rahm et al. (2012) developed the simulation tool to investigate the advancement rate of the TBM. Rahm et al. (2016) introduced a model to analyze the production and logistical processes of mechanized tunnelling processes in a transparent and understandable way.

Marzouk et al. (2008a, 2008b) used DES for planning the cut and cover construction method. Abdallah and Marzouk (2013) used DES simulation for planning tunneling projects using open cut method. Zhang et al. (2010) used 3D animations for modeling and visualization of tunnel construction using TBM.

Table 2.1 Related works in simulation of tunnel construction

Reference	Construction Method			Methodology			Objectives
	C&C	MTBM	TBM	DES	SD	4D BIM	
(Touran and Asai, 1987)			✓	✓			Analyzing different variables affecting the tunnel advance rate.
(Ruwanpura et al., 2001)			✓	✓			Analyzing construction process.
(Zhou et al., 2009)			✓	✓			Finding optimum construction site layout.
(Liu et al., 2010)			✓	✓			Estimating the penetration rate.
(Al-Bataineh et al., 2013)			✓	✓			Planning the tunneling project.
(Nido et al., 1999)		✓		✓			Analyzing the effect of soil conditions and various resources on productivity of MTBM.
(Luo and Najafi, 2007)		✓		✓			The effect of different soil conditions on productivity of MTBM.
(Marzouk et al., 2010)		✓		✓			Planning MTBM projects.
(Dang, 2015)		✓		✓			The effect of soil conditions and various resources on productivity in MTBM projects.
(Rahm et al., 2012)			✓	✓	✓		Investigating the advance rate of TBM.
(Rahm et al., 2016)			✓	✓	✓		Analyzing production and logistical processes of mechanized tunneling processes.
(Marzok et al., 2008a; Marzouk et al., 2008b)	✓			✓			Planning tunneling projects using Open-Cut method.
(Abdallah and Marzouk, 2013)	✓			✓			Planning Open-Cut tunneling projects.
(Zhang et al., 2010)			✓			✓	3D modeling and visualization of tunnel construction.
This research	✓	✓		✓		✓	Comparing the durations and costs of MUT construction using C&C and microtunneling as well as constructability assessment.

2.3.4 Advantages and Disadvantages of Process Simulation

The use of process simulation for analyzing systems has several advantages over analytical or mathematical methods, which are more than just the ability to simulate forward in time (Kieran et al., 2007). The following provides some of the advantages of process simulation, as described by other authors, such as: Oloufa (1993), Shannon (1977), Kieran et al. (2007), Karatza (1993):

(1) Choosing the best alternative: a desired alternative can be selected by simulating the new design, layouts, resources etc., before implementing it.
(2) Understanding the system: managers can predict the future behavior of the system by implementing the simulation model. As a result, they can reorganize the system and see the operation to understand the interaction of each element in the system.
(3) Bottleneck analysis: analyzing the bottlenecks of the system is possible through simulation, which allows to test different options in order to improve the operation of the system.
(4) Problem identification: simulation enables for the identification of problems that may happen in the system. As a result, the causes of problems can be recognized. Therefore, managers can plan to solve the causes of problems instead of solving the problems itself.
(5) Ability to explore new suggestions: simulation can be used for testing and evaluating the new initiatives, designs, resources, etc., without putting the current system at risk.
(6) Ability to control the time of the system: simulation enable to decrease or increase the pace of a system in order to evaluate it. For instance, when a problem arises, it is possible to slow down the system to find the cause of the problem. Also, simulation can run the system for several months or years of production in just a few minutes, by which the managers can investigate a large period quickly.
(7) Visualizing the plan: when a new alternative has been designed, many problems can not be predicted by evaluating a real job site. Therefore, the managers can detect and eliminate the weaknesses by using simulation models.
(8) Finding the optimal solutions: simulation helps to find the optimal solutions for inputs like number of workers by using sensitivity analysis with different variations.

Using process simulation has also some disadvantages including (Dang, 2015):

(1) Simulation is a time-consuming method, which requires significant amounts of time and large amount of data.
(2) Since simulation requires specialized training, the skill levels of modelers may vary widely, which can affect the functionality of the developed model.
(3) Simulation cannot provide the optimal solutions; instead, it can be used for comparing different alternatives and selecting the best one.

2.3.5 Process Simulation Software

There are many companies producing simulation software. Most of these software have been developed based on the most common simulation methodologies, which are discrete-event simulation (DES), system dynamics (SD) and agent-based modelling (ABM) (Dang, 2015). In this section, some of the simulation software are introduced.

Arena simulation software is developed based on discrete event simulation method by Rockwell Automation and the former Systems Modeling Corporation, which was acquired by Rockwell in 2000 (Automation Rockwell, 2021). The software is widely used in simulation of industrial processes and supply chains. The development of simulation models using Arena software includes three main steps, which are (Neubauer and Stewart, 2009):

(1) Analyzing and identification of the operation processes.
(2) Creation of a basic model by using window flowchart view.
(3) Adding parameters, such as processing times and resources to the model elements.

SIMUL8 simulation software is developed by SIMUL8 Corporation, which is used for simulation of the systems using processing of discrete entities at discrete times. This software is used for planning, design and optimization of manufacturing, logistics or service providing systems. The main steps of using SIMUL8 software are (SIMUL8 Corporation, 2021):

(1) Analyzing and identification of the operation processes.
(2) Adding objects to SIMUL8 software.
(3) Defining the properties of objects as well as their relationships.

EZStrobe software, which is used in this research has been introduced by Martinez, (2001). EZStrobe is a general-purpose simulation system based on activity cycle diagrams and is defined as "a simpler discrete-event simulation system suitable for learning and modeling processes and operations that do not require the explicit identification of resources." (Rekapalli and Martinez, 2011). Developing simulation models using the EZStrobe includes four main steps, which are (Dang, 2015):

(1) Identification of the activities, the flow, and the construction processes.
(2) Using an activity cycle diagram to present the resources, activities, and their interaction through the construction process.
(3) Connecting the activities by drawing links between them.
(4) Defining the properties of the resources.

AnyLogic is a simulation modeling, which enables analysts, engineers, and managers to gain deeper information about the complex systems and processes. This software was presented at the winter simulation conference in the year 2000. Developing simulation models using AnyLogic software includes three steps, which are (Anylogic Company, 2021):

(1) Analyzing and identification of the structures within the model.
(2) Creating a basic simulation model by dragging, dropping, and integrating the simulation elements using pre-defined simulation elements in the object libraries.
(3) Expansion of the basic simulation model by using code in Java, Eclipse.

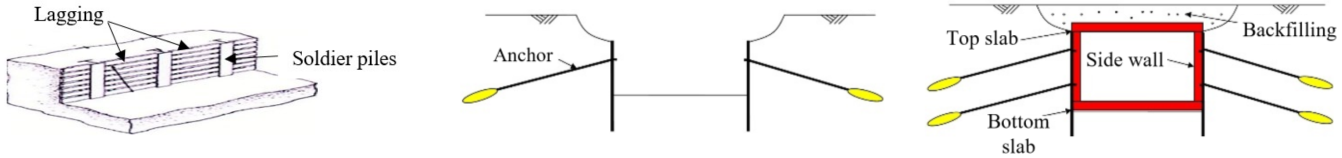
2.4 MUT Construction Methods

The C&C and trenchless methods are two main groups of construction methods for MUT projects (Clé de Sol, 2005; Ramírez Chasco et al., 2011). Trenchless methods can be divided in two main categories, which are trenchless construction methods (Auger boring, Horizontal Directional Drilling (HDD), Microtunneling, Pipe Jacking and Pipe Ramming) and trenchless renewal/replacement methods (Cured In Place Pipe (CIPP), Slip Lining) (Najafi, 2004). The main concept of the C&C, microtunneling and drill and blast methods will be discussed in following sections.

2.4.1 C&C Method

The C&C method is the most common method for construction of utility tunnels (Razieh Tavakoli et al., 2018). C&C tunnels are constructed in the following order: a trench is created, the tunnel structure is implemented, the trench is filled up, and the pavement is restored (EOT and FTA, 2008). The support of the vertical sides is the main consideration with different C&C techniques including C&C using diaphragm walls, secant pile walls, soldier piles and lagging, and steel sheet pile walls (Abdallah and Marzouk, 2013; Marzouk et al., 2008b). The type of the retaining wall can be selected based on three parameters: proximity of the trench to other buildings, type of the soil, and existence of water table (Valdenebro et al., 2019).

One of the oldest retaining systems that is widely used in supporting deep excavations is C&C using soldier piles and lagging technique. Soldier piles and lagging structures are constructed in a cyclic pattern, with soldier piles being placed at regular intervals (2-4 m) and lagging being excavated and installed between soldier piles (FORASOL, 2008). The C&C method using soldier piles and lagging is performed by dividing tunnel length into equal segments and involves four main steps: (1) Installing the soldier piles and lagging (Figure 2.4(a)), (2) Excavating and installing the anchors (Figure 2.4(b)), (3) Construction of side walls, top and bottom slab segments (Figure 2.4(c)), and (4) backfilling (Figure 2.4(c)) (Abdallah and Marzouk, 2013).



(a) Installing soldier piles and lagging

(b) Excavation and installing anchors

(c) Tunnel construction and backfilling

Figure 2.4 Construction process of C&C method using soldier piles and lagging (Abdallah and Marzouk, 2013)

Sheet pile walls are simply rows of interlocking vertical pile segments that are built to form a straight wall wide enough to support soil. Steel sheet pile walls are used in soft soils, especially when there is a risk of bottom heave in soft clay soil or sand (Deep Excavation, 2011). The sheet piles can be pushed into the ground using a pneumatic jacking system. This method combined with the use of precast concrete boxes is the fastest C&C method and, in addition, it causes the least inconvenience and risks to the neighbors (Megaw and Bartlett, 1982; Ou, 2006).

One of the most common techniques used in the construction of cut and cover tunnels is the secant pile walls technique. The secant piles are wide diameter bored piles that are overlapped at near center and can be used to form a wall. In this method, the secant piles (without reinforcement) are driven first along fixed distances followed by the reinforced piles between every two secant piles (Figure 2.5) (Marzouk et al., 2008a).

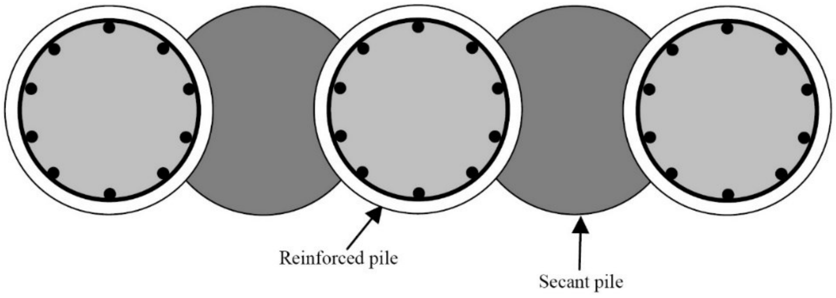
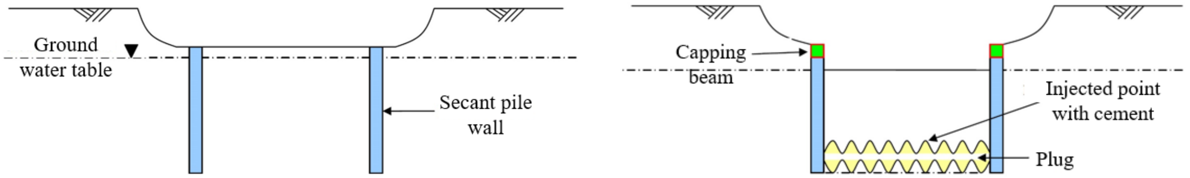


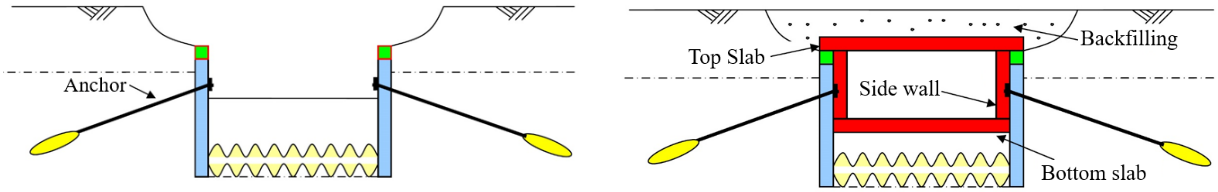
Figure 2.5 Secant pile wall (Abdallah and Marzouk, 2013)

The C&C method using secant pile walls is performed by dividing tunnel length into equal segments and involves three main steps: (1) Construction of secant pile walls (Figure 2.6(a)), (2) Construction of capping beams, plug and dewatering (Figure 2.6(b)), (3) Construction of anchors and installing steel anchors' connecting beams (Figure 2.6(c)), and (4) Construction of side walls, top and bottom slab segments (Figure 2.6(d)), and (4) backfilling (Figure 2.6(d)) (Marzouk et al., 2008b).



(a) Construction of secant pile walls

(b) Construction of capping beams, plug and dewatering



(c) Construction of anchors and installing steel anchors' connecting beams

(d) Construction of side walls, top and bottom slab segments, and backfilling

Figure 2.6 Construction process of C&C method using secant pile walls (Abdallah and Marzouk, 2013)

Diaphragm walls are also used in the C&C method as the support for the vertical sides. A diaphragm wall is a reinforced concrete structure constructed in-situ panel by panel. The wall could be designed to reach very great depths (sometimes up to 50 m). The construction of diaphragm walls includes four main steps: (1) Construction of the guide wall: The guide wall consists of two parallel concrete beams built along the side of the wall to serve as a guide for the excavation of the diaphragm wall trench, (2) Excavation of the trench, (3) Reinforcement, and (4) Concrete pouring (RailSystem, 2021). Figure 2.7 shows the different steps of diaphragm wall construction.

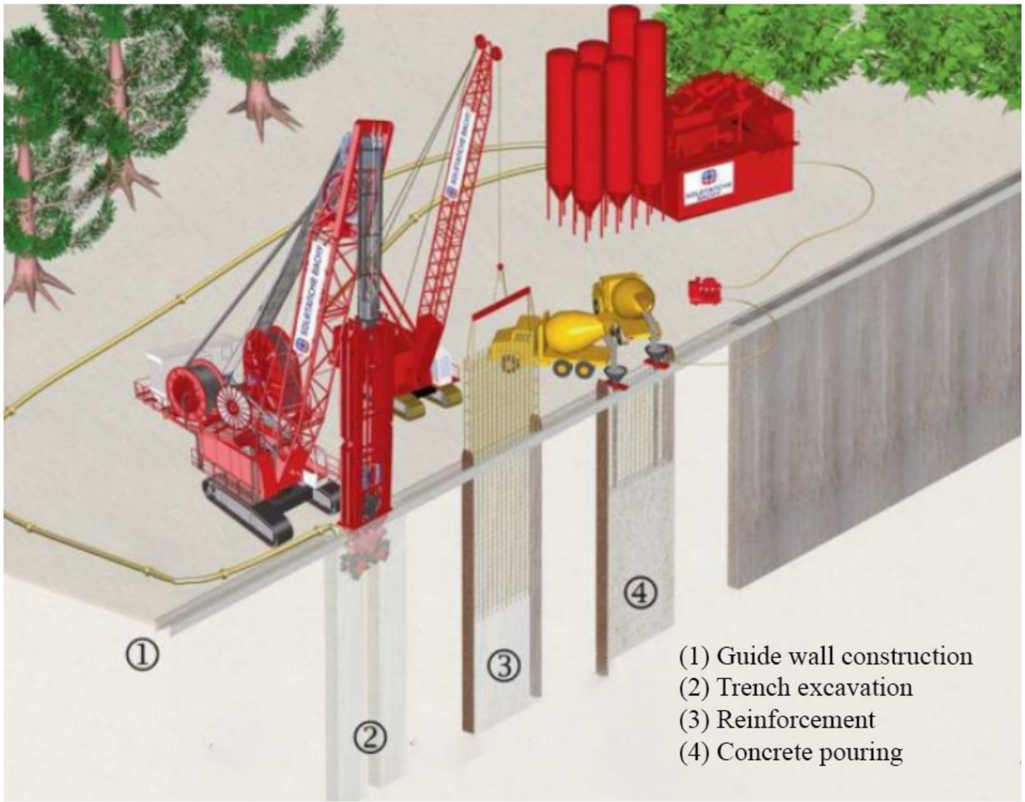
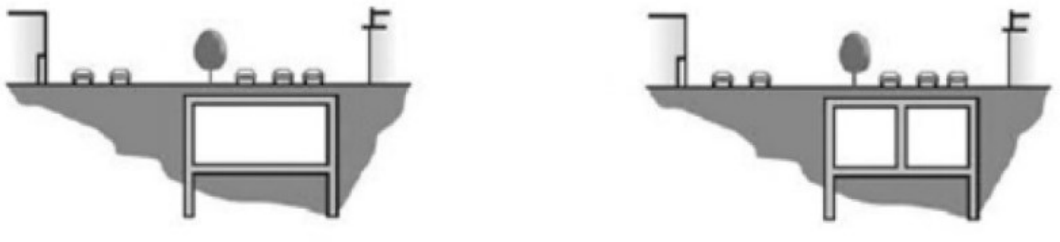


Figure 2.7 Diaphragm wall construction (RailSystem, 2021)

Top-down C&C is another form of the C&C method. In this method, diaphragm walls are used for the construction of capping beams and side support walls from the ground level (Figure 2.8(a)). Then the tunnel roof can be built in the excavated ground at shallow depth (Figure 2.8(b)). Except for the opening accesses, the surface is then restored (Figure 2.8(c)). At the end, the excavation of the ground and construction of the tunnel base slab are done underneath the tunnel roof using the opening accesses (Figure 2.8(d)) (Arshad and Abdullah, 2016).

