Modeling Microtunneling Projects using Computer Simulation

Mohamed Marzouk[1]; Moatassem Abdallah[2]; and Moheeb El-Said[3]

Abstract: Tunnels projects are constructed to facilitate the execution of underground works with minor disturbance on surface structures and traffic. This is deemed important especially in downtown cities where disturbances should be minimized to assure flowability on surface and underground infrastructures. Microtunneling involves the use of a remotely controlled, guided pipe-jacking process in order to support excavation face. Microtunneling aids in avoiding the need of open trench for pipe laying, which causes extreme disruption to the surrounding. This paper presents a tool for planning microtunnels projects using computer simulation. The proposed tool aids contractors in planning microtunneling by estimating their associated time and cost of construction. There are six models that are coded in the proposed tool in order to capture the construction of microtunnels and shafts. The tool breaks down microtunnels projects into microtunnels segments and shafts which constitute several construction zones. An application example is presented to demonstrate the features of the proposed tool.

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Introduction

Microtunneling are executed in different site conditions which increase uncertainties that influence rate of production that might lead to deviation from original work plan. These uncertainties include unexpected soil types, unusual or complex works, and equipment breakdown. Traditional planning techniques such as critical-path method, precedence diagram method, or line of balance method do not account for such uncertainties. In addition, they do not plan the construction operation along with the total available number of resources. Also, microtunneling construction projects are characterized by a high degree of mechanization and repetitive operations. These features of microtunneling construction propose computer simulation as suitable modeling technique to mimic tasks found in construction sites. Computer simulation has proved to be an efficient planning tool for construction projects, taking into consideration the interaction among available resources. Also, it allows the use of several probability density functions in defining tasks duration in order to account for uncertainties that may happen during construction. Several efforts have been made in planning construction operations using computer simulation. These include earthmoving operation (Marzouk 2002), concrete operations (Hassan and Gruber 2008), bridges (Marzouk et al. 2006), and tunnels (Tanaka 1993; AbouRizk et al. 1999).

Studying microtunnel projects have been carried out in literature by introducing decision aid tools (Sinfield and Einstein 1996; Ueki et al. 1999; Myers et al. 1999; Nido et al. 1999; Chung et al. 2004; Luo and Najafi 2007). Sinfield and Einstein (1996) studied the effect of changes in tunneling technology on tunneling cost and time. The study dealt with tunneling with a closed-face TBM. Ueki et al. (1999) presented a decision tool that outputs appropriate underground pipeline installation methods for specific site conditions. The tool aids in three major processes: method selection, pipe selection, and machine selection. Myers et al. (1999) discussed the economic, productivity, and safety issues associated with microtunneling. They presented the key factors affecting the selection of the microtunneling technology for conduit construction. Nido et al. (1999) used simulation to study microtunneling operations to identify problems at the different stages of the project. They analyzed and evaluated the factors that affect the productivity in microtunneling operations. Further, they used CYCLONE simulation methodology to study an actual project; Holes Creek Tunnel Project site in Montgomery County, Ohio.

Chung et al. (2004) presented a computerized decision support system (DSS) for microtunneling to support decision making for contractors who want to bid on microtunneling projects. To use the system, the user enters basic information about the potential project such as drive length, installation depth, pipe diameter, and soil condition, the DSS evaluates the economic feasibility and advice on the appropriate types of microtunneling methods. Luo and Najafi (2007) analyzed the factors that affect the productivity in microtunneling operations. They presented a computer simulation model which is used to study microtunneling operations. They conducted an actual microtunneling field study conducted at Louisiana Tech University. None of previous efforts takes into

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consideration the different methods that are used in the construction of microtunneling and shafts. This paper presents a tool that aids in planning microtunneling projects by modeling microtunnels and shafts using computer simulation. The tool is generic since it models three construction methods of microtunneling and three construction methods of shafts. First, the paper reviews the construction methods and techniques that are used in execution of microtunneling and shafts. Then, it describes the developments made in the tool, illustrating its main components along with their designated functions. Finally, an actual case example is presented to illustrate the practical use of the developed tool.

