Discrete Event Simulation of Multi-purpose Utility Tunnels Construction Using Microtunneling

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Abstract

The traditional method of burying underground utilities (e.g., water, sewer, gas pipes, and electrical cables) has been used for many decades. Repeated excavations related to this method cause many problems, such as traffic congestion and business disruption, which can significantly increase the social costs. Multi-purpose Utility Tunnels (MUTs) are a good alternative for buried utilities. Although MUTs are more expensive than the traditional method, social cost savings can make them more practical, especially in dense areas. The construction method is one of the most important factors that should be carefully assessed to have a successful MUT project. Simulation can be used for investigating the different construction methods of MUTs. In this paper, simulation of the MUT construction methods is done using Discrete Event Simulation (DES) to analyze the duration of MUT projects focusing on microtunneling.

Keywords –

Discrete Event Simulation, Multi-purpose Utility Tunnel, Construction Method, Trenchless Technologies, Microtunneling

1 Introduction

Utility networks are installed above and below the ground. Different reports have stated that underground utilities in developed areas have reached or are nearing the end of their service lives, which results in the need of many repair and replacement projects [Gagnon *et al.*, 2008; Ormbsy, 2009]. The maintenance or replacement of buried utilities have imposed many street closures and traffic disruption in urban areas (i.e., social cost) [Oum, 2017].

Tunnelling projects are designed to enable the execution of underground work with minimal disruption to surface structures and traffic [Marzouk *et al.*, 2010]. Multi-purpose Utility Tunnels (MUTs) are defined as "underground utilidors containing one or more utility systems, permitting the installation, maintenance, and removal of the systems without making street cuts or excavations" [Canto-Perello and Curiel-Esparza, 2013]. MUTs are more expensive than conventional methods, but they could be more practical in dense areas due to social cost savings. To make MUTs an affordable and efficient alternative to buried utilities, different factors, such as utility specifications, the 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 MUTs can be classified in two main groups, which are Cut-and-Cover (C&C) methods [Cle de Sol, 2005; Ramírez Chasco *et al.*, 2011] and trenchless methods (e.g., microtunneling) [Byron *et al.*, 2015]. Despite the high initial cost of the trenchless methods, 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, in deep MUT projects or in some special geological conditions (e.g., hard rocks).

Construction can benefit greatly from simulation. 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). The main aim of this paper is to analyse the duration of MUT construction projects using DES focusing on microtunneling.

2 Literature Review

2.1 MUT Construction Methods

C&C and trenchless methods are two main groups of construction methods for MUT projects [Cle de Sol, 2005; Ramírez Chasco *et al.*, 2011].Trenchless methods can be divided in two main categories, which are trenchless construction methods (e.g. auger boring, horizontal directional drilling, microtunneling) and trenchless renewal/replacement methods (e.g. Cured In Place Pipe (CIPP), slip lining) [Najafi and Gokhale, 2005].

C&C is the most common method for construction of utility tunnels [Ahmadian, 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, 2008]. The support of the vertical sides is the main consideration with different C&C techniques including C&C using diaphragm walls, C&C using secant pile walls, C&C using soldier piles and lagging, and C&C using steel sheet pile walls [Abdallah and Marzouk, 2013; Marzouk *et al.*, 2008]. 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]. 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]. One of the most common techniques used in the construction of C&C tunnels is the secant pile walls technique. The secant piles are wide diameter bored piles that are overlapped at near centre and can be used to form a wall [Marzouk *et al.*, 2008].

Microtunneling is a competing alternative to the C&C method from different aspects, such as economics and environmental conditions. According to Stein (2012), "In microtunnelling 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 microtunnelling 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". Depending on the way of conveying the spoil, there are three types of Micro Tunneling Boring Machines (MTBM), including auger spoil removal, hydraulic spoil removal and pneumatic spoil removal [Stein, 2012]. According to FSTT (2006), the type of ground, ground water level and existence of boulders are three main parameters which should be considered for choosing the type of MTBM. The hydraulic type of MTBM can be used in most situations.

2.2 Process Simulation

Process simulation has been widely used in different fields, such as manufacturing, business, computer science and construction [Banks et al., 2010; Roberts and Dessouky, 1998]. 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 behaviour 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, which are DES, System Dynamics (SD) and Agent-Based-Modelling (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 understanding and analysing the behaviour of a system over time [Forrester, 1961; Trung Thanh Dang, 2013]. Individual agents are simulated in the ABM method, which is a class of computational models for simulating the behaviours and interactions of autonomous agents [Macal and North, 2006]. In this paper, DES will be used for the simulation of the microtunneling construction of MUT.