(a) Construction of support wall (b) Construction of tunnel roof



(c) Restoration of the surface (d) Excavation and construction of tunnel

Figure 2.8 Construction sequence of top-down C&C method (Arshad and Abdullah, 2016)

Valdenebro et al., (2019) presented a construction process for building MUTs in dense and historic cities using precast reinforced concrete sections instead of cast-in-place concrete and using of a temporary trench shoring system that can be removed after finishing each segment and be used for other sections. Cast-in-place concrete takes more time than precast concrete sections and causes more inconvenience due to vibration, noise, and dust (Tao and Zhang, 2011). The activities in this method can be divided in four main groups: (1) Preliminary works, which are the preparations for the dismantling of old pavements, excavation, and the opening of street trenches. These activities can be done without affecting the functioning of the city; (2) Execution of a MUT section, which includes the installation of the trench shoring system, excavation, backfilling, and disassembly and transferring the trench shoring system to the next section; (3) Installation of utilities in the MUT; and (4) Street paving. Although all of the mentioned C&C methods can be used for MUT construction, this solution is the fastest one. In addition, this method offers the least inconvenience to the neighbors (Ou, 2006).

2.4.2 Microtunneling Method

Microtunneling as a trenchless method, is a competing alternative to the C&C method because it does not require road closure and diverting the existing utilities. According to the Stein (2005), "In microtunneling methods, jacking pipes are jacked from a starting shaft with the aid of a jacking station up to a target shaft. At the same time, an unmanned, remote-controlled microtunneling machine carries out the displacement or full faced excavation of the working face. In the latter variant, the spoil is transported though the jacked pipe string" (Figure 2.9).

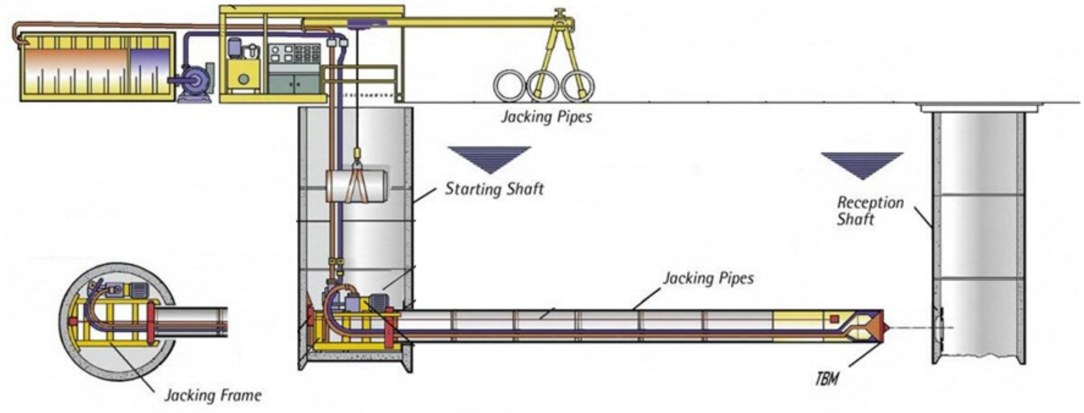


Figure 2.9 Microtunneling main components (Herrenknecht, 2013)

Depending on the way of conveying the spoil, there are three types of Microtunnling Boring Machine (MTBM) (Stein, 2005), which are shown in Figure 2.10.

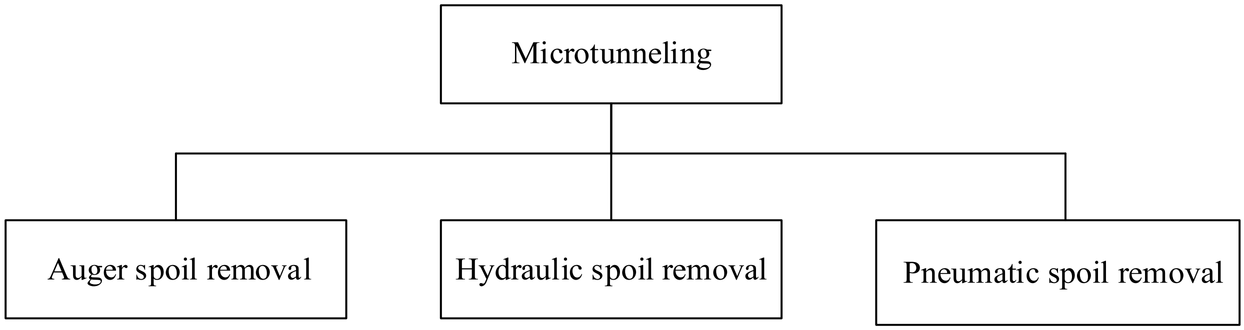


Figure 2.10 Basic classification of MTBM (Herrenknecht, 2013)

According to Colson (2010), the type of soil, ground water level and existence of boulders are three main parameters, which should be considered for choosing the type of MTBM. Table 2.2, 2.3, and 2.4 show the field of application of MTBM according to the mentioned parameters.

Table 2.2 The fields of application of MTBM according to the type of ground (Colson, 2010)

Machines for mucking	Clay	Pebbles	Gravel	Sand	Silt	
					IP<30	IP>30
Hydraulic	**	**	**	**	**	*
Auger	N	*	**	**	*	N
Pneumatic	N	**	**	**	*	*

**: Machine well suited

*: Machine can be convenient

N: Machine not recommended

PI: Plastic Index

Table 2.3 The fields of application of MTBM according to ground water level classification (Ueki et al., 1999)

Condition	Machine selection
Water table is more than 3m above pipe.	Auger types cannot be used. The hydraulic types can be selected.
Water table is above invert and no more than 3m above pipe.	Auger types could be used but slurry types are more appropriate.
Water table is below invert of pipe.	Desirable condition for auger types.

Table 2.4 The fields of application of MTBM according to existence of boulders (Ueki et al., 1999)

Condition	Machine types
No boulders	Both hydraulic and auger types can be selected
Small boulders (up to 1/3 of machine outer diameter)	Auger types could be used but hydraulic types are more appropriate
Large boulders (larger than 1/3 of machine diameter)	Not suitable for auger machines

The basic advantages and disadvantages of three type of MTBM are shown in Table 2.5. It can be concluded that the hydraulic type of MTBM machines can be used in the most situations.

Table 2.5 Basic advantages and disadvantages of the three types of MTBM (Stein, 2012; Ueki et al., 1999)

Type of MTBM	**Advantages**	**Disadvantages**
Hydraulic	• Available for wider range of soils, and diameters • Tunneling more than 3 m below groundwater table can be achieved • Application in soil and rock with and without ground water • Longer drives can be achieved • Driving pits can be cleaner because material is automatically sent to separation plans	• There may be problems on driving through cohesive soils when installation depth is shallow • System is more complicated and costly than other types
Auger	• Whole system is simpler and less expensive than slurry systems • Effective for smaller diameters and shallow installations • More effective for cohesive soils and low water level sites	• Tunneling below water table is limited • Limited diameter variations. Usually available for less than 120cm pipes • Drive length is limited to typically around 90m due to the cutter torque • Application in rock is usually impossible
Pneumatic	• Possible high jacking lengths can be achieved • Application in temperatures below 0 degree	• Usually used in non-cohesive soils that jacking performance reduces remarkably • Total waterproofing is difficult to obtain in joints

2.4.3 Drill and Blast (D&B)

The first stage of tunneling operations is rock fragmentation (primary breaking), which can be done with or without explosives. As shown in Figure 2.11, the first step in rock fragmentation using explosives (Drill and Blast method) is boring the drill holes in the working face of the tunnel (as determined in the blasting design). Then, the drill holes will be filled by explosives and the detonators are attached to the explosive devices. After that, the drill holes will be blasted in a proper sequence planned in blasting design. Since the blasting disperse clouds of dust and explosion gases, the contaminated air in the tunnel must be removed using a ventilation system. The next step is dislodging, which refers to the removal of loose rocks, which were not completely released from the surrounding ground during the blasting. After the loose rocks are dislodged from the tunnel face, the blasted materials are carried out of the tunnel, which can be done using dump trucks or conveyor belts. The next step is securing the work area by using bolts or shotcrete. When the tunnel face is secured, the position of the drill holes for the next round will be determined on tunnel face and the whole cycle is repeated.

The mentioned activities have a low level of automation and mechanization, and there is a lot of hard manual work involved. Worker's safety is a major concern during temporary support installation and mucking. This is because there is a high chance of rock falls in the tunnel's unsupported portion immediately after blasting (Girmscheid and Schexnayder, 2002).

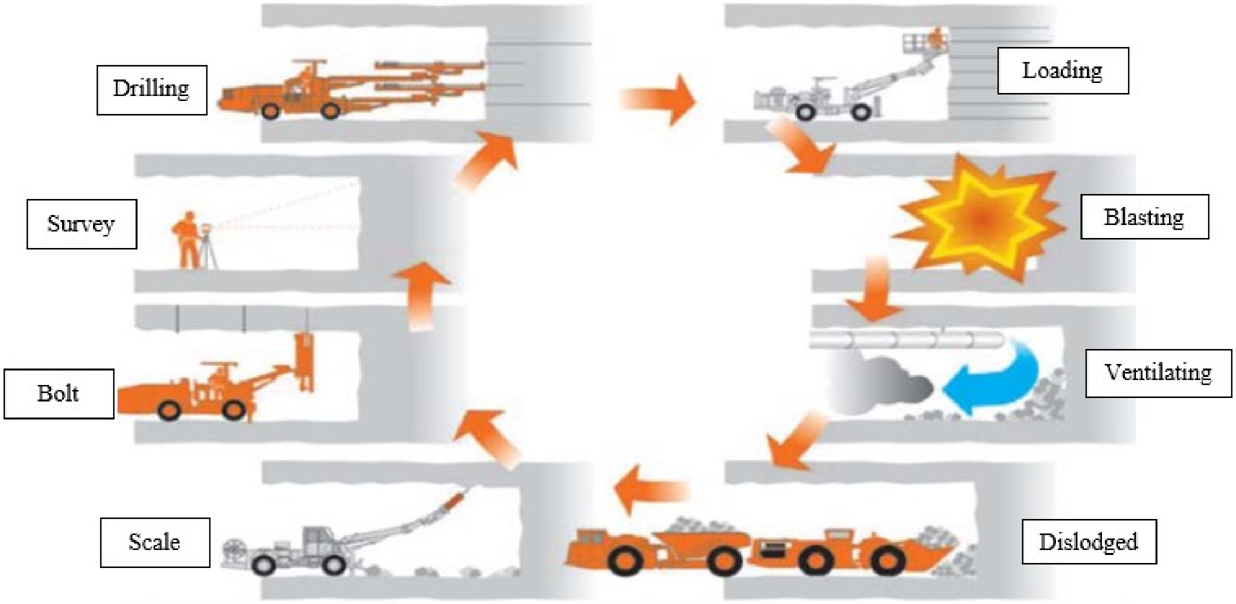


Figure 2.11 Drill and Blast cycle (Tatiya, 2005)

2.5 Summary

This chapter provided a comprehensive critical review of all the domains of this research with respect to MUTs. A general review of MUTs including classification, construction methods, benefits, and disadvantages, provides an understanding of the nature, necessity, and challenges of MUTs. One of the most important factors affecting the expense, productivity, and performance of MUT projects is the construction method. Therefore, it is important to simulate different construction methods to be able to compare them in a quantitative way. The review of related works in simulation of tunnel construction was presented. Although simulation has been used for different tunneling projects, such as water and metro tunnels, there is still lack of research about using stochastic simulation for MUT construction.

CHAPTER 3: PROPOSED METHODOLOGY

3.1 Introduction

As mentioned in Section 1.2 and Chapter 2, one of the most important factors affecting the cost and efficiency of MUT projects is the construction method. To address this problem and research objectives mentioned in Section 1.3, the proposed method is developed in six steps (Figure 3.1). Each step is introduced in this chapter.

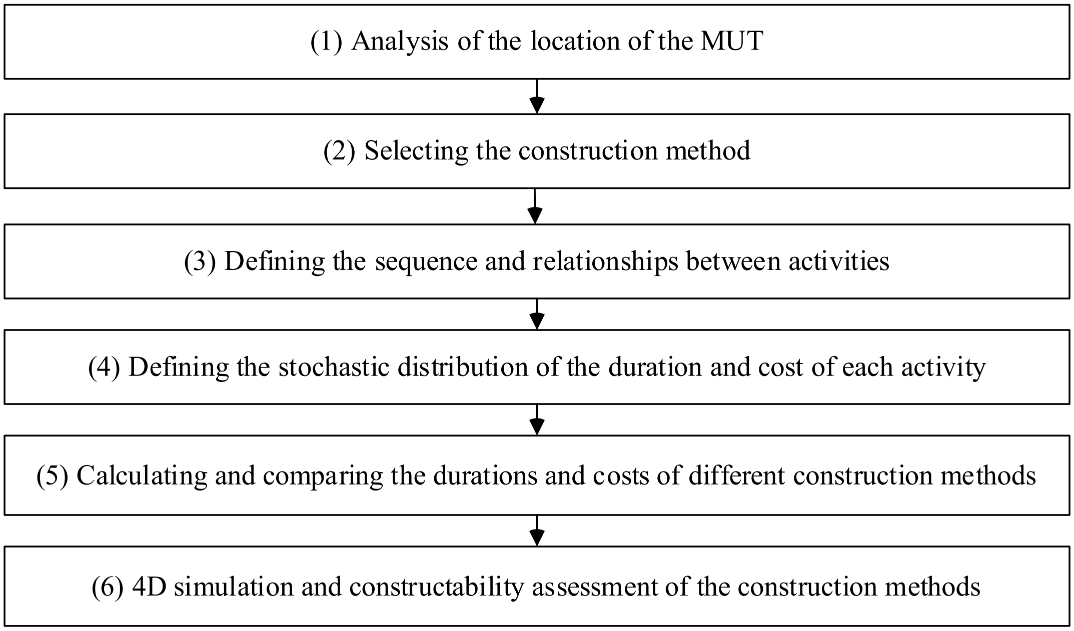


Figure 3.1 Methodology of developing DES of the MUTs

3.2 Analysis of the Location of the MUT

The location of the project is an important factor in selecting the construction method. Several issues should be investigated for MUT location selection in the planning phase, such as population and traffic density, the existence of metro lines or roads, utility reconstruction projects, etc. (Genger et al., 2021). After selecting the location, it will be analyzed for determining different data that could affect the construction method, such as soil data (e.g., type of the soil, cohesion, underground water) using a Geographic Information System (GIS).