Microtunneling Construction Methods

Microtunneling is a competing alternative method to the open-cut method from different aspects including; economics and environmental conditions. As such, there is a need to increase its applications and accuracy (Yoshida and Tsujimura 2002). Casing sizes of microtunneling usually range from 0.9 to 2.4 m in diameter, with the casing being made of steel, reinforced concrete, or fiberglass. In recent years, pipe-jacking methods have been developed for microtunneling (Brusey 1998). Pipe-jacking is a trenchless excavation technique for installing pipes where a hydraulic jacks push the pipe through the ground behind a microtunneling boring machine. The microtunnel boring machine (MTBM) excavates the soil while the pipe is being pushed. Pipe-jacking using mechanical excavation methods have several advantages:

- Mechanization and high advance rate;
- Keeping exact tunnel profile;
- Construction is performed under existing utilities and obstructions; including small rivers, so, there is minimal surface disruption; and
- Least impact on the surface structures.

On the other hand, the main disadvantages of pipe-jacking technique are:

- Long preparation time for planning, manufacturing, and assembling;
- Varying ground conditions causes risk on system performance; and
- Difficult in the preparation of the construction-site and associated costs, (only economic with long driving lengths).

The pipe-jacking technique is classified into three methods, depending on type of excavation and removal of excavated soil, including; manual open face excavation, mechanical closed-face excavation, and mechanical excavation using slurry system. The following subsections describe those excavation methods that are used in microtunneling.

Open Face Manual Excavation

Hand excavation is usually accomplished inside a shield attached to the leading section of pipe. The shields are typically articulated which allows some degree of alignment and grade control. The purpose of the shield is to provide a safe working environment for the workers and to allow the bore to stay open for the pipe to be jacked into place. Open face manual excavation is one of the oldest methods of microtunneling. This system is economic in case of very short driving lengths and accessible shield diameter. The accessible diameter is defined as the minimum diameter that allows a labor to enter and excavate the tunnel face (about 1.3 m). The disadvantages of this system are: (i) it cannot be used in the existence of groundwater; (ii) it provides low advance rates; and (iii) it cannot be used for long tunnel length and extreme size of diameters (very big and/or very small).

Fig. 1. Mechanical excavation using MTBM

Mechanical Excavation

In order to facilitate microtunneling through firm ground and to increase advance rates in lose ground, a closed-face mechanical excavation tool is applied. In mechanical excavation, the soil is excavated by revolving the cutting head in front of the MTBM. The excavated soil is transported, in this system, using skip from the tunnel face to the ground level. The system provides the following advantages over manual excavation: the tunnel profile is cut very accurately. It provides higher level of safety for the personnel, and it provides less impact to the surface structures. The main components of the system are: MTBM, skips, jacking unit, bentonite pump, crane, control chamber, and guiding system. The construction of microtunneling using closed-face mechanical excavation is divided into three processes: site setup, tunnel construction, and dismantling equipment and finishing tunnel. Fig. 1 illustrates mechanical excavation using MTBM.

The first process (named site setup) starts by construction of supporting wall behind the jacking unit. Then, the jacking unit can be installed into shaft. During the construction of supporting wall and installing jacking unit, the MTBM can be erected. After words, the MTBM is lowered into the shaft by using a high capacity crane. Then, the jacking arms are connected to it. After lowering the MTBM into shaft, the bentonite pump can be installed. The second process (named tunnel construction) is started by excavating the tunnel entrance ring to get into soil. During excavation, the excavated soil is collected in the skip and the surface between pipe and ground is lubricated by a bentonite pump. After filling the skip with excavated soil, the excavation is stopped and the skip is transported to the shaft, then, hoisted to ground using crane to dump its soil. Once the load is dumped, the skip is lowered to the shaft and transported to tunnel face. At this time, the MTBM can resume its excavation again. Each time the pipe is installed in the soil, the excavation is stopped and the jacking arms are retrieved back. After that, a new pipe is lowered into the shaft, in front of the jacking unit. Then, the jacking arms are extended to pipe. At this time, the excavation can be resumed. The processes of excavation and lowering pipe are repeated till the MTBM reaches the receiving shaft. In case of double driving shaft (construction of two tunnels with the same driving shaft to save time required for site setup), the MTBM is used to construct the first tunnel, then, it is transported back to the driving shaft to construct the second tunnel (see Fig. 2). The final process (named