The DES paradigm is commonly used to model and evaluate construction sequences in simulation studies. In this method, people, equipment, documents, tasks, etc., are represented by passive objects called entities. These entities move thorough the flowchart's blocks, where they can be waiting in queues, processed, delayed, seizing and releasing resources, split and combined, etc. [Borshchev and Filippov, 2004]. DES models are developed by breaking down activities into tasks. Each of these tasks' duration is presented by a probabilistic distribution, such as the triangular distribution, instead of a deterministic one [Beck, 2008].

3 Proposed Methodology

As mentioned in Section 1, one of the most important factors affecting the cost and efficiency of MUT projects is the construction method. To address this problem, the proposed method is developed in six steps.

1. **Analysis of the location of the MUT:** The location of the project is an important parameter for selecting the construction method. The location will be analysed for determining different data, such as soil data (e.g., type of the soil, cohesion, underground water), traffic volume, density of utilities and buildings in the area, etc., using a Geographic Information System (GIS).
2. **Selecting the construction method:** After collecting the data related to the location of the project, the construction method, suitable for the location will be selected. As an example, using the

C&C method for the construction of McGill University MUT was impossible since it is located under several buildings; therefore, the Drill and Blast (D&B) method was selected for constructing the MUT [Habimana *et al.*, 2014].

3. **Defining the sequence and relationships between activities:** Each construction method includes different activities. Once the 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. Since the focus of this paper is on microtunneling, the sequences, relationships between the different activities and the resources needed for them will be introduced briefly.
4. **Defining the probabilistic distribution of the duration of each activity:** In this step, the duration of each activity should be defined. The duration of the activities can be defined by probabilistic distributions.
5. **Calculating the duration of the project:** In this step, the sequence and relationships between activities and the duration of each activity are used to determine the total duration of the project.
6. **Comparing the duration of the construction methods:** In the last step, the total duration of the construction methods will be compared for selecting the fastest method for constructing the MUT.

It should be mentioned that, in this paper, only the fifth step of the proposed method, which is calculating the duration, has been implemented.

The construction of MUTs using microtunneling can be divided into three main steps, which are shaft construction, tunnel construction and placement of the utilities in the tunnel. In this paper, the second step (tunnel construction) has been simulated. 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) Transporting and attaching tunnel sections: These activities are required to transport the tunnel sections to the shaft and attach them to the crane; (4) Lowering tunnel section: This activity is required to prepare the jacking system for tunnel section placement, lower tunnel section to the jacking frame and place the tunnel section on the lunch skid; (5) Placing the jacking collar behind the tunnel section; (6) Connecting cables and pipelines; (7) Jacking processes: This activity represents the pipe driving operation, which advances the tunnel. Also, the activities related to handling and separating the materials spoil, which is transported from the working face of the tunnel to the separation plant are considered; (8) Replacing the jacking collar; (9) Disconnecting the cables and pipelines; (10) Dissembling MTBM: When the tunnel is completely excavated, the MTBM will be dissembled from the receiving shaft; and (11) Cleaning the tunnel.

Figure 1 shows the sequence and relationships between the activities in tunnel construction using microtunneling. The resources required for each activity are shown in blue circles. The grey circles show the queues made for representing the sequence of the process.

4 Implementation and Case Study

This section presents the implementation of the proposed model for analyzing the total duration of tunnel construction using microtunneling. Among the different activities involved in microtunneling, jacking the tunnel sections into the ground has the biggest effect on the total duration of the project. Also, the diameter and the length of the tunnel sections and the geotechnical conditions of the soil can directly affect the duration of this activity. Therefore, two different diameter and three different geotechnical conditions have been evaluated to analyze the total duration of tunnel construction using microtunneling.

Some assumptions were made to analyze the total duration of the tunnel construction. The proposed method was implemented for two different assumed diameters (3 m or 4 m) and three different geotechnical conditions including the presence of fine sand, sand and gravel, or clay/marl in the location of the project. Also, it was assumed that the resources required by each activity are always available and free to be used. Table 1 shows the other assumptions used in the case study.

Table 1 Assumptions made for the case study

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
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 (2013) and Marzouk *et al.*, (2010), as well as the fourteen projects monitored by the French National Research Project *Microtunnels* [FSTT, 2006] have been reviewed. Table 2 shows the characteristics of these projects.