3.3 Selecting the Construction Method

After collecting the data related to the location of the project, the construction methods suitable for the location will be selected. As an example, using the C&C method for the construction of the McGill University MUT was impossible since it is located under several buildings; therefore, the D&B method was selected (Habimana et al., 2014).

3.4 Defining the Sequence and Relations Between Activities

Each construction method includes different activities. Once a construction method is selected and the required activities are determined, the sequence and relationships between different activities, as well as the resources for each of them, will be defined. In this research, the stochastic simulation of microtunneling and C&C methods has been developed. Therefore, the sequences, relationships between the different activities and the resources needed for these methods will be introduced briefly in the next sections.

3.5 Defining the Stochastic Distribution of the Duration and Cost of Each Activity

In this step, the duration and cost of each activity should be defined by a stochastic distribution in order to study the range of potential durations and costs of the project considering the interactions between the activities.

3.6 Calculating and Comparing the Durations and Costs of Different Construction Methods

In this step, the DES models of MUT construction methods are developed and used to determine and compare the total durations and costs of different MUT construction methods.

3.7 4D Simulation and Constructability Assessment of the Construction Methods

In the last step, 4D simulation models are created to visualize and assess the constructability of the construction methods. These models are created by extracting the durations of activities from the DES and linking them to the corresponding 3D models. The 4D simulation includes the construction equipment in order to analyze the spatio-temporal conflicts and the impact of the MUT project on the surrounding area. By using stochastic simulation, the probability of potential stochastic spatio-temporal clashes can be calculated (Mawlana et al., 2015). These clashes may happen, for example, in the event of an equipment breakdown, which will delay the installation of new sections, combined with the continuous delivery of sections to the site, which will make the site congested. The case study in Section 4.4 will demonstrate this example. As a first step towards the generation of stochastic 4D simulation models based on the results of the DES, deterministic models are developed in this study using the average durations of activities.

It should be mentioned that, in this research, it has been assumed that the location of MUT is already decided, which allows for extracting the data related to soil and underground utilities.

3.8 Simulation of C&C Construction Method

As mentioned in Section 2.4.1, C&C using precast concrete sections and a temporary trench shoring system is the fastest C&C method. The process of MUT construction using this method consists of three main groups including: (1) Preliminary works; (2) execution of a MUT segment and implementation of utility networks; and (3) paving of the street.

Preliminary works include the works done before the demolition of old pavement and excavation of the trench. These works do not affect the functions of the city. The main activities in this group are surveying and demolition of urban furniture. Execution of a MUT segment and implementation of utility networks include the following activities: (1) Excavation of the surface for diverting the current utilities; (2) Diversion of the old utilities that already exist in the location; (3) Trench excavation; (4) Assembly of the trench shoring system; (5) Preparation of the bed for placing the precast concrete sections; (6) Delivery of the precast concrete sections to the construction site; (7) Attaching the sections to the crane and lifting them; (8) Placement of the sections; (9) Sealing the joint between sections; (10) Installation of the required supports (e.g., trays and hangers) for the utility systems; (11) Installation of the utilities; (12) Displacement of the trench shoring system; and (13) Backfilling. These activities will be repeated until the entire length of the MUT is constructed. After the MUT is completely constructed, the MUT's own networks (e.g., security cameras, fire detectors and hoists) are installed in the tunnel. The last step in this method is pavement restoration. Figure 3.2 shows the sequence and relationships between the activities in the MUT construction using C&C method. The resources required for each activity are shown in blue circles as a group and some of them are shared between different activities. As an example, the crane is a resource, which is shared between placement of the tunnel sections and attaching the sections to the crane and lifting them from the truck (i.e., unloading the truck) activities. It means the truck cannot be unloaded until the previous section is placed in the shaft and the crane is available for unloading the truck. Table A-1 in Appendix A shows the elements of these groups. Also, since in Figure 3.2, the activities are shown using abbreviation, Table A-2 in Appendix A shows the name of the activities.

In Figure 3.2 "NEC1" and "NEC2" represent the numbers of excavation cycles, which are calculated according to the excavation volume and the trucks' capacity. These parameters and the duration needed to transport the soil to the dump area, unload the soil, and return to the construction site are used to determine the number of trucks. "NSEG" represents the number of segments. The gray circles show the dummy queues made for representing the process sequence.

The process starts with surveying the location of the project. Then, the urban furniture (e.g., benches and light poles) are demolished. After, the surface of the street in the location of the first segment of the MUT is excavated and the existing utilities are diverted to start excavating the trench. When the first segment of the MUT is excavated, the trench shoring system is installed, and the trench bed is constructed to place the sections. The MUT sections are transported to the construction site using a truck, where a crane will unload the truck and place the section in the trench. After being unloaded, the truck will return to bring another section. After the sections are placed in the trench, the joints between them will be sealed. Afterwards, the required supports for the utilities will be installed and the utility networks will be implemented. Finally, the trench shoring system will be removed, and the trench will be filled. These activities will be repeated for each segment. When all the MUT segments are completely constructed, the networks of the MUT, such as cameras and fire detectors, will be implemented in the tunnel and pavement of the street will be restored.

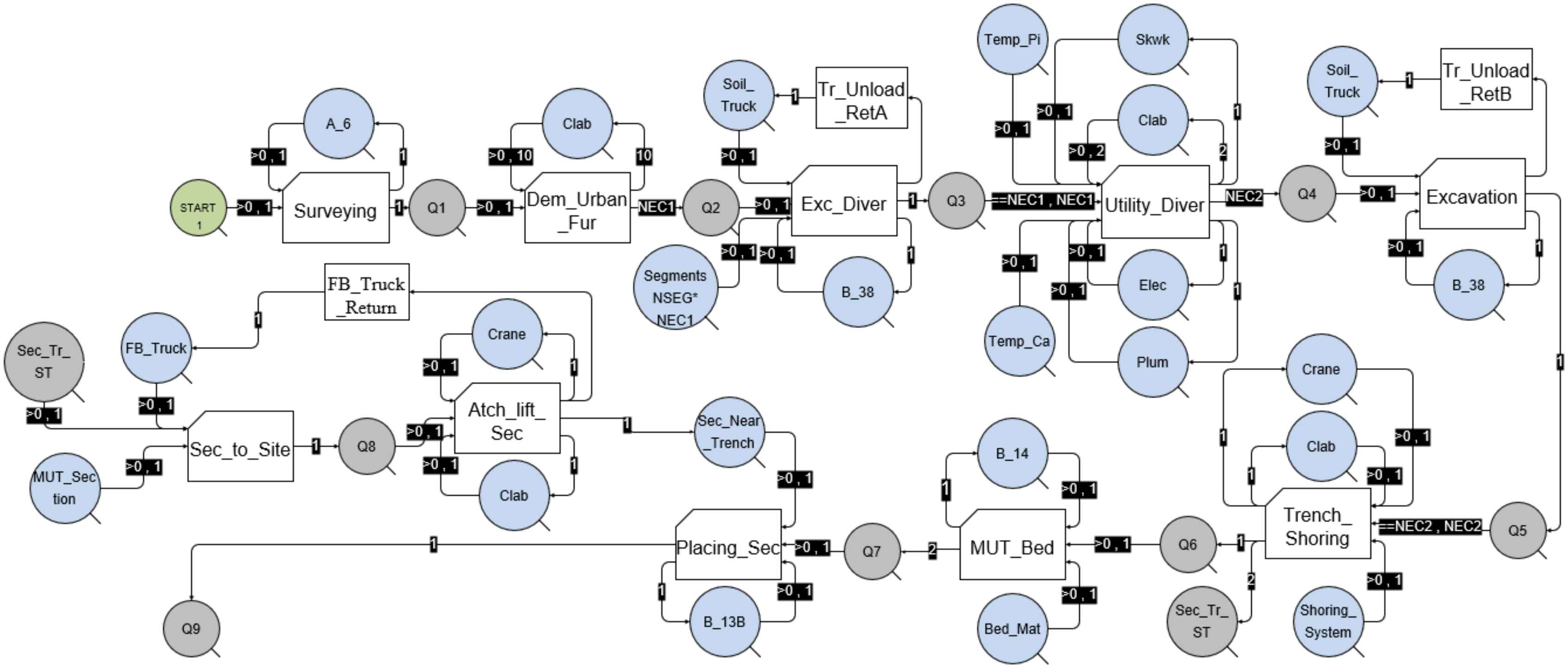


Figure 3.2 MUT construction sequence using C&C method

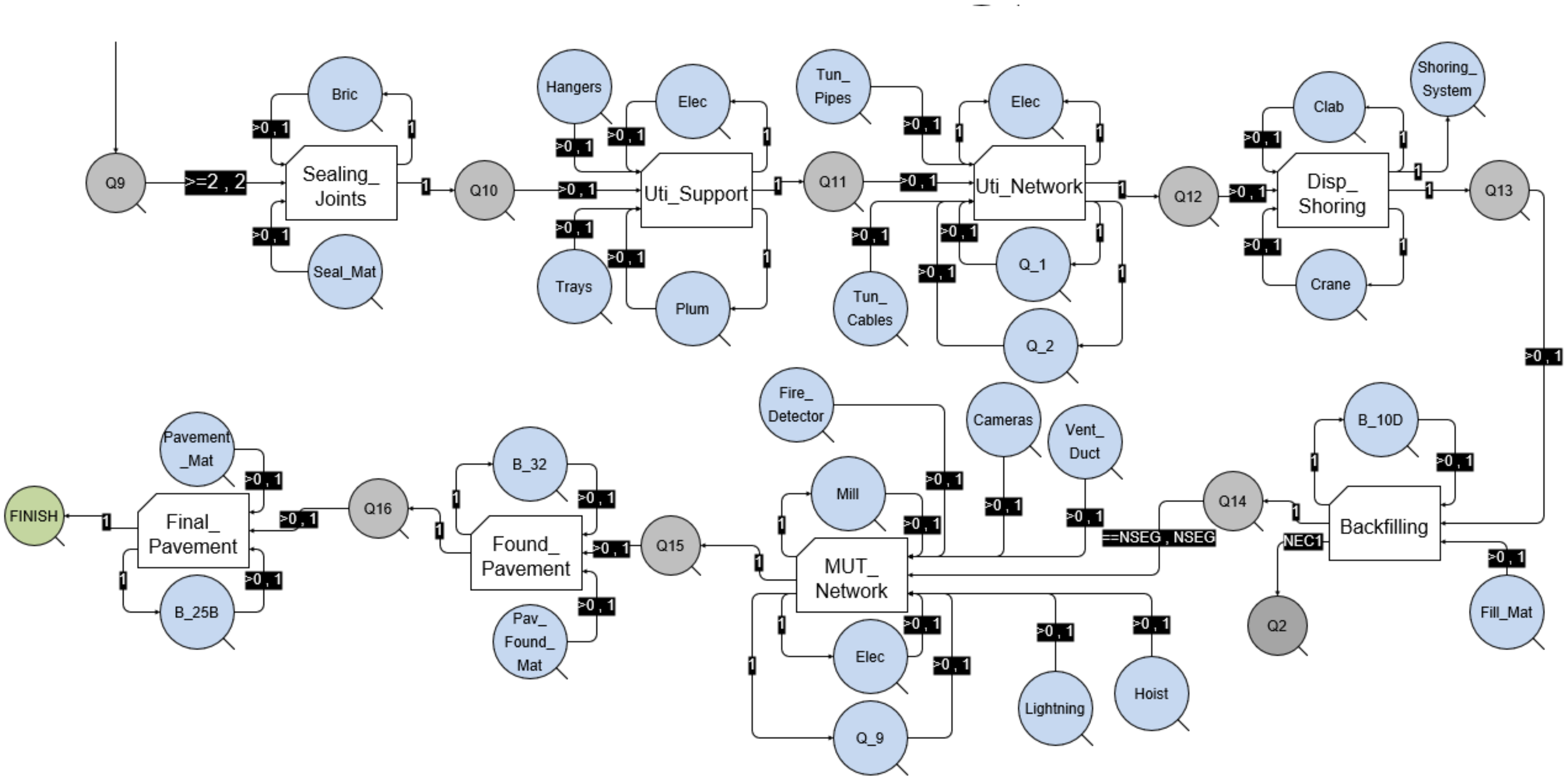


Figure 3.2 MUT construction sequence using C&C method (Cont.)

3.9 Simulation of Microunneling Construction Method

The construction of MUTs using microtunneling can be divided into three main steps: shaft construction, tunnel construction and placement of the utilities in the tunnel. The detailed activities involved in these steps and their relations will be described in the following sections.

3.9.1 Shaft Construction

The construction methods of shafts can be classified in three groups: traditional method, slip forms, and precast concrete segmental method. The advantages of the segmental method include minimum noise and ground vibration during construction, significantly reduced installation times as excavation and ring placement can be done on a continuous cycle and reducing the hazards of underground construction since most works carried out above ground. Since most recent MUTs are constructed in dense areas, these advantages have increased the use of the segmental method for shaft construction (Humes, 2014). In the segmental method, the shaft is constructed by placing the cutting edge and segmental rings on the surface and pushing them into the ground using jacking arms. At the same time, the soil inside the ring is excavated and removed. This process is repeated until the shaft reaches the required depth.

The segmental shaft construction method includes the following activities: (1) Surveying the location of the shaft; (2) Excavation of the required depth and area for placing the cutting edge; (3) Placing the cutting edge; (4) Building the foundation for jacking arms; (5) Placing the jacking arms on the foundation; (6) Bringing shaft sections to the construction site; (7) Attaching the sections to the crane and lifting them; (8) Placement of the sections; (9) Pushing the sections into the ground; (10) Soil removal; (11) Removing the cutting edge; when (12) Dewatering the shaft; and (13) Building the foundation of the shaft. Figure 3.3 shows the sequence and relationships and the activities in shaft construction. It should be mentioned that “Dummy_Delay1” and “Dummy_Delay2” are two dummy activities defined in the model to delay the transportation of the sections to the construction site so that the sections will arrive to the site in a timely manner, which will minimize the need for storing the sections on the site.

3.9.2 Tunnel Construction

The main activities of tunnel construction using microtunneling are: (1) Installation of MTBM in the starting shaft; (2) Pushing the MTBM into the ground: Once the MTBM is installed in the starting shaft, it will excavate the ground through the entrance ring so there will be a free space in the shaft for placing the tunnel sections; (3) Bringing the tunnel sections to the shaft; (4) Attaching the sections to the crane and lifting them; (5) Placement of the sections; (6) Placing the jacking collar behind of the sections; (7) Connecting the cables and pipelines; (8) Pushing the sections into the ground (jacking process); (9) Replacing the jacking collar; (10) Disconnecting the cables; (11) Disassembling the MTBM: When the tunnel is completely excavated, the MTBM is disassembled; and (12) Cleaning the tunnel.

Figure 3.4 shows the sequence and relationships between the activities in tunnel construction using microtunneling. Similar to explanation in Section 3.9.1 “Dummy_Delay3” and “Dummy_Delay4” are two dummy activities defined in the model to delay the transportation of the sections to the construction site.