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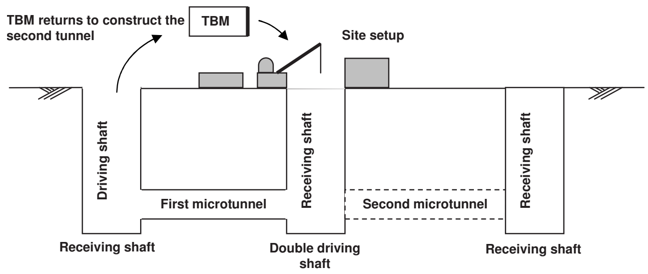

Fig. 2. Construction of two microtunnels with the same driving shaft

dismantling equipments and finishing tunnel) is started by dismantling the MTBM, jacking unit, and bentonite pump. Subsequently, tunnel cleaning is performed followed by injecting grout around pipes. Once the grout is injected around pipes, the space between pipes is filled with cement, and welded by T-lock.

Slurry Mechanical Excavation

In this method, the ground soil is excavated mechanically while the slurry supports tunnel face. The muck is transported by the slurry discharge system from the suspension chamber right behind the cutter head to the surface. The main components of the system are: MTBM, jacking unit, bentonite pump, slurry pump, feeding

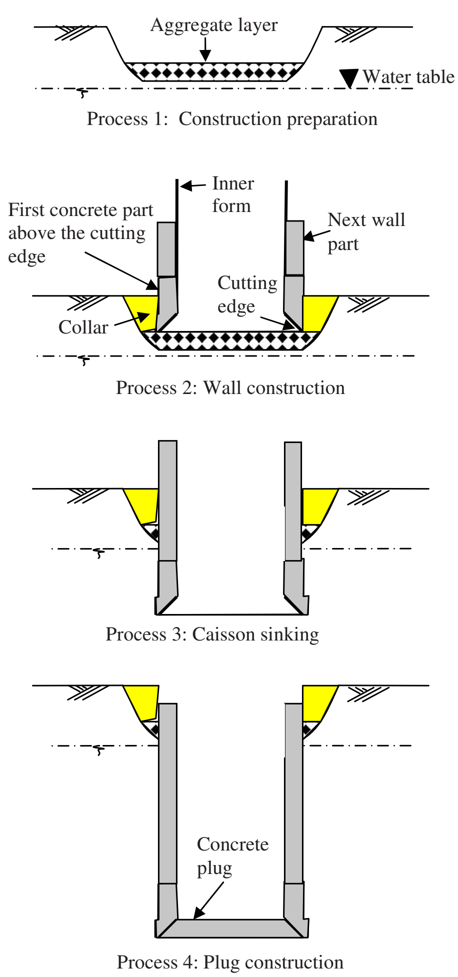

Fig. 3. Processes of shafts construction using traditional forms

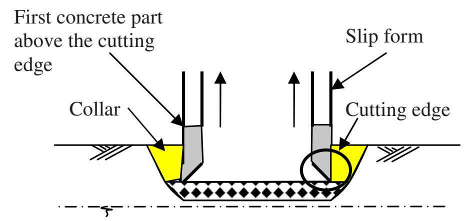

Fig. 4. Wall construction using slip forms

pump, separation plant, crane, control room, and guiding system. The construction of microtunnels by slurry closed-face mechanical excavation is divided into three processes: site setup, tunnel construction, and dismantling equipment and finishing tunnel. The first and third processes are similar to the corresponding processes in mechanical excavation.

The second process (named tunnel construction) is started by excavating the tunnel entrance ring to get into soil. During excavation, the excavated material is handled to the shaft by using either water or bentonite. The transportation medium is pumped to the tunnel face from the driving shaft by one or several feed pumps using the tunnel boring machine's feed line to stabilize and support the tunnel face. The mixture of soil and transportation medium is exhausted out of the excavation chamber through the slurry line and conveyed to the separation plant. To prevent slurry line from getting blocked, any major lumps of rock are crushed by the cone crusher in the working chamber before passing into the slurry line. In the separation plant, the charged transportation medium is separated from the loose soil using screens, cyclones and, if necessary, centrifuges as well. Efficient separation means that a large proportion of the medium can be treated and sent back to transportation circuit. The separated soil is loaded into trucks to be hauled to the dumping area. To install a new pipe in the soil, the following steps are followed: (1) the excavation is stopped; (2) the jacking arms are retrieved back; and (3) the feed pump and slurry pump are disconnected at shaft zone. After that, the new pipe is lowered into the shaft in front of the jacking unit. Then, the feed pump and slurry pump are connected again with line extension and the jacking arms are extended to pipe. As such, the excavation can be resumed. The process of excavation and lowering pipe is repeated till the MTBM reaches the receiving shaft.