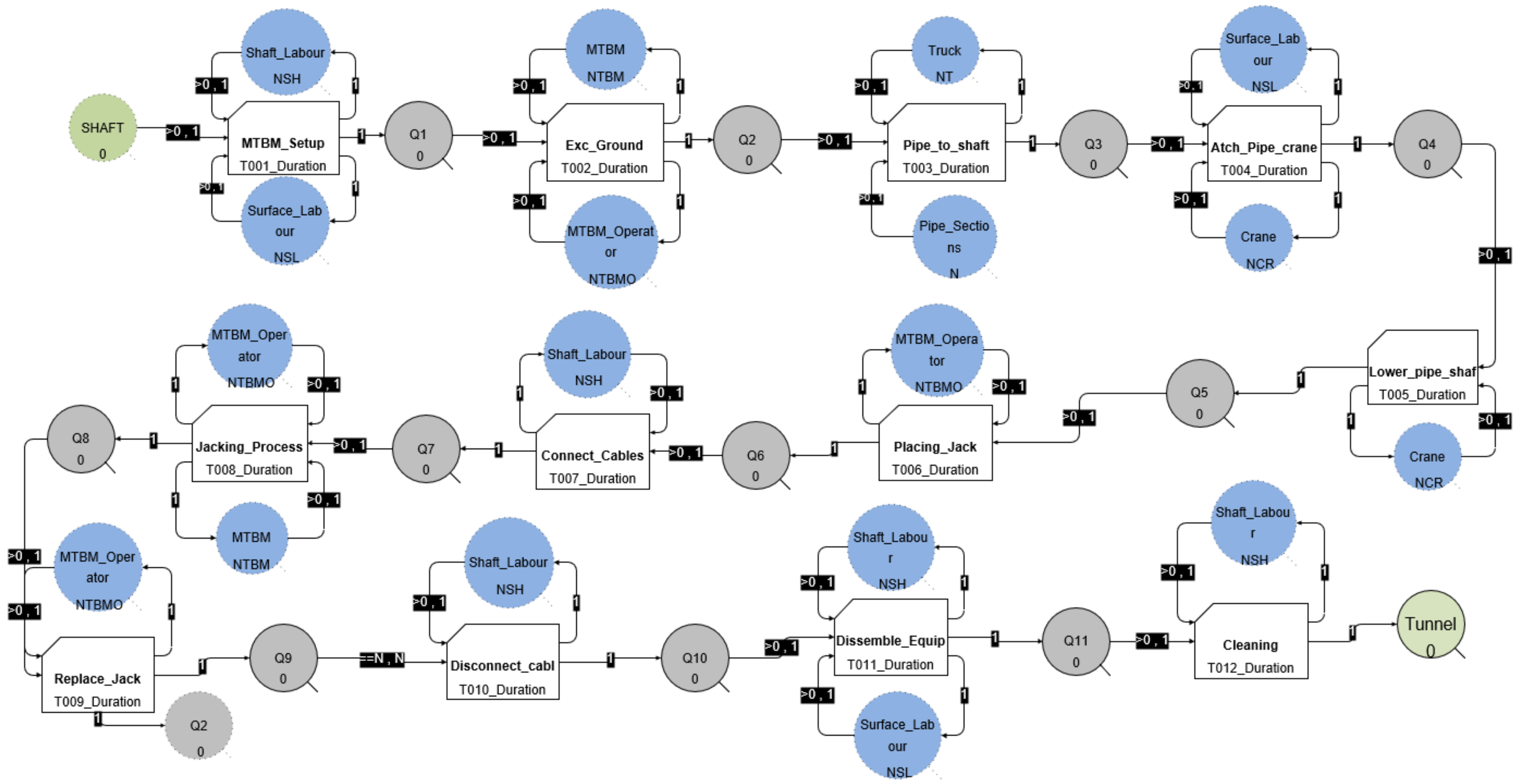

Figure 1. Tunnel construction sequence in microtunneling method

It should be mentioned that because of the difference between the dimensions of the assumed tunnel and those of the tunnels in reviewed projects, the jacking duration was modified according to the diameter and length of the sections. Table 3 shows the assumed durations of the jacking activity for different tunnel diameters and different geotechnical conditions. For other activities, the average durations of reviewed projects have been used (Table 4).