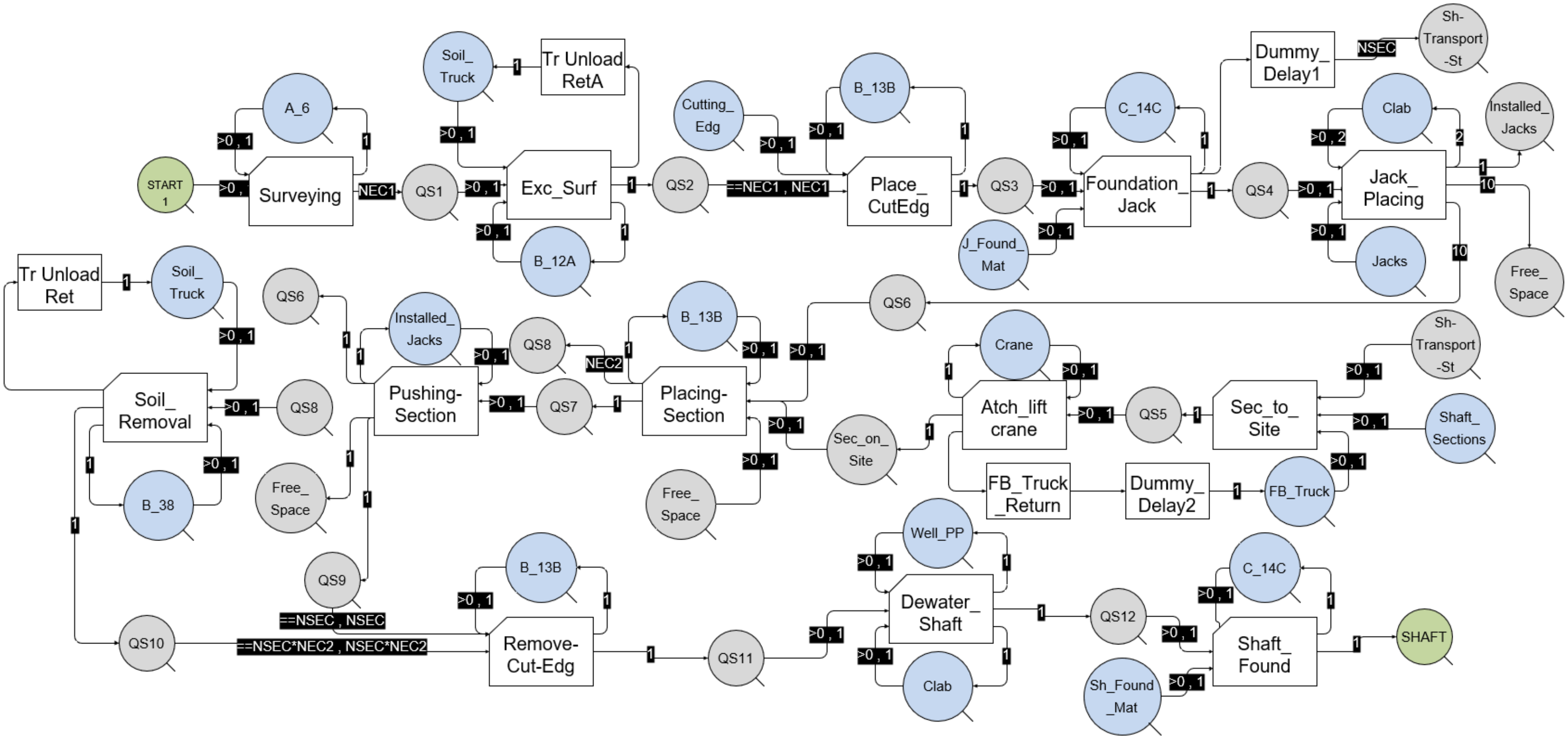


Figure 3.3 Shaft construction sequence using segmental method

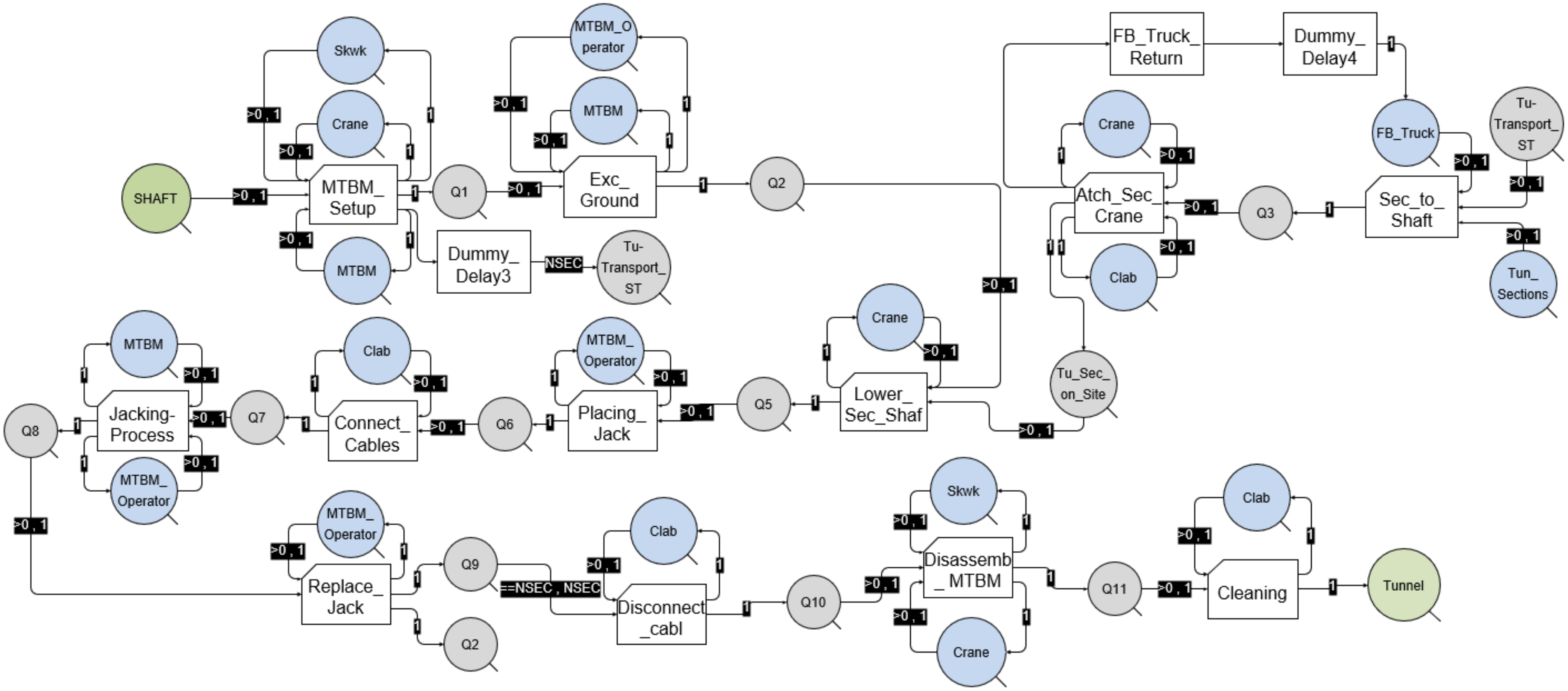


Figure 3.4 Tunnel construction sequence in microtunneling method

3.9.3 Placement of Utilities in the Tunnel

Once the shaft and the tunnel are constructed, the utilities can be installed in the tunnel. The first step is sealing the joints between the tunnel sections. Then, the required supports (e.g., hangers, trays) for utilities are installed inside the tunnel. After installing the supports, the utility networks (e.g., cables, water pipes, gas pipes) can be installed. The MUT has its own networks, such as lightning system, surveillance cameras and fire detectors, which should be installed in the tunnel for security and safety reasons. After the placement of the utilities in the tunnel, the surface of the street at the place of the starting and receiving shafts are repaired (Valdenebro et al., 2019). Figure 3.5 shows the sequence and relationships and the activities in the placement of utilities. Table B-1 in Appendix B shows the elements of the resource groups for microtunneling activities and Table B-2 shows the name of the activities.

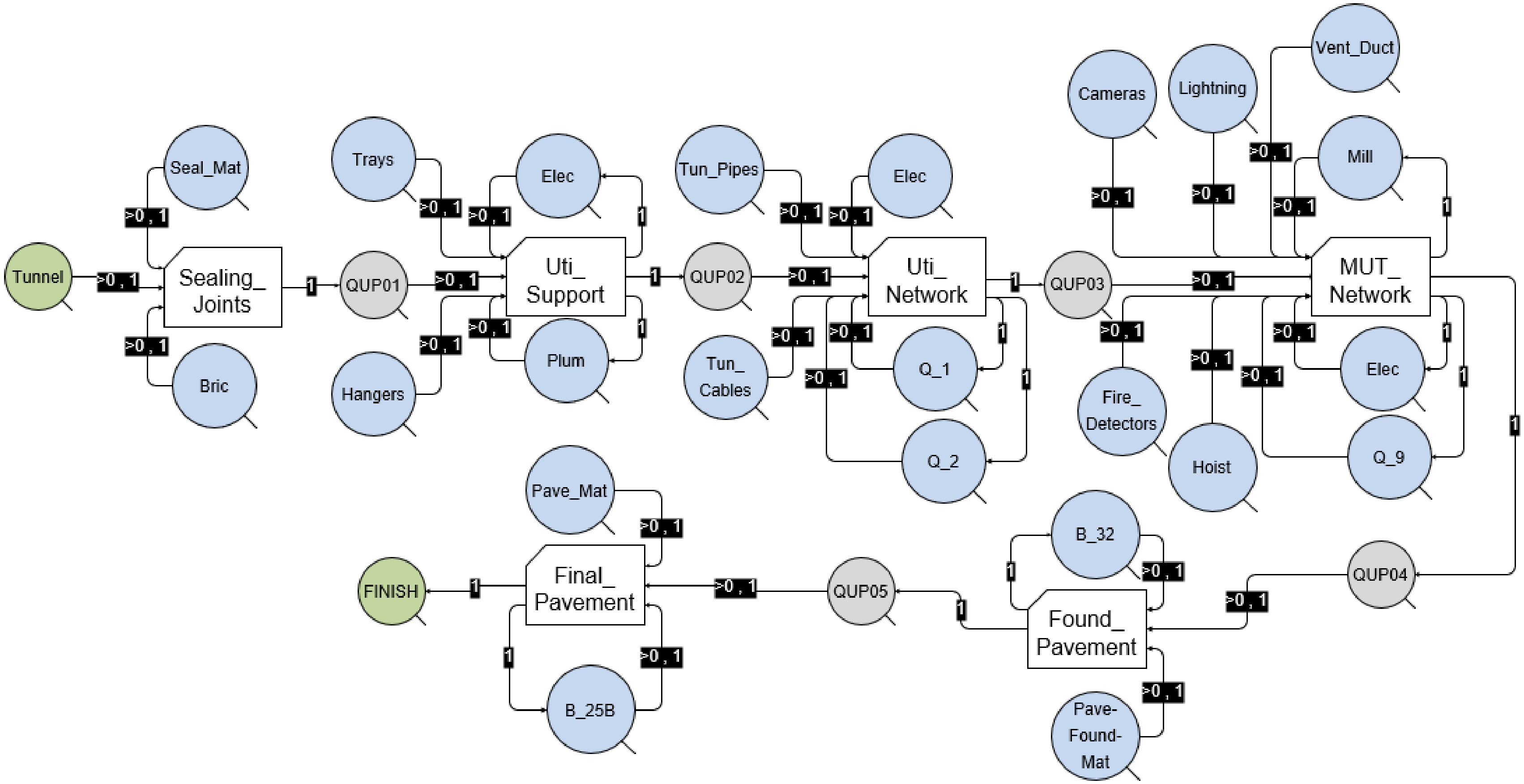


Figure 3.5 Construction sequence in placement of utilities in the tunnel

3.10 Summary

This chapter proposed a methodology for DES of MUT construction methods, which has six steps (Figure 3.1). The sequence and relationships between different activities and their required resources are described in detail for C&C and micotunneling methods. Chapter 4 will show the implementation of the proposed method to compare the total durations and costs of MUT construction methods.

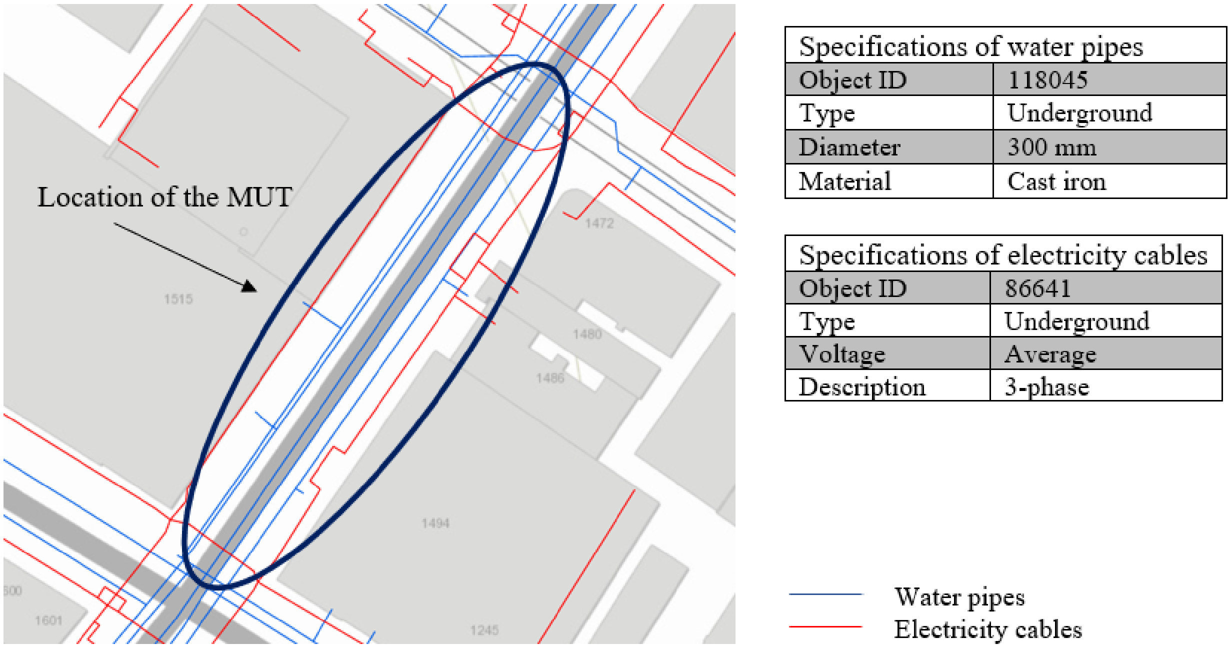
CHAPTER 4: IMPLEMENTATION AND CASE STUDY

4.1 Introduction

This chapter presents the case study of applying the proposed method for MUT construction using C&C and microtunneling methods. The required data, such as durations and costs of the activities are obtained from different references. Then, these data are fed to the DES model to calculate and compare the durations and costs of MUT construction methods. Furthermore, the constructability assessment and the impact of the construction method to the surrounding area is also done.

4.2 Implementation

As mentioned in Section 3.1, the first step of the proposed method is analyzing the location of the MUT. It has been assumed that the location of the MUT is already decided, which allows for extracting the data related to soil and underground utilities. The assumed location is on Saint-Catherine Street in Montreal. As an example, Figure 4.1 shows the specification of the electricity cables (red highlighted) and water pipes (blue highlighted), in the location of the project in GIS, which can be used for assuming the cost of these cables.



Specifications of water pipes	
Object ID	118045
Type	Underground
Diameter	300 mm
Material	Cast iron

Specifications of electricity cables	
Object ID	86641
Type	Underground
Voltage	Average
Description	3-phase

Figure 4.1 Specifications of electricity cables and water pipes in the location of MUT in ArcGIS

The diameter and the length of the sections and the geotechnical conditions of the soil can directly affect the duration and cost of the project. Therefore, two different diameters (i.e., 3 m or 4 m) and three different geotechnical conditions (i.e., fine sand, sand and gravel, or clay/marl) have been evaluated to analyze the total duration and cost of MUT construction using microtunneling and C&C methods. The duration and cost of each activity are presented by probabilistic distributions based on the literature. For those activities that were not mentioned in the literature, the RSMeans Cost Data (R.S. Means, 2021) is used to assume the deterministic duration and cost, which is then used to define a uniform distribution within a margin of ± 30 %. The duration and cost of the construction methods are analyzed based on DES models using EZStrobe software (Martinez, 2001). Since the MUT specific families are not available in modelling software, the Revit software (Revit, 2021), which has the ability to create new families has been used for modelling the MUT. In order to add the 3D map of the area, Infraworks Model Builder (Infraworks, 2021), which can easily build a 3D model of the area using different available data sources has been used. Then, the modelled MUT and the 3D map of the area are imported to the Fuzor software (Fuzor, 2022), where using the library of the software, the construction equipment and the schedule of the project can be added to make 4D simulation of the construction methods. The 4D simulation can be used for constructability assessment of the MUT considering the spatio-temporal conflicts and impacts of the project on the surrounding area. The following sections present the implementation of the proposed models for the C&C and microtunneling methods.