Shafts Construction Methods

Most of microtunneling are built through urban areas that require shafts to reach the working area and to provide outlet for tunnel

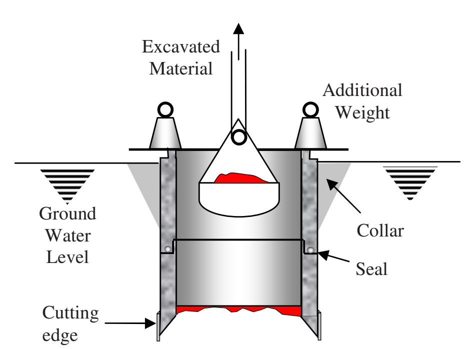

Fig. 5. Shafts constructing using precast concrete segments

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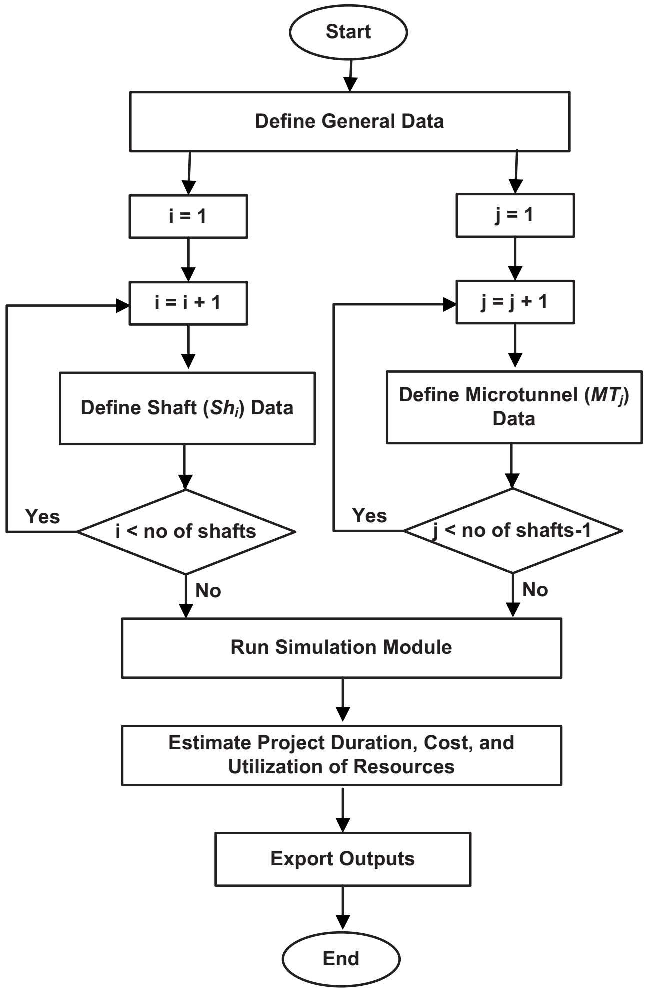

Fig. 6. Flowchart of microtunnel analyzer module processes

muck. The dimension of the shaft relates to the type of equipment being used. The diameter of shaft is in direct relationship to the diameter of the pipe being driven, plus an allowance for working space. Also, it is determined by the length of pipe section to be installed and the space needed for jacking equipment. The choice of shaft construction for driving and receiving shafts depends on the required depth, the size of equipment and pipe section, soil condition, and groundwater. The following sections present three methods for caisson construction of driving and reception shafts.

Table 1. Developed Simulation Models

File name	Description
Shaft1	Shaft construction using traditional forms
Shaft2	Shaft construction using slip form
Shaft3	Shaft construction using precast concrete segments
Microtunneling1	Microtunneling construction using manual excavation
Microtunneling2	Microtunneling s construction using mechanical excavation
Microtunneling3	Microtunneling construction using slurry mechanical excavation