Table 2 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, 2013)
** Adapted from (Marzouk *et al.*, 2010)
*** Adapted from (FSTT, 2006)

Table 3 Assumed durations for jacking tunnel sections

Geotechnical condition	Jacking duration (minute)					
	3 m diameter			4 m diameter		
	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

Table 4 Assumed durations for microtunneling activities

Activity	Duration (minute)		
	Min	Mode	Max
MTBM installation in the shaft		N [10080,1440]	
Bringing sections to the shaft	10.00	20.00	40.00
Attaching and lifting sections by the crane	1.60	1.70	2.32
Lowering and laying sections in the shaft	2.44	3.38	4.49
Placing jacking collar	4.36	5.64	6.73
Connecting cables	28.88	36.18	48.13
Replacing jacking collar	5.18	6.38	7.33
Disconnecting cables	16.41	18.53	20.97
Disassembling MTBM in the receiving shaft		N [10080,1440]	
Cleaning the tunnel		N [3600,720]	

N [a,b]: Normal distribution; a is the mean; b is the standard deviation

The assumed data were fed to the DES model using EZStrobe software and 100 simulation replications were made to calculate the total duration of tunnel construction. Figure 2 shows the results of the simulation for the two assumed diameters and three geotechnical conditions.

For the 3 m diameter tunnel, the estimated average total duration of tunnel construction are 40.88, 43.32 and 48.39 working days for fine sand, sand and gravel and clay/marl geotechnical conditions, respectively. For the 4 m diameter tunnel, the average total duration of tunnel construction are estimated as be 41.66, 45.49 and 52.37 working days in fine sand, sand and gravel and clay/marl geotechnical conditions, respectively. In addition, it can be observed that the total durations in clay/marl and sand and gravel are greater than in fine sand. Also, according to Figure 2 it is obvious that by increasing the diameter of the tunnel the total duration of construction will increase.

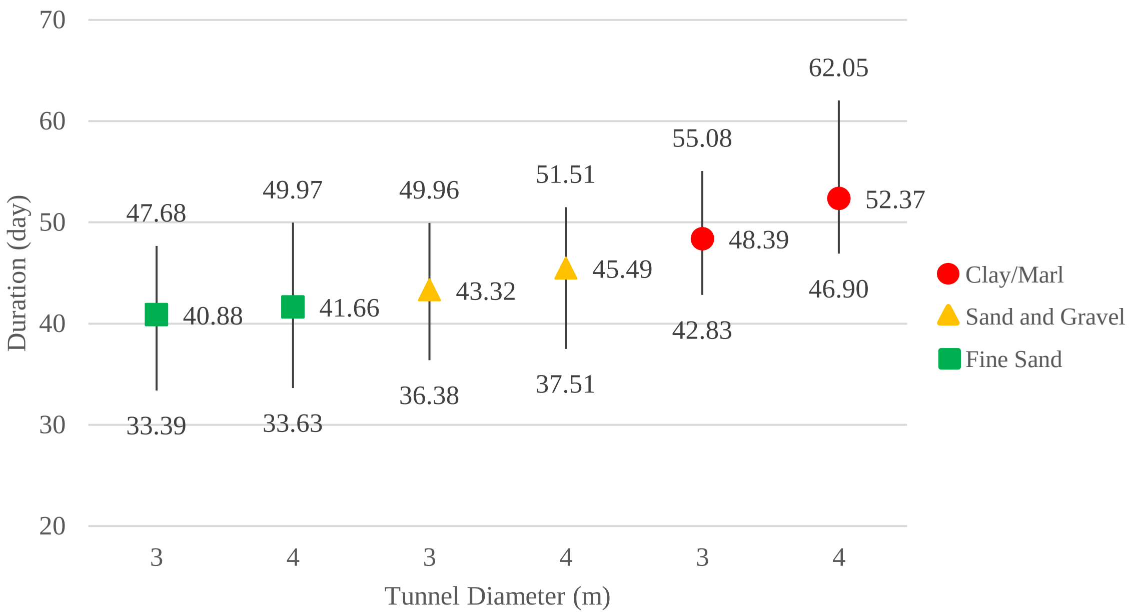

Figure 2 Results of DES of MUT construction using microtunneling

5 Conclusions and Future Work

This paper presented DES of MUT construction using microtunneling for different tunnel diameters and geotechnical conditions. The proposed model estimates the total duration of tunnel construction project. The main conclusions of this paper are: (1) by increasing the size of the tunnel, the total duration will also increase; and (2) the type of the soil affects the total duration of the project. By increasing the cohesiveness and hardness of soil, the duration of tunnel construction will increase. Future work will simulate other steps in MUT construction (e.g., shaft construction and placement of the utilities) and compare microtunneling with C&C method using DES.

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