4.3 Case Study of C&C Method

As mentioned in Section 3.8, in C&C method, the entire length of the MUT is divided into equal segments, which are built one by one until the entire length of the MUT is constructed. Each of these segments includes two precast concrete sections. Table 4.1 shows the general assumptions used in analyzing the C&C method.

Table 4.2 shows the assumed specifications for the different utilities, which are installed in the MUT. Table 4.3 shows the assumed durations and costs for different activities of MUT construction using the C&C method. It should be mentioned that the elements of the resource group for activities are shown in Table A-1 in Appendix A. These resources are not needed throw out the duration of the project and they could be reused in different tasks. The total number of laborers and machinery used in the model are shown in Appendix C.

Table 4.1 Assumptions of the case study of C&C method

Attribute	Value
Tunnel length	100 m
Tunnel diameter	3 m or 4 m
Length of the precast concrete sections	4 m
Number of precast concrete sections in each segment	2
Depth of the tunnel	10 m
Working hours per day	12 h
Soil type	Fine sand, sand and gravel, or clay/marl

Table 4.2 Assumed specifications for different components of MUT

Type of the components	Number	Length (m)	Diameter (mm)	Material/Type
Water pipe	1	100	300	PVC
Sewer pipe	1	100	600	PVC
Gas pipe	1	100	114	Steel
Electricity cables	4	100	NA	Medium voltage, 3 phase, copper
Cable tray	5	100	NA	Galvanized steel
Pipe hanger	150	NA	NA	Malleable iron
Ventilation duct	1	100	100	Galvanized steel
Security camera	4	NA	NA	NA
Lightning	82	NA	NA	NA
Fire detectors	25	NA	NA	NA
Hoist	10	NA	NA	NA
NA: Not applicable				

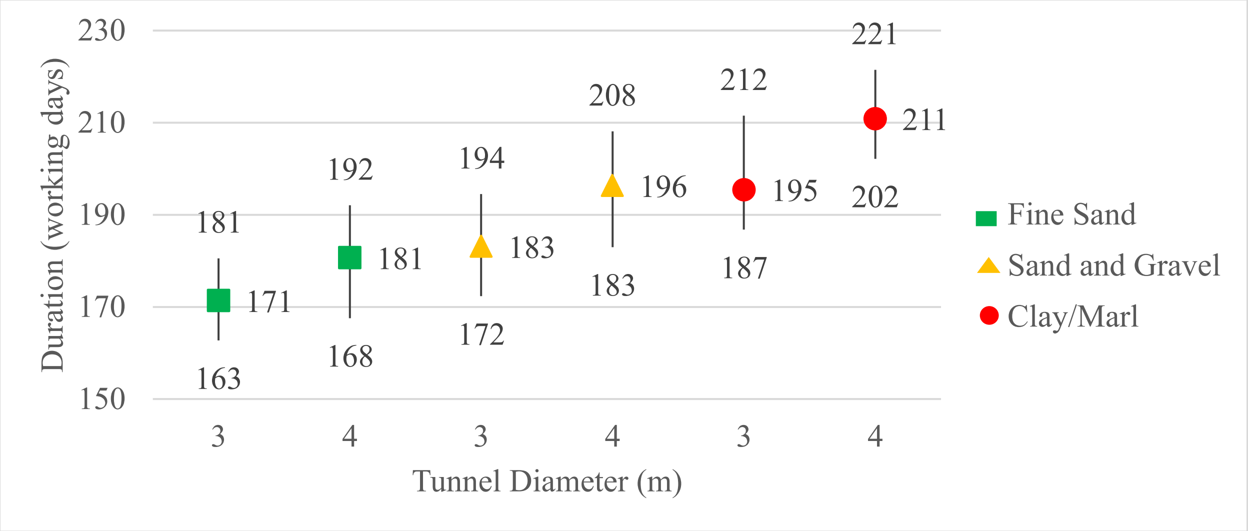
The assumed data were fed to the DES model using EZStrobe software and 100 simulation replications were made to calculate the total duration and cost of the MUT construction. Verification and validation of the simulation model are done by tracing the entities in the simulation model to assure that the logic of the model is correct, and it is running as expected. Figure 4.2 shows the results of the simulation for the two assumed diameters and three geotechnical conditions.

Table 4.3 Assumed durations and costs for C&C activities

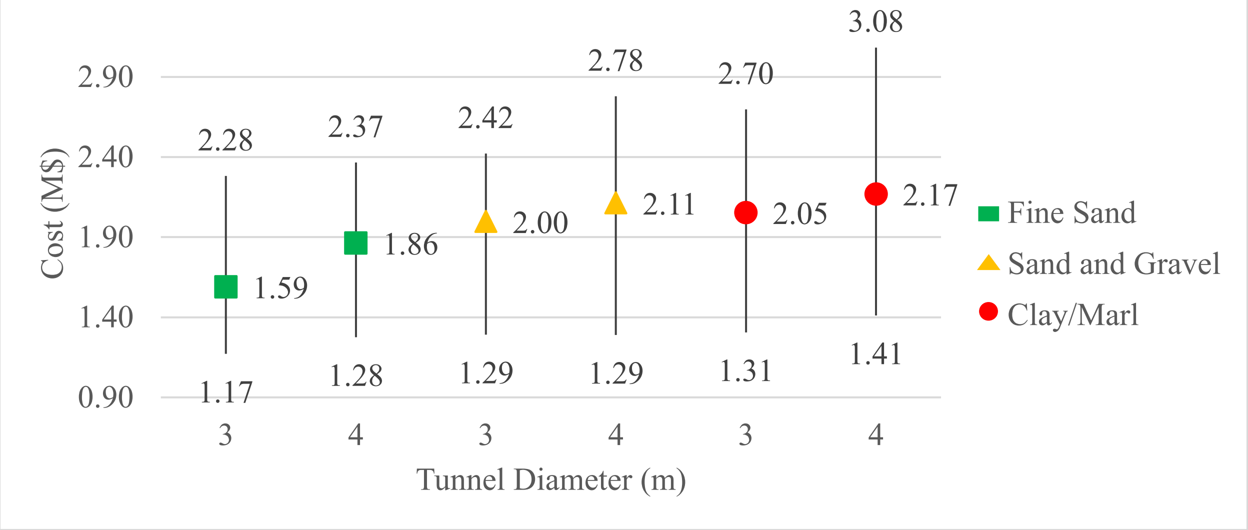
Activity		Duration (minutes)		Cost (US$/min)	
		3 m tunnel	4 m tunnel	3 m tunnel	4 m tunnel
Surveying		U [120, 180]		U [0.99, 1.83]	
Demolition of urban furniture		N [4,320, 5,040]		U [7.73, 14.35]	
Excavation for utility diversion	Fine sand	U [272, 506]	U [327, 607]	U [2.95, 5.45]	
	Sand and gravel	U [372, 690]	U [446, 828]	U [3.00, 5.58]	
	Clay/Marl	U [463, 861]	U [557, 1,034]	U [3.18, 5.91]	
Dump truck cycle		U [40,80]		U [0.65, 1.21]	
Diversion of the existing utilities		N [720, 120]		U [8.12, 15.08]	
Trench excavation	Fine sand	U [636, 1,182]	U [764, 1,420]	U [2.95, 5.45]	
	Sand and gravel	U [867, 1,611]	U [1,042, 1,934]	U [3.00, 5.58]	
	Clay/Marl	U [1,083, 2,011]	U [1,300, 2,414]	U [3.18, 5.91]	
Assembly of trench shoring system		U [90, 120]		U [2.55, 4.73]	
Preparation of MUT bed		U [39, 73]	U [47, 87]	U [15.74, 29.24]	
Bringing sections to the site		U [20, 40]		U [0.32, 0.59]	
Flatbed Truck returning		U [20, 40]		U [0.32, 0.59]	
Attaching sections to the crane and lifting		T [1.6, 1.7, 2.3]		The cost of this activity is included in the cost of placing the MUT sections.	
Placement of the MUT sections		T [2.4, 3.3, 4.5]		U [6,408, 11,902] US$/section	U [8,544, 15,869] US$/section
Sealing of the segment joints		U [22, 41]	U [29, 55]	U [1.25, 2.33]	
Installation of the utility supports		U [649.6, 1,206]		U [6.98, 12.96]	
Installation of the utility networks		U [817, 1,517]		U [37.72, 70.06]	
Displacement of shoring system		U [90, 120]		U [2.55, 4.73]	

Table 4.3 Assumed durations and costs for C&C activities (Cont.)

Activity	Duration (minutes)		Cost (US$/min)	
	3 m tunnel	4 m tunnel	3 m tunnel	4 m tunnel
Backfilling	U [368, 683]	U [419, 779]	U [4.53, 8.41]	
Installation of MUT’s networks	U [8,269, 15,357]		U [28.93, 53.73]	
Construction of the pavement foundation	U [48, 88]	U [57, 107]	U [85.44, 158.68]	
Final pavement	U [97, 179]	U [116, 216]	U [236.07, 438.41]	
U [a,b]: Uniform distribution; a is the low and b is the high limit. T [a,b,c]: Triangular distribution; a is the low, b is the mode and c is the high value. N [a,b]: Normal distribution; a is the mean and b is the standard deviation.				



(a) Durations of MUT construction Vs. tunnel diameters in different geological conditions



(b) Costs of MUT construction Vs. tunnel diameters in different geological conditions

Figure 4.2 Results of DES of MUT construction using C&C

For the 3 m diameter tunnel, the estimated average total durations of MUT construction are 171, 183 and 195 working days and the total costs are 1.59, 2.00 and 2.05 million U.S. dollars for fine sand, sand and gravel and clay/marl geotechnical conditions, respectively. For the 4 m diameter tunnel, the average total durations of tunnel construction are 181, 196 and 211 working days and the total costs are 1.86, 2.11 and 2.17 million U.S. dollars in fine sand, sand and gravel and clay/marl geotechnical conditions, respectively. In addition, it can be observed that by increasing the diameter of the tunnel or the hardness of the soil the total duration and cost of the MUT will increase.

Figure 4.3 shows some snapshots from the 4D simulation of MUT construction using C&C method in Fuzor software. In this figure, the pavement of the street is demolished (Figure 4.3(a)), the trench is excavated (Figure 4.3(b)) and the trench shoring system is installed (Figure 4.3(c)).

Then the tunnel section is transported to the site (Figure 4.3(d)) and is placed into the trench (Figure 4.3(e)).

(a) Demolition of the pavement

(b) Trench excavation

(c) Installation of trench shoring system

(d) Bringing a section to the site

(e) Placing the tunnel section

Figure 4.3 4D simulation of MUT construction using C&C in Fuzor

4.4 Case Study of Microtunneling Method

Table 4.4 shows the assumptions used in the case study, which are similar to those in Table 4.1. The diameter of the starting and receiving shafts is assumed to be 6 m and 8 m for 3 m and 4 m tunnel diameter, respectively.

Table 4.4 also shows the other assumptions used in the case study.

Table 4.4 Assumptions of the case study of microtunneling method

Attribute	Value
Type of MTBM	Hydraulic
Tunnel length	100 m
Tunnel diameter	3 m or 4 m
Length of tunnel sections	4 m
Depth of the tunnel	10 m
Length of the shaft	10 m
Shaft diameter	6 m or 8 m
Length of the shaft segments	2 m
Working hours per day	12 h
Soil type	Fine sand, sand and gravel, or clay/marl

To assume the duration of each activity, four different microtunneling projects introduced by Dang (2015) and Marzouk et al. (2010), as well as the fourteen projects monitored by Colson (2010) have been reviewed. Also, RSMeans Cost Data (R.S. Means, 2021) have been used to assume the cost and duration of the activities, which were not mentioned in the reviewed projects (e.g. placement of the utilities in the tunnel). Table 4.5 shows the characteristics of the reviewed projects. It should be mentioned that because of the difference between the assumed dimensions of the tunnel and those of the tunnels in reviewed projects, the pushing duration was modified according to the diameter and length of the sections. As an example, the modification of the duration of jacking the tunnel sections is shown in Appendix D. As mentioned in Section 3.9.2, when the MTBM is installed in the shaft, it will be pushed into the ground to make free space in the shaft for placing the tunnel sections. Therefore, the duration and cost of pushing MTBM is assumed to be the same as the duration and cost of pushing the tunnel sections.

Table 4.5 Characteristics of the reviewed microtunneling projects

Project	Type of MTBM	Length (m)	Diameter (m)	Length of sections (m)	Depth (m)	Geotechnical condition
BV Recklinghausen V.5.1*	Hydraulic	79.4	2.2	3.5	7.4	Fine sand
BV Recklinghausen V.8*	Hydraulic	145	1.56	4	8.7	Clay/Marl
BV Recklinghausen V.15*	Hydraulic	86.23	1.46	4.02	-	Sand and Clay/marl
Dar-El Salam, Segment 1**	-	77.5	2.5	-	-	-
Dar-El Salam, Segment 2**	-	402	2.5	-	-	-
Dar-El Salam, Segment 3**	-	70	2.5	-	-	-
Dar-El Salam, Segment 4**	-	142	2.5	-	-	-
FSTT***	Hydraulic / Pneumatic	40-170	0.5-1	2	1-30	Sand, Gravel, Clay/marl
* Adapted from (Dang, 2015)						
** Adapted from (Marzouk et al., 2010)						
*** Adapted from (Colson, 2010)						

As mentioned in Section 3.9, the last step in MUT construction using microtunneling method is placement of utilities inside the tunnel. The specifications of different utilities, which are installed in the MUT are shown in Table 4.2. Table 4.6 shows the assumed durations and costs for different activities of MUT construction using microtunneling method. It is worth to mention that the cost of the installation and disassembling the MTBM is US$268,000, which is divided between the "MTBM installation in the shaft" and "Disassembling MTBM in the receiving shaft" activities. Same as the C&C method the elements of resource groups are shown in Table B-1 in Appendix B. Also, the total number of laborers and machinery used in the model are shown in Appendix E.

Table 4.6 Assumed durations and costs for microtuneling activities

Activity			Duration (minutes)		Cost (US$/min)	
			6 m shaft	8 m shaft	6 m shaft	8 m shaft
Shaft Construction	Surveying the location of shaft		U [120, 180]		U [0.99, 1.83]	
	Excavating the required depth for placing cutting edge		U [31, 57]	U [55, 103]	U [2.17, 4.03]	
	Dump truck cycle		U [40, 80]		U [0.65, 1.21]	
	Placing cutting edge		T [14, 25, 47]		U [39.70, 73.74]	U [52.93, 98.31]
	Building the foundation for jacking arms		U [58, 108]	U [76, 140]	U [28.76, 53.42]	
	Placing jacking arms on the foundation		U [480, 960]		U [4.26, 7.90]	
	Bringing sections to the site		U [20, 40]		U [0.32, 0.59]	
	Truck return		U [20, 40]		U [0.32, 0.59]	
	Attaching sections to the crane and lifting		T [1.6, 1.7, 2.3]		The cost of this activity is included in the cost of placing the shaft sections.	
	Placing the sections		T [2.4, 3.3, 4.5]		U [6,408, 11,902] US$/section	U [8,544, 15,869] US$/section
	Pushing shafts sections into the ground	Fine sand	T [88, 159, 278]	T [117, 213, 375]	U [1.94, 3.60]	
		Sand and gravel	T [255, 356, 376]	T [344, 477, 500]		
		Clay	T [476, 535, 667]	T [643, 711, 865]		
	Soil removal	Fine sand	U [86, 160]	U [152, 282]	U [2.95, 5.45]	
		Sand and gravel	U [117, 217]	U [207, 385]	U [3.00, 5.58]	
		Clay	U [146, 270]	U [258, 480]	U [3.18, 5.91]	
	Removing the cutting edge		T [14, 25, 47]		U [4.1, 7.61]	
	Dewatering the shaft		N [600, 120]		U [2.28, 4.24]	
	Building the foundation of the shaft		U [161, 299]	U [286, 530]	U [28.76, 53.42]	

Table 4.6 Assumed durations and costs for microtuneling activities (Cont.)