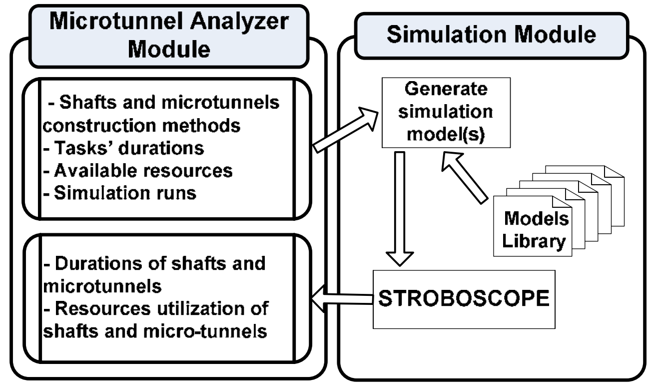

Fig. 7. Interaction between microtunnel analyzer module and simulation module

Shafts Construction using Tradition Forms

The essential feature of a caisson is that the circular structure is constructed above ground and then sunk as a single unit to the required depth, where it remains part of the permanent work. Excavation, which is carried out during the caisson sunk, is often under water work and soft ground conditions. The construction of shafts using traditional forms is divided into four processes: construction preparation, wall construction, caisson sink and plug construction, and ground injection (see Fig. 3). The first process (named construction preparation) is executed by locating the position of shaft using survey. Then, excavating soil with the required depth (1–2 m) is performed. After excavating soil, the soil is covered with aggregate layer of (0.5–1.0 m) thickness. The second process (named wall construction) is started by setting and welding segments of the cutting edge. After that, the inner form of the wall shaft can be erected. During the erection of inner formwork, the outer form can be erected for the first part above the cutting edge. Once the forms are assembled, the reinforcement bars are placed to form the reinforcement of the first part above the cutting edge. At this stage, the concrete of first part can be poured and cured. After curing the concrete of the first part, the outer forms can be dismantled then the concrete of the collar can be poured and cured. The rest of the wall is divided into segments, each segments is constructed by fixing the prepared reinforcement bars (either in shop or site) into wall segment. After fixing steel bars into segment, the outer form of the wall can be erected. At this stage, the concrete of the segment can be poured and cured. This process is repeated for each wall segment.

The third process (named caisson sink and plug construction) is started after dismantling the inner and outer form of the shaft. This process is started by excavating the inner ground soil of the shaft while the caisson is sinking. Excavation is usually done by clamshell excavator to facilitate more efficient excavation. During excavation, a bentonite pump may be used to lubricate the surface between shaft's wall and ground through small pipes, installed into wall during construction. It is necessary to sink caisson at least 6 m below the final manhole base. After sinking the shaft to the required level, concrete plug can be poured and cured. Once concrete is cured, the water in the shaft can be pumped out to get a dry caisson. It should be noted that the inlet and outlet of the tunnel are not concreted during construction by filling the hole with brick or wooden forms.

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Table 2. Tasks Involved in Tunnel Construction Process

MD1PJ02	
Excavate, pipe-jacking, and hydraulic soil removal	
Resources	TBM machine, TBM crew, and two dummy queues
Start condition	It draws one resource from each of "Q1" and "Q5" dummy queues. The dummy queue "Q5" contains number of pipes needed forconstruction of the microtunnel
Finish	It sends one resource to a dummy queue named "Q2"
MD1PJ03	
Lowering, and laying pipe into position	
Resources	Cranes and two dummy queues
Start condition	It draws one resource from cranes queue, and one resource from each of two dummy queues named "Q2," and "Npipes." The dummy queue, named "Npipes," contains total number of pipes required for construction of the microtunnel
Finish	It returns the drawn resource from cranes queue, and sends one resource to each of "Q1" and "Q3" dummy queues
MD1PJ04	
Receiving equipment in the second shaft	
Resources	TBM machine, TBM crew, and two dummy queues
Start condition	It draws number of pipes needed for construction of microtunnel from dummy queue named "Q3"
Finish	It sends one resource to dummy queue named "Q4"

Shafts Construction using Slip Forms

Shafts construction using slip form is similar to traditional forms except for the second process which starts also by setting and welding segments of the cutting edge. After welding the cutting edge segments, the slip form is erected to be used in the construction of the wall. Once the slip form is assembled, the reinforcement bars (which are either fabricated in site or outer workshop) are placed to form the reinforcement of the first part above the cutting edge. At this stage, the concrete of the first part can be poured and cured. After curing the concrete of the first part, the concrete of the collar can be poured and cured. After pouring the collar concrete, the slip form starts moving upward with very slow rate. During the movement of the slip form, the steel bars are fixed into wall to form the steel mesh of shaft's wall and concrete is pored and cured for each finished part. The slip form moves continuously until it reaches the required height of the shaft then it stops (see Fig. 4).

Shafts Construction using Precast Concrete Segments

Segments are also used to build caissons which can be sunk to construct underground shafts. The bottom ring is installed into cutting shoe to assist sinking action. At the surface, a concrete ring collar is casted around the caisson to act as a guide during sinking. Shaft construction using precast concrete segments in-

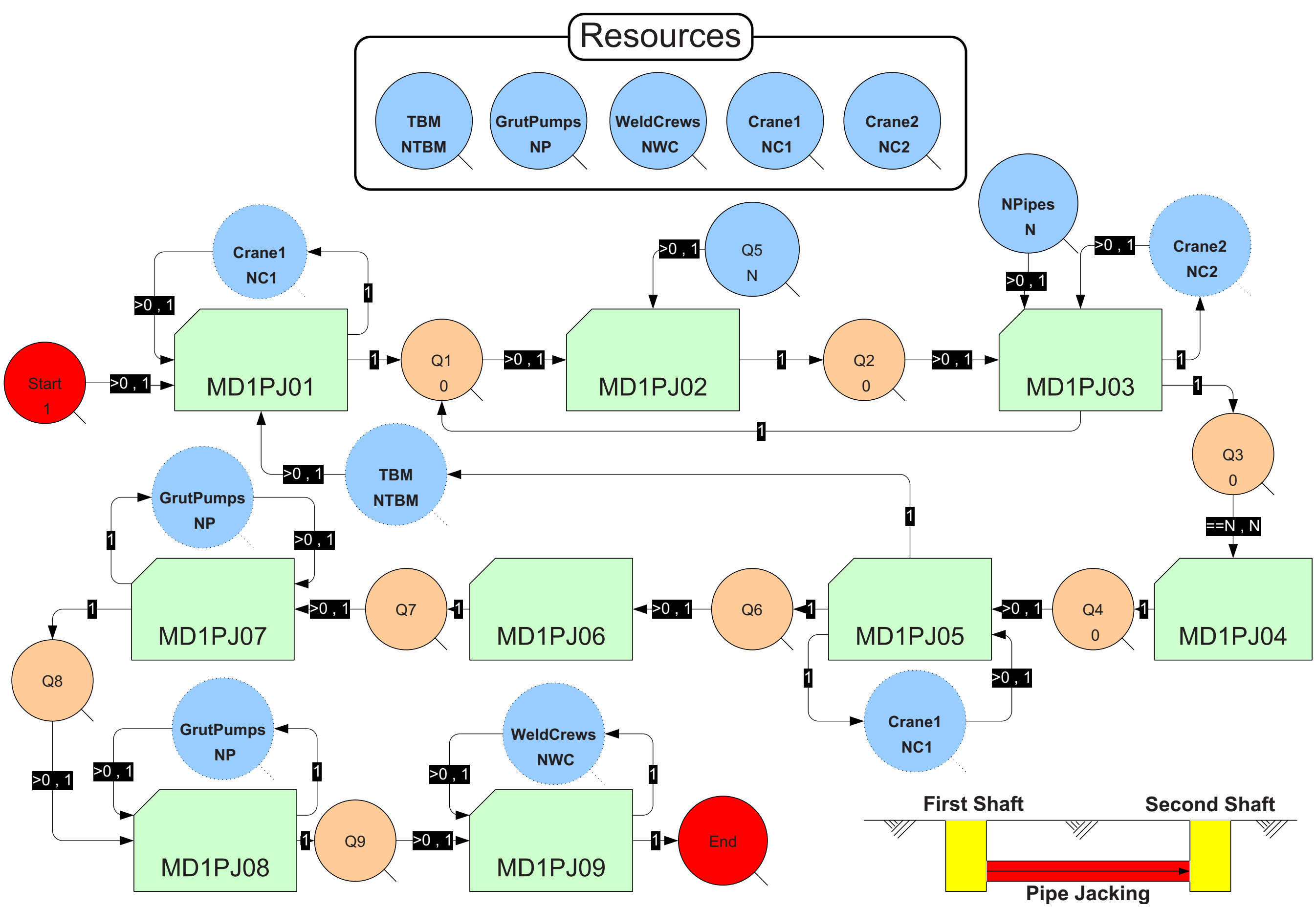

Fig. 8. Simulation model for slurry mechanical excavation

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Table 3. Tasks Involved in Dissembling Equipment and Finishing Tunnel Process