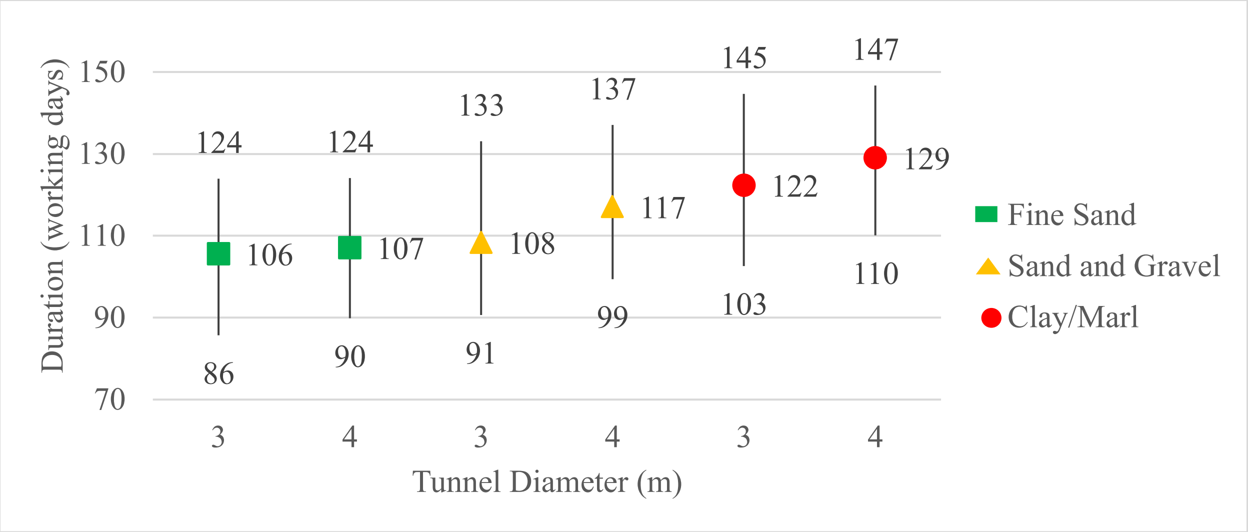
Activity			Durations (minutes)		Cost (US$/min)	
			3 m tunnel	4 m tunnel	3 m tunnel	4 m tunnel
Tunnel Construction	MTBM installation in the shaft		N [1,440, 480]		US$ 134,000	
	Pushing MTBM (one time)	Fine sand	T [72, 130, 227]	T [87, 157, 275]	U [21,813, 40,509] US$	U [29,084, 54,012] US$
		Sand and gravel	T [152, 217, 234]	T [197, 277, 296]	U [27,4630, 51,003] US$	U [36,618, 68,004] US$
		Clay	T [301, 355, 449]	T [386, 433, 548]	U [33,114, 61,498] US$	U [44,452, 81,997] US$
	Bringing sections to the shaft		U [20, 40]		U [0.32, 0.59]	
	Truck return		U [20, 40]		U [0.32, 0.59]	
	Attaching sections to the crane and lifting		T [1.6, 1.7, 2.3]		The cost of these activities is included in the cost of pushing the tunnel sections.	
	Placing the sections		T [2.4, 3.3, 4.5]			
	Placing jacking collar		T [4.4, 5.6, 6.7]			
	Connecting cables		T [28.9, 36.2, 48.1]			
	Pushing tunnel sections	Fine sand	T [72, 130, 227]	T [87, 157, 275]	U [21,813, 40,509] US$/section	U [29,084, 54,012] US$/section
		Sand and gravel	T [152, 217, 234]	T [197, 277, 296]	U [27,463, 51,003] US$/section	U [36,618, 68,004] US$/section
		Clay	T [301, 355, 449]	T [386, 433, 548]	U [33,114, 61,498] US$/section	U [44,452, 81,997] US$/section
	Replacing jacking collar		T [5.18, 6.38, 7.33]		The cost of these activities is included in the cost of pushing the tunnel sections.	
	Disconnecting cables		T [28.9, 36.2, 48.1]			
	Disassembling MTBM in the receiving shaft		N [10,080, 1,440]		US$ 134,000	
	Cleaning the tunnel		N [3,600, 720]		U [2.97, 5.51]	

Table 4.6 Assumed durations and costs for microtuneling activities (Cont.)

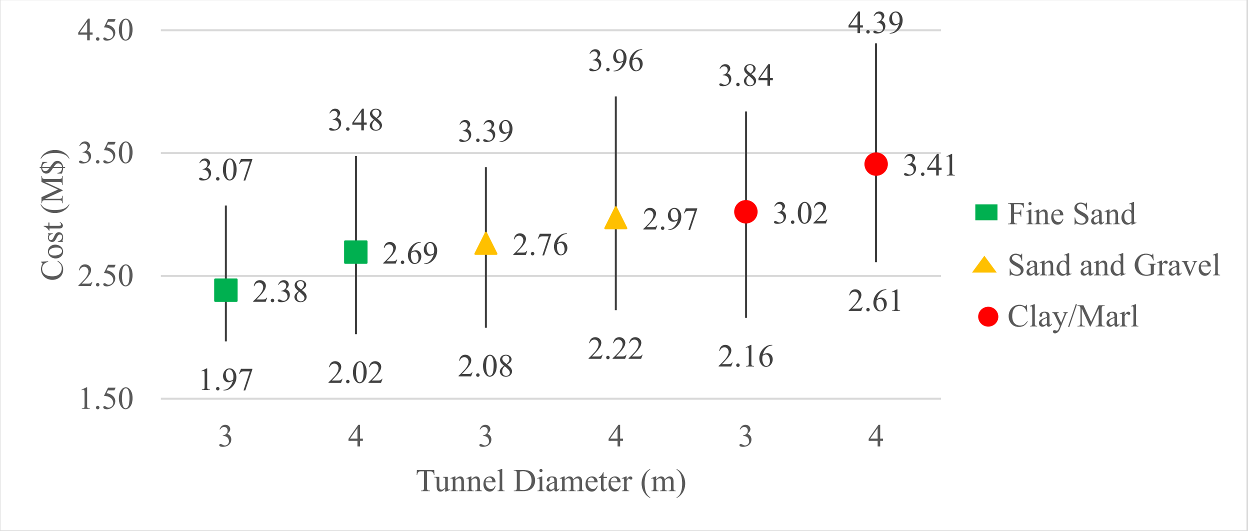
Activity		Durations (minutes)		Cost (US$/min)	
		3 m tunnel	4 m tunnel	3 m tunnel	4 m tunnel
		3 m tunnel	4 m tunnel	3 m tunnel	4 m tunnel
Placement of utilities	Sealing the joints of the tunnel sections	U [551, 1,024]	U [736, 1,367]	U [1.25, 2.33]	
	Installation of the utility supports	U [8117, 15,074]		U [6.98, 12.96]	
	Installation of the utility networks	U [10,200, 18942]		U [37.72, 70.06]	
	Installation of the MUT's own network	U [10,347, 19,216]		U [28.93, 53.73]	
	Construction of the foundation of the pavement	U [23, 42]	U [40, 57]	U [85.44, 158.68]	
	Final pavement of the street	U [125, 232]	U [222, 413]	U [236.07, 438.41]	

N [a,b]: Normal distribution; a is the mean and b is the standard deviation.
T [a,b,c]: Triangular distribution; a is the low, b is the mode and c is the high value.
U [a,b]: Uniform distribution; a is the low and b is the high limit

The assumed data were fed to the DES model using EZStrobe software and 100 simulation replications were made to calculate the total duration and cost of the MUT using the microtunneling method. Figure 4.4 shows the results of the simulation for the two assumed diameters and three geotechnical conditions.



(a) Durations of MUT construction Vs. tunnel diameters in different geological conditions



(b) Costs of MUT construction Vs. tunnel diameters in different geological conditions

Figure 4.4 Results of DES of MUT construction using microtunneling

For the 3 m diameter tunnel, the estimated average total durations of MUT construction are 106, 108 and 122 working days and the total costs are 2.38, 2.76 and 3.02 million U.S. dollars for fine sand, sand and gravel and clay/marl geotechnical conditions, respectively. For the 4 m diameter tunnel, the average total durations of MUT construction are 107, 117 and 129 working days and the total costs are 2.69, 2.97, 3.41 million U.S. dollars in fine sand, sand and gravel, and clay/marl geotechnical conditions, respectively. In addition, it is obvious that by increasing the diameter of the tunnel or increasing the hardness of the soil the total duration and cost of MUT construction will increase as in the C&C case study.

Figure 4.5 shows some snapshots from the 4D simulation of MUT construction using microtunneling method in Fuzor software. In this figure, the tunnel section is transported to the construction site by a truck (Figure 4.5(a)), the crane lifts it and moves it into the starting shaft (Figure 4.5(b)), where it is pushed into the ground using jacking station (Figure 4.5(c)), and at the same time the MTBM is excavating the tunnel face.

(a) Bringing tunnel section to the construction site

(b) Lifting and placing the section into the starting shaft

(c) Pushing the section into the ground

Figure 4.5 4D simulation of MUT construction using microtunneling

Figure 4.6 shows the imported MUT model and 3D map of the area in Fuzor. As shown in this figure, since the MUT is built under the current utilities, removing or diversion of the old utilities is not necessary in microtunneling method, which is one of the main advantages of this method.

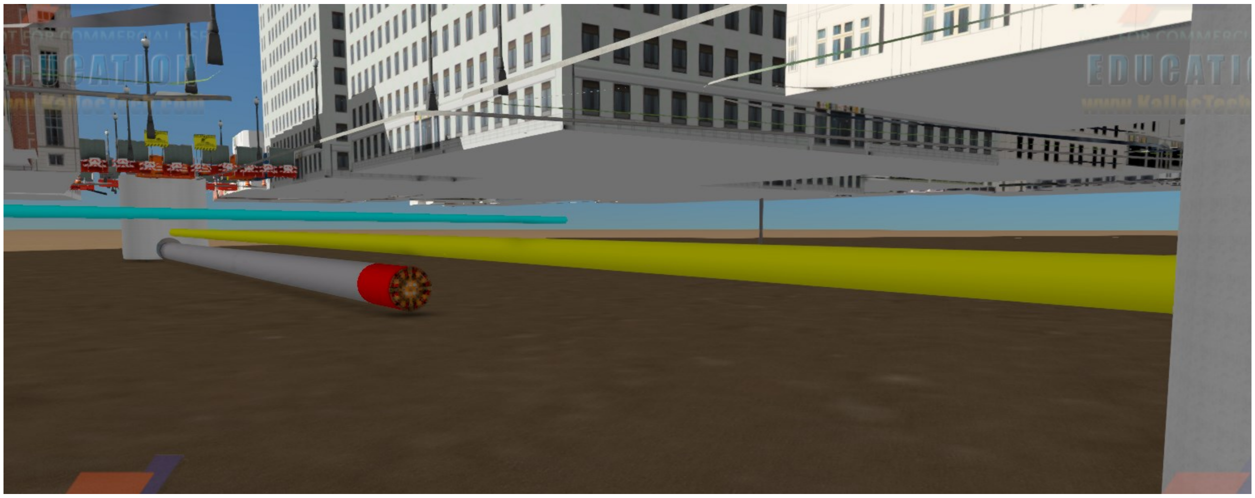


Figure 4.6 Underground view of the MUT in Fuzor

The 4D simulation can be used for constructability assessment (e.g., consider the spatio-conflicts and impacts of the construction on the surrounding areas) and ascertain that there are no errors in modeling the construction process (verification). In addition, experts, field personnel, and decision makers can discover differences between the way they understand the operation and the way the model developer understands it (validation). As an example of potential spatio-temporal conflicts, if there was a mechanical problem of the micotunneling boring machine that took 450 minutes to repair, then the duration of finishing the activity of pushing the next tunnel section will extend from the average value of 150 minutes to 600 minutes because of the mechanical problem. Consequently, not only the whole project will be delayed, but also the new tunnel sections transported near the shaft should be stacked on the site assuming that it was not possible to postpone the delivery of the sections to the site. Knowing that the average time for transporting one section to the site is 30 minutes, 15 sections will arrive to the site during this delay. Figure 4.7 shows an example of this situation, where 15 sections have been stored next to the shaft, which may create a spatio-temporal conflict with the crane movement.

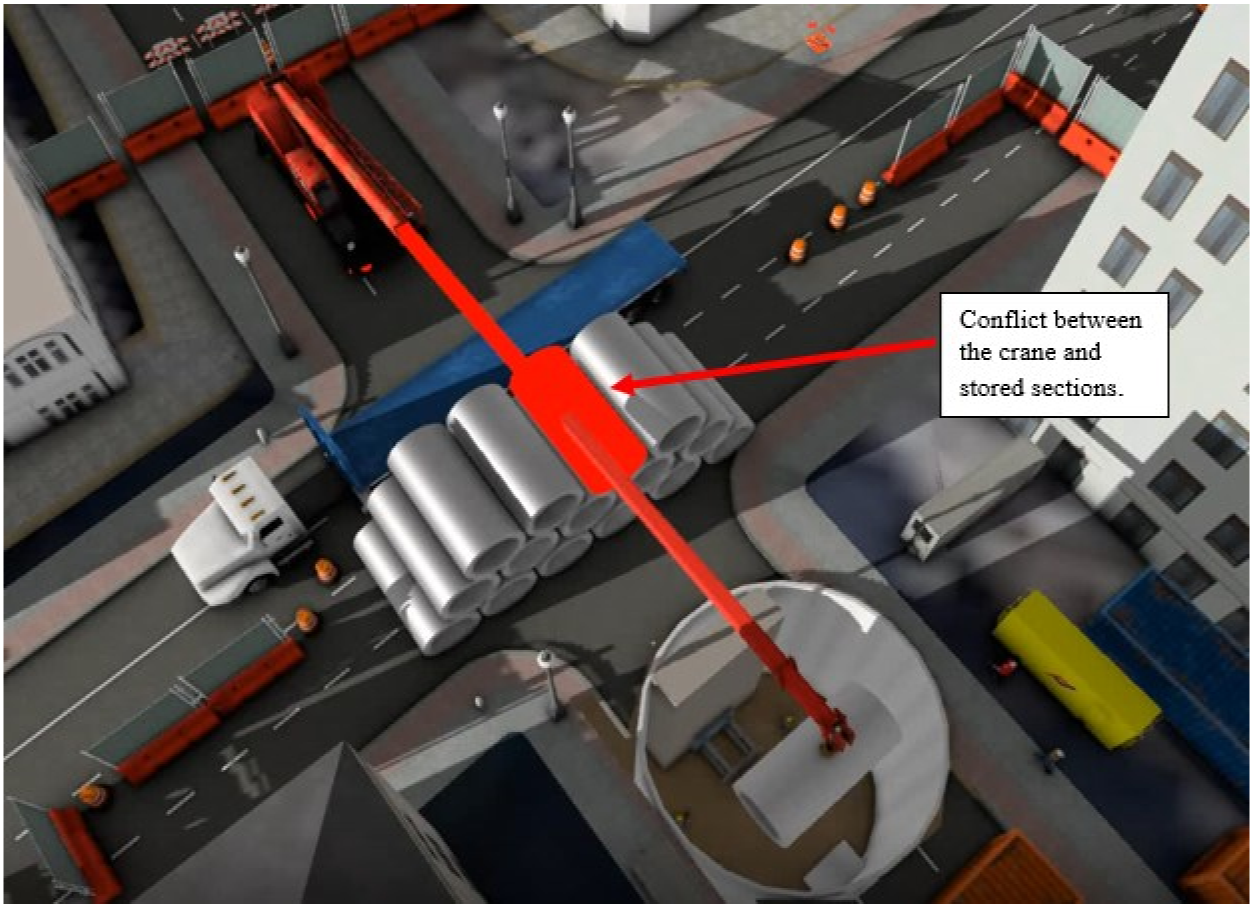


Figure 4.7 Example of a situation that can cause spatio-temporal conflict

4.5 Summary

This chapter provided the implementation of the proposed method for the case study of MUT construction using C&C and microtunneling methods. Two tunnel diameters and three soil types were assumed to evaluate the durations and costs of the project using DES. The durations and costs of the activities are defined using probabilistic distributions in order to have a range for possible durations and costs of the project. Also, the 4D simulation of the construction method, including construction equipment, is developed for constructability assessment and evaluating the impact of the construction method on the surrounding area.

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

5.1 Summary of Research

This research presented the first attempt to apply the stochastic simulation approach of MUT construction. A review of MUTs including their classification, benefits, disadvantages, construction methods, and MUT projects around the world are presented in the literature review. Also, different simulation methods and related works in simulation of tunnel construction are reviewed in the literature review. The detailed explanation of the proposed approach and the implementation of the proposed simulation models in a case study are also presented.

The particular focus of this research was on (a) analyzing the durations and costs of the MUT construction projects according to different soil conditions and different sizes of the tunnel; (b) comparing different MUT construction methods based on DES method; and (c) constructability assessment of the MUT projects and their impact on the surrounding area using 4D simulation including construction equipment.

5.2 Research Contributions and Conclusions

The research contributions to the body of knowledge are:

(1) Developing DES models of two MUT construction methods (i.e., microtunneling and C&C) for different tunnel diameters and geotechnical conditions. Based on the results of the simulation, it can be concluded that:
  - In microtunneling method, by increasing the diameter of the tunnel from 3 m to 4 m, the total duration of the project increases by 2%, 7% and 5% and the total cost of the project increases by 10%, 11% and 16% in fine sand, sand and gravel and clay/marl geotechnical conditions, respectively;
  - In C&C method, by increasing the diameter of the tunnel from 3 m to 4 m, the total duration of the project increases by 5%, 7% and 7% and the total cost of the project increases by 10%, 7% and 9% in fine sand, sand and gravel and clay/marl geotechnical conditions, respectively;
  - The duration of MUT construction using C&C is more sensitive than microtunneling to the changes in tunnel diameter;
  - The cost of MUT construction using microtunneling is more sensitive than C&C to changes in tunnel diameter;
  - In average, microtunneling is 52% more expensive and 66% faster than C&C method.

(2) Constructability assessment of the MUT project considering the spatio-temporal conflicts and impacts of the MUT on the surrounding area using 4D simulation including construction equipment. It can be concluded that the impact of the microtunneling method on the surrounding area and old utilities is less than the C&C method for the following reasons, (a) By using microtunneling method, the tunnel can be constructed under the current utilities, and therefore, the diversion of the current utilities will not be necessary; while in the C&C method the current utilities should be diverted in order to keep the service of utilities; (b) By using the microtunneling method, the closure of the street in the location of the project could be limited to the area around the shaft, where in the C&C method a larger part of the street should be closed.

5.3 Limitations and Future Work

While this research achieved the mentioned contributions, it has the following limitations, which need to be addressed in the future. The limitations of this research can be categorized in three groups, which are:

(a) Limitations related to the development of the DES models:

1. The DES models should be extended in future work to consider special events, such as malfunctioning of equipment, which may create spatio-temporal conflicts.
2. In this research, specific values are used to define a uniform distribution for the durations and costs of activities within a margin of ± 30%. In future work, sensitivity analysis can be applied to study the effect of different margins (e.g., ± 10%, 20%) on the total duration and cost of the MUT projects.
3. The limitations for evaluating of the proposed DES models in the case study include lack of data for some activities. In future work, more sample data should be collected in order to improve the accuracy of the results.
4. The developed DES models can be shared with experts in future work in order to validate the logic of the models.

(b) Limitations related to the 4D simulation of MUT construction methods:

1. The 4D simulation is developed manually. Future work should automate the process of developing a stochastic 4D simulation of MUT construction methods.
2. In future work, generating dynamic workspace for equipment should be done, which can help to improve clash detection by considering safety buffers.

(c) General limitations:

1. The social cost of the MUT construction is an important factor, which is not considered at this point. As an example, the City of Montreal had a plan for building a MUT under Sainte-Catherine Street because it will reduce the social cost during the operation phase (Gagnon, 2020). However, they only considered the C&C construction method, which will result in a high social cost during the construction phase. Therefore, the project was canceled. Future work will compare the costs of MUT construction methods including social costs, by considering different factors, such as the period of time that the road is closed because of construction.
2. In this research, the proposed method is done for a short MUT of 100 m length. According to the results of this research, the mobilization cost of the microtunneling method is about 10% of the total cost. Therefore, by increasing the length of the tunnel, the microtunneling method can become a more competing alternative to the C&C method because the mobilization cost is a fixed cost. Future work will apply the proposed method for different lengths of MUTs.
3. In this research, only the main tunnel is considered. Future work should consider connecting the utilities from the MUT to the surrounding buildings and the construction of the transversal tunnels.
4. In this research, it has been assumed that the location of the project is already decided. In future work different locations will be evaluated and compared based on different data,

such as soil data, traffic and other construction projects in the location using GIS to select the best location for the MUT.

(5) Comparing the microtunneling and C&C methods with other construction methods like D&B can be done in future work.

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APPENDICES

Appendix A: The Elements of the Resource Groups and Name of the Activities in C&C method

Table A-1 shows the resource groups for the activities in MUT construction using C&C method and the elements in each group. It should be noted that these resources will not be needed throughout the duration of the project, and they could be reused in different tasks.

Table A-1 Resource groups for the C&C activities

Resource group code	Elements	Type			Activity
		Laborer	Machinery	Material	
A-6	1 Instrument Man	✓			Surveying
	1 Rodman/Chainman	✓			
	1 Level/Electronic		✓		
Bed_Mat	Materials for bed of the trench			✓	MUT_Bed
Bric	1 Bricklayer	✓			Sealing_Joints
B_10D	1 Medium equipment operator	✓			Backfilling
	1 Laborer	✓			
	1 Dozer 200 H.P.		✓		
	1 Sheepsfoot roller		✓		
B_13B	1 Labor foreman	✓			Placing_Sec
	4 Laborers	✓			
	1 Equipment operator (crane)	✓			
	1 Hydraulic crane		✓		
B_14	1 Labor foreman	✓			MUT_Bed
	4 Laborers	✓			
	1 Light equipment operator	✓			
	1 Backhoe loader		✓		
B_25B	1 Labor foreman	✓			Final_Pavement
	7 Laborers	✓			
	4 medium equipment operators	✓			
	1 Asphalt paver, 130 H.P.		✓		
	2 Tandem rollers, 10 Ton		✓		
	1 Pneumatic wheel roller, 12 Ton		✓		
B_32	1 Laborer	✓			Found_Pavement
	3 Medium equipment operators	✓			
	1 Grader		✓		
	1 Tandem roller		✓		
	1 Dozer, 200 H.P.		✓		
	2 Laborers	✓			

Table A-1 Resource groups for the C&C activities (Cont.)

Resource group code	Elements	Type			Activity
		Laborer	Machinery	Material	
B_38	1 Labor foreman	✓			Exc_Diver
	2 Laborers	✓			
	1 Light equipment operator	✓			
	1 Medium equipment operator	✓			
	1 Hydraulic hammer		✓		
	1 Hydraulic excavator 1 C.Y.		✓		
Cameras	4 Security cameras			✓	MUT_Netwrok
Clab	Laborer	✓			Dem_Urban_Fur, Utility_Diver, Trench_Shoring, Atch_lift_Sec, Disp_Shoring
Crane	1 Hydraulic crane		✓		Trench_Shoring, Atch_lift_Sec, Disp_Shoring
	1 Equipment operator (crane)	✓			
Elec	2 Electricians	✓			Utility_Diver, Uti_Support, Uti_Network, MUT_Network
FB_Truck	1 Flatbed truck		✓		Sec_to_Site
	1 Equipment operator (truck)	✓			
Fire_Detector	25 Fire detectors			✓	MUT_Network
Fill_Mat	Materials for backfilling the trench			✓	Backfilling
Hangers	12 Pipe hangers			✓	Uti_Support
Hoist	10 Hoist			✓	MUT_Network
Lightning	82 Lightning			✓	MUT_Network
Mill	1 Millwright	✓			MUT_Network
MUT_Section	Prefabricated MUT sections			✓	Sec_to_Site

Table A-1 Resource groups for the C&C activities (Cont.)

Resource group code	Elements	Type			Activity
		Laborer	Machinery	Material	
Pave_Found_Mat	Materials for foundation of the pavement			✓	Found_Pavement
Pavement_Mat	Materials for final pavement			✓	Final_Pavement
Plum	2 Plumbers	✓			Utility_Diver, Uti_Support,
Q_1	1 Plumber	✓			Uti_Network
	1 Plumber apprentice	✓			
Q_2	2 Plumber	✓			Uti_Network
	1 Plumber apprentice	✓			
Q_9	1 Sheet metal worker	✓			MUT_Network
	1 Sheet metal apprentice	✓			
Seal_Mat	Materials for sealing the joints			✓	Sealing_Joints
Shoring_System	1 Trench shoring system			✓	Trench_Shoring
Skwk	2 Skilled workers	✓			Utility_Diver
Soil_Truck	Soil removal trucks (dump truck) (8 C.Y.)		✓		Exc_Diver, Excavation
	Equipment operators (truck)	✓			
Temp_Pi	8 m temporary water Pipe			✓	Utility_Diver
	8 m temporary sewer Pipe			✓	
	8 m temporary gas Pipe			✓	
Temp_Ca	4 Electricity cables (8 m each)			✓	Utility_Diver

Table A-1 Resource groups for the C&C activities (Cont.)

Resource group code	Elements	Type			Activity
		Laborer	Machinery	Material	
Trays	5 Trays (8 m each)			✓	Uti_Support
Tun_Pipes	8 m water Pipe			✓	Uti_Network
	8 m sewer Pipe			✓	
	8 m gas Pipe			✓	
Tun_Cables	4 medium voltage, 3 phase electricity cables (8 m each)			✓	Uti_Network
Vent_Duct	100 m ventilation duct			✓	MUT_Network

The activities of MUT construction using C&C method are shown in Figure 3.2 using abbreviation. Table A-2 shows the name of these activities.

Table A-2 Name of the activities in C&C method

Abbreviation	Activity
Surveying	Surveying
Dem_Urban_Fur	Demolition of urban furniture
Exc_Diver	Excavation for utility diversion
Tr_Unload_RetA	Dump truck cycle
Utility_Diver	Diversion of the existing utilities
Excavation	Trench excavation
Trench_Shoring	Assembly of trench shoring system
MUT_Bed	Preparation of MUT bed
Sec_to_Site	Bringing sections to the site
FB_Truck_Return	Flatbed Truck returning
Atch_lift_Sec	Attaching sections to the crane and lifting
Placing_Sec	Placement of the MUT sections
Sealing_Joints	Sealing of the section joints
Uti_Support	Installation of the utility supports
Uti_Network	Installation of the utility networks
Disp_Shoring	Displacement of shoring system
Backfilling	Backfilling
MUT_Network	Installation of MUT's networks
Found_Pavement	Construction of the pavement foundation
Final_Pavement	Final pavement

Appendix B: The Elements of the Resource Groups and Name of the Activities in Microtunneling Method

Table B-1 shows the resource groups for the activities in MUT construction using microtunneling method and the elements in each group. It should be noted that these resources will not be needed throughout the duration of the project and they could be reused in different tasks.

Table B-1 Resource groups for the microtunneling activities

Resource code group	Elements	Type			Activity
		Laborer	Machinery	Material	
A-6	1 Instrument Man	✓			Surveying
	1 Rodman/Chainman	✓			
	1 Level/Electronic			✓	
Bric	Bricklayer	✓			Sealing_Joints
B_12A	1 Medium equipment operator	✓			Exc_Surf
	1 Laborer	✓			
	1 Hydraulic excavator. 1 C.Y.		✓		
B_13B	1 Labor foreman	✓			Placing_Section
	4 Laborers	✓			
	1 Equipment operator (crane)	✓			
	1 Hydraulic crane		✓		
B_25B	1 Labor foreman	✓			Final_Pavement
	7 Laborers	✓			
	4 medium equipment operators	✓			
	1 Asphalt Paver, 130 H.P.		✓		
	2 Tandem Rollers, 10 Ton		✓		
	1 Pneumatic wheel roller, 12 Ton		✓		
B_32	1 Laborer	✓			Found_Pavement
	3 Medium equipment operators	✓			
	1 Grader		✓		
	1 Tandem roller		✓		
	1 Dozer, 200 H.P.		✓		

Table B-1 Resource groups for the microtunneling activities (Cont.)

Resource code group	Elements	Type			Activity
		Laborer	Machinery	Material	
B_38	1 Labor Foreman	✓			Soil_Removal
	2 Laborers	✓			
	1 Light equipment operator	✓			
	1 Medium equipment operator	✓			
	1 Hydraulic hammer		✓		
	1 Hydraulic excavator 1 C.Y.		✓		
Cameras	4 Security cameras			✓	MUT_Network
Clab	Laborer	✓			Jack_Placing, Dewater_Shaft, Atch_Sec_Crane, Connect_Cables, Disconnect_Cabl
Crane	Hydraulic crane		✓		Atch_lift_crane, MTBM_Setup, Atch_Sec_Crane, Lower_Sec_Shaft, Disassemb_MTBM
	Equipment operator (crane)	✓			
Cutting_Edg	1 Cutting edge			✓	Place_CutEdg
C_14C	1 Carpenter foreman	✓			Foundation_Jack, Shaft_Found
	6 carpenters	✓			
	2 Rodman (reinforcement)	✓			
	4 Laborers	✓			
	1 Cement finisher	✓			
	1 Gas engine vibrator		✓		
Elec	2 Electricians	✓			Uti_Support, Uti_Network, MUT_Network
FB_Truck	Flatbed truck		✓		Sec_to_Site
	Equipment operator (truck)	✓			
Fire_Detector	25 Fire detectors			✓	MUT_Network
Hangers	150 Pipe hangers			✓	Uti_Support
Hoist	10 Hoist			✓	MUT_Network

Table B-1 Resource groups for the microtunneling activities (Cont.)

Resource group code	Elements	Type			Activity
		Laborer	Machinery	Material	
Jacks	6 Hydraulic jacks		✓		Jack_Placing
J_Found_Mat	Materials for foundation of jack			✓	Foundation_Jack
Lightning	82 Lightning			✓	MUT_Network
Mill	Millwright	✓			MUT_Network
MTBM	1 Microtunnel boring machine		✓		MTBM_Setup, Exc_Ground, Jacking_Process
MTBM_Operator	Operator of MTBM	✓			Exc_Ground, Placing_Jack, Jacking_Process, Replace_Jack
Pave_Found_Mat	Materials for foundation of the pavement			✓	Found_Pavement
Pavement_Mat	Materials for final pavement			✓	Final_Pavement
Plum	2 Plumbers	✓			Uti_Support
Q_1	1 Plumber	✓			Uti_Network
	1 Plumber Apprentice	✓			
Q_2	2 Plumber	✓			Uti_Network
	1 Plumber Apprentice	✓			
Q_9	1 Sheet metal worker	✓			MUT_Network
	1 Sheet metal apprentice	✓			
Seal_Mat	Materials for sealing the joints			✓	Sealing_Joints
Soil Truck	Soil removal trucks (dump truck) (8 C.Y.)		✓		Exc_Surf, Soil_Removal
	Equipment operator (truck)	✓			
Shaft_Sections	Prefabricated shaft sections			✓	Sec_to_Site
Sh_Found_Mat	Materials for foundation of shaft			✓	Shaft_Found
Skwk	2 Skilled workers	✓			MTBM_Setup, Disassemb_MTBM
Trays	5 Trays (100 m each)			✓	Uti_Support

Table B-1 Resource groups for the microtunneling activities (Cont.)

Resource group code	Elements	Type			Activity
		Laborer	Machinery	Material	
Tun_Sections	Prefabricated MUT sections			✓	Sec_to_Shaft
Tun_Pipes	100 m Water Pipe			✓	Uti_Network
	100 m Sewer Pipe			✓	
	100 m Gas Pipe			✓	
Tun_Cables	4 medium voltage, 3 phase electricity cables (100 m each)			✓	Uti_Network
Vent_Duct	100 m Ventilation duct			✓	MUT_Network
Well_PP	1 Well point pump		✓		Dewater_Shaft

The activities of MUT construction using microtunneling method are shown in Figure 3.3, 3.4, and 3.5 using abbreviation. Table B-2 shows the name of these activities.

Table B-2 Name of the activities in microtunneling method

Abbreviation	Activity
Surveying	Surveying the location of shaft
Exc_Surf	Excavating the required depth for placing cutting edge
Tr_Unload_RetA	Dump truck cycle in shaft construction
Place_CutEdg	Placing cutting edge
Foundation_Jack	Building the foundation for jacking arms
Jack_Placing	Placing jacking arms on the foundation
Sec_to_site	Bringing sections to the site
FB_Truck_Return	Flatbed truck return for bringing another section
Atch_lift_crane	Attaching shaft sections to the crane and lifting
Placing_Section	Placing the sections
Pushing_Section	Pushing shafts sections into the ground
Soil_Removal	Soil removal
Remove_Cut_Edg	Removing the cutting edge
Dewater_Shaft	Dewatering the shaft
Shaft_Found	Building the foundation of the shaft
MTBM_Setup	MTBM installation in the shaft
Exc_Ground	Pushing MTBM into the ground
Sec_to_Shaft	Bringing sections to the shaft
Atch_Sec_Crane	Attaching tunnel sections to the crane and lifting
Lower_Sec_Shaf	Placing the tunnel sections into the shaft
Placing_Jack	Placing jacking collar
Connect_Cables	Connecting cables
Jacking_Process	Pushing tunnel sections
Replace_Jack	Replacing jacking collar
Disconnect_cabl	Disconnecting cables
Disassemb_MTBM	Disassembling MTBM in the receiving shaft
Cleaning	Cleaning the tunnel
Sealing_Joints	Sealing the joints of the tunnel sections
Uti_Support	Installation of the utility supports
Uti_Network	Installation of the utility networks
MUT_Network	Installation of the MUT’s own network
Found_Pavement	Construction of the foundation of the pavement
Final_Pavement	Final pavement of the street

Appendix C: Total Number of Resources Used in C&C Method

Table C-1 Total number of resources used in C&C method

Element		Number
Asphalt paver 130 H.P.		1
Backhoe loader		1
Bricklayer		1
Crane operator		1
Dozer 200 H.P.		1
Electricians		2
Flatbed truck		1
Flatbed truck operator		1
Grader		1
Hydraulic crane		1
Hydraulic Hammer		1
Hydraulic excavator 1 C.Y.		1
Instrument Man		1
Laborer		10
Labor foreman		1
Level/Electronic		1
Light equipment operator		1
Medium equipment operator		4
Millwright		1
MUT section		25
Plumber		2
Plumber Apprentice		1
Pneumatic wheel roller, 12 Ton		1
Rodman/Chainman		1
Sheepsfoot roller		1
Sheet metal worker		1
Sheet metal worker apprentice		1
Shoring system		1
Skilled workers		2
Soil removal trucks (dump truck) (8 C.Y.)	Fine sand	10
	Sand and gravel	8
	Clay/marl	6
Soil removal trucks operator	Fine sand	10
	Sand and gravel	8
	Clay/marl	6
Tandem roller		2
Trench shoring system		1

Appendix D: Duration of Jacking Sections in Microtunneling

Table D-1 shows the duration of jacking tunnel sections, tunnel diameter and length of the sections in reviewed projects, which were mentioned in Table 4.5.

Table D-1 Duration of jacking tunnel sections

Project		Length of sections (m)	Tunnel Diameter (m)	Jacking Duration (minutes)								
				Fine Sand			Sand and gravel			Clay/Marl		
				Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
BV-V.5.1*		3.5	2.2	53	95	165						
BV- V.8*		4	1.56							120	155	271
BV-V.15*	Clay, Marl	4.02	1.46							234	280	336
	Sand and Gravel	4.02	1.46				83	124	138			
FSTT**		2	0.75	10	16	25	20	38	50	35	70	145
* Adapted from (Dang, 2015)												
** Adapted from (Colson, 2010)												

In order to modify the jacking durations in reviewed projects according to the assumed tunnel diameter and length of sections, the durations in Table D-1 were plotted against the tunnel diameter and the length of the sections (Figure D-1 and Figure D-2). Using the equation of the linear trendline, two durations are calculated according to the tunnel diameter and length of the tunnel sections (Table D-2). Then, the average of these two durations has been used for the case study (Table D-3).

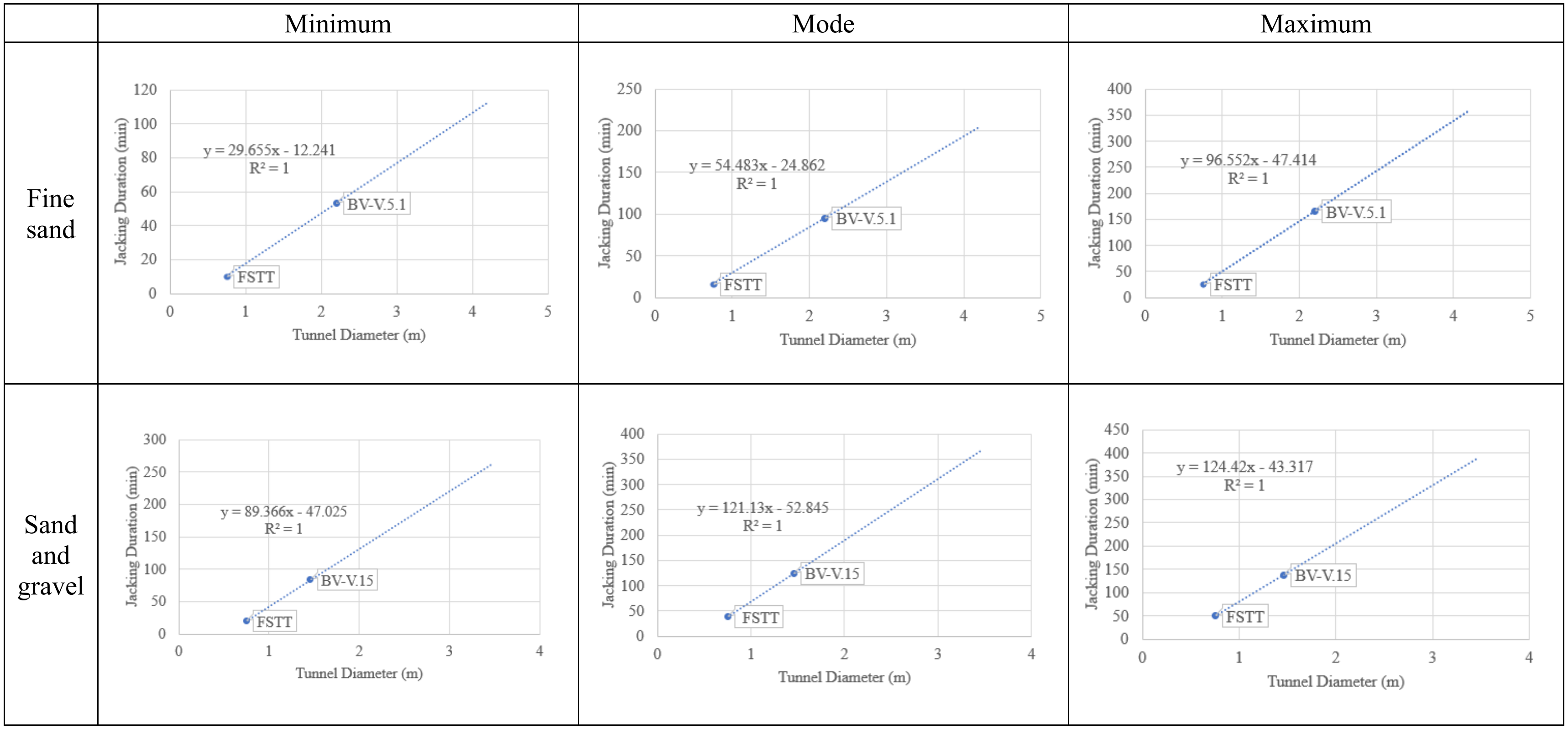


Figure D-1 Jacking duration Vs. tunnel diameter

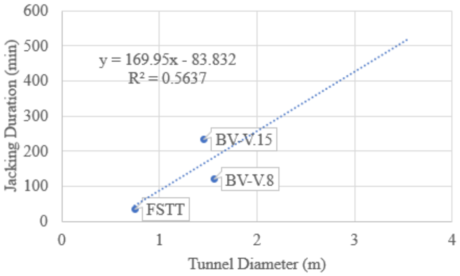
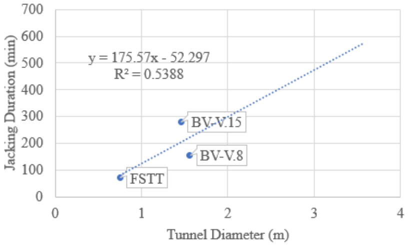
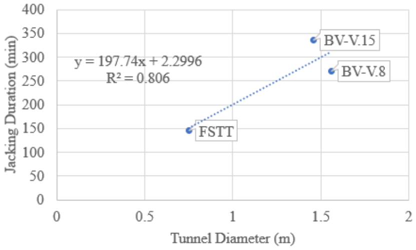
	Minimum	Mode	Maximum
Clay/Marl			

Figure D-1 Jacking duration Vs. tunnel diameter (Cont.)

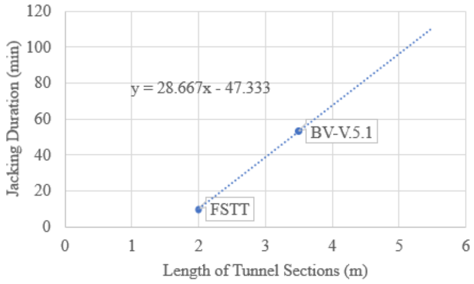
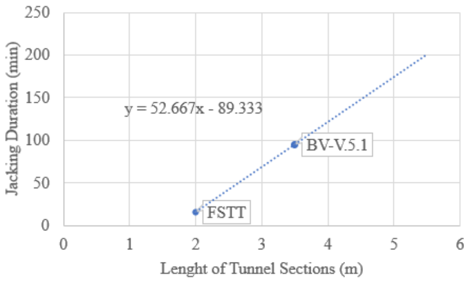
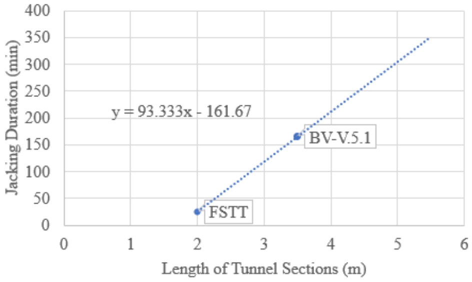
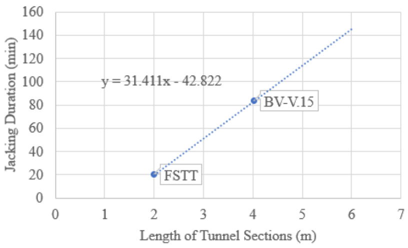
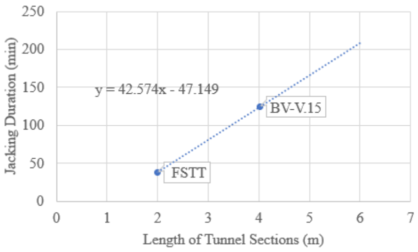
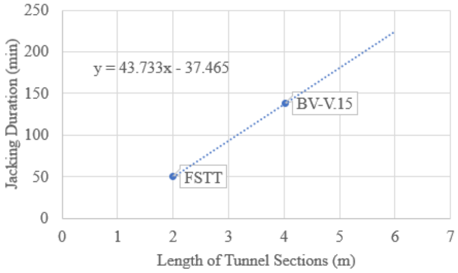
	Minimum	Mode	Maximum
Fine sand			
Sand and gravel			

Figure D-2 Jacking duration Vs. length of tunnel sections

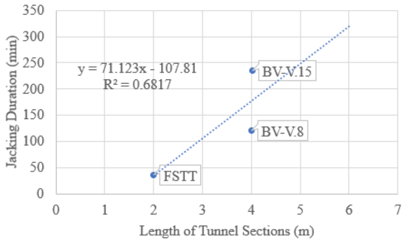
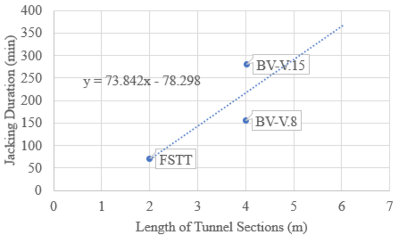
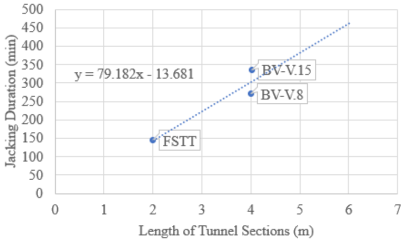
	Minimum	Mode	Maximum
Clay/Marl			

Figure D-2 Jacking duration Vs. length of tunnel sections (Cont.)

Table D-2 Calculated durations according to tunnel diameter and length of sections for tunnel sections

Assumed Diameter	Converting Jacking Duration According to:	Fine Sand			Sand and Gravel			Clay/Marl		
		Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
4 m tunnel	Tunnel Diameter	106.379	193.07	338.794	310.439	431.675	454.363	595.968	649.983	793.2596
	Length of Sections	67.335	121.335	211.662	82.822	123.147	137.467	176.682	217.07	303.047
3 m tunnel	Tunnel Diameter	76.724	138.587	242.242	221.073	310.545	329.943	426.018	474.413	595.5196
	Length of Sections	67.335	121.335	211.662	82.822	123.147	137.467	176.682	217.07	303.047

Table D-3 Assumed durations for jacking tunnel sections

Geotechnical condition	Jacking duration (minutes)					
	3 m tunnel (6 m Shaft)			4 m tunnel (8 m shaft)		
	Min	Mode	Max	Min	Mode	Max
Fine sand	72.03	129.96	226.95	86.86	157.20	275.23
Sand and gravel	151.95	216.85	233.71	196.63	277.41	295.92
Clay/marl	301.35	354.74	449.28	386.33	433.53	548.15

Appendix E: Total Number of Resources Used in Microtunneling Method

Table E-1 Total number of resources used in microtunneling method

Element	Number
Asphalt paver 130 H.P.	1
Bricklayer	1
Carpenter foreman	1
Carpenters	6
Cement finisher	1
Cutting edge	1
Crane operator	1
Dozer 200 H.P.	1
Electricians	2
Flatbed truck	1
Flatbed truck operator	1
Gas engine vibrator	1
Grader	1
Hydraulic crane	1
Hydraulic Hammer	1
Hydraulic excavator 1 C.Y.	1
Instrument Man	1
Jacks	6
Labor foreman	1
Laborer	7
Level/Electronic	1
Light equipment operator	1
Medium equipment operator	4
Microtunnel boring machine	1
Microtunneling boring machine operator	1
Millwright	1
Plumber	2
Plumber Apprentice	1

Table E-1 Total number of resources used in microtunneling method (Cont.)

Element		Number
Pneumatic wheel roller, 12 Ton		1
Rodman/Chainman		1
Rodman (reinforcement)		2
Shaft sections		5
Sheet metal worker		1
Sheet metal worker apprentice		1
Skilled workers		2
Soil removal trucks (dump truck) (8 C.Y.)	Fine Sand	10
	Sand and gravel	8
	Clay/marl	6
Soil removal truck operator	Fine Sand	10
	Sand and gravel	8
	Clay/marl	6
Tandem roller		2
Tunnel sections		25
Well-point pump		1