MD1PJ05	
Dissembling equipment	
Resources	TBM, crane1, and dummy queues
Start condition	It draws one resource from crane1 queue, and another one resource from dummy queue named "Q4"
Finish	It sends one resource to each of the following: crane1 queue, TBM queue, and dummy queue named "Q6"
MD1PJ06	
Clean the tunnel	
Resources	Dummy queue
Start condition	It draws one resource from dummy queue named "Q6"
Finish	It sends one resource to dummy queue named "Q7"
MD1PJ07	
Grout injection	
Resources	Grouting pump and dummy queues
Start condition	It draws one resource from grouting pump queue and other one resource from dummy queue named "Q7"
Finish	It returns the drawn resource from grouting pump queue, and sends one resource to dummy queue named "Q8"
MD1PJ08	
Putting material fillers between pipes	
Resources	Grouting pump and dummy queues
Start condition	It draws one resource from grouting pump queue and other one from dummy queue named "Q8"
Finish	It returns the drawn resource from grouting pump queue, and sends one resource to dummy queue named "Q9"
MD1PJ09	
Weld T-lock between pipes	
Resources	Welding crew and dummy queues
Start condition	It draws one resource from welding crew queue and other one from dummy queue named "Q9"
Finish	It returns the drawn resource from welding crew queue, and sends one resource to dummy queue named "END"

volves three processes: construction preparation, wall construction and caisson sinking, and plug construction and ground injection (see Fig. 5). The first process (named construction preparation) is executed by locating the position of shaft using survey. Then, soil excavation is performed to the required depth (1–2 m). After excavating soil, the soil is covered with aggregate layer (0.5–1.0 m) thickness. The second process (named wall construction) is started after placing aggregate layer by setting and welding the cutting edge segments. After that, the first part of wall segments is installed. Once the segments of the first part are installed, the concrete collar can be poured and cured to provide permanent support to the excavation of shaft and acts as a guide for shaft sinking. At this stage, the excavation is started to sink caisson.

The caisson sinks under its own weight in very soft soil. In case of hard soils, it is necessary to use the arms of the hydraulic excavator to exert pressure on the top section. The shaft should be

Table 4. Tasks of Slurry Shafts Construction using Traditional Forms

Process	Task ID	Description
Construction preparation	Shaft201	Survey to locate shaft position
	Shaft202	Excavate the required depth and put of aggregate layer
Wall construction	Shaft203	Set and weld cutting edge segments
	Shaft204	Shuttering inner forms of the wall and outer part above the cutting edge
	Shaft205	Steel work for the wall part above the cutting edge
	Shaft206	Concrete pouring of the wall part above the cutting edge
	Shaft207	Concrete curing
	Shaft208	Concrete pouring for collar
	Shaft209	Concrete curing for collar
	Shaft210	Steel work for the next wall part
	Shaft211	Shuttering forms for the next wall part
	Shaft212	Concrete pouring of the next wall part
	Shaft213	Concrete curing of the next wall part
Caisson sinks and construction of plug	Shaft214	Excavation and caisson sink
	Shaft215	Concrete pouring of plug under water (if exist)
	Shaft216	Concrete curing of plug
	Shaft217	Dewatering for the surplus (if exist)
Ground injection	Shaft218	Injecting of cement grout around the shaft (if required)

checked for accuracy of sinking by using a spirit level or plumb line. Adjustments can be made by applying pressure to the highest point. Selective excavation of ground helps to control sinking. A bentonite pump may be used to lubricate the surface between the concrete segments and ground by injecting bentonite between them. Excavation should proceed and caisson segments are added until the required depth is reached. Once the bottom segments reach the required depth, the concrete plug can be poured and cured. After curing of concrete plug, the water can be pumped out to get a dry caisson. The final process (named ground injection) is executed only in weak soil to increase the bearing capacity of soil, or to provide a firmer soil in beginning the construction of the tunnel.

Proposed Tool

The proposed tool aids contractors in planning microtunneling projects by estimating the total cost and duration of construction. It consists of two main components: microtunnel analyzer module and simulation module. The tool is coded in a computer system using MS Visual Basic 6.0 to assure the connectivity among its components. The following sections describe the main components of the proposed tool.

Microtunnel Analyzer Module

Microtunnel analyzer module is considered the planning unit of the proposed tool. It is responsible for entering and processing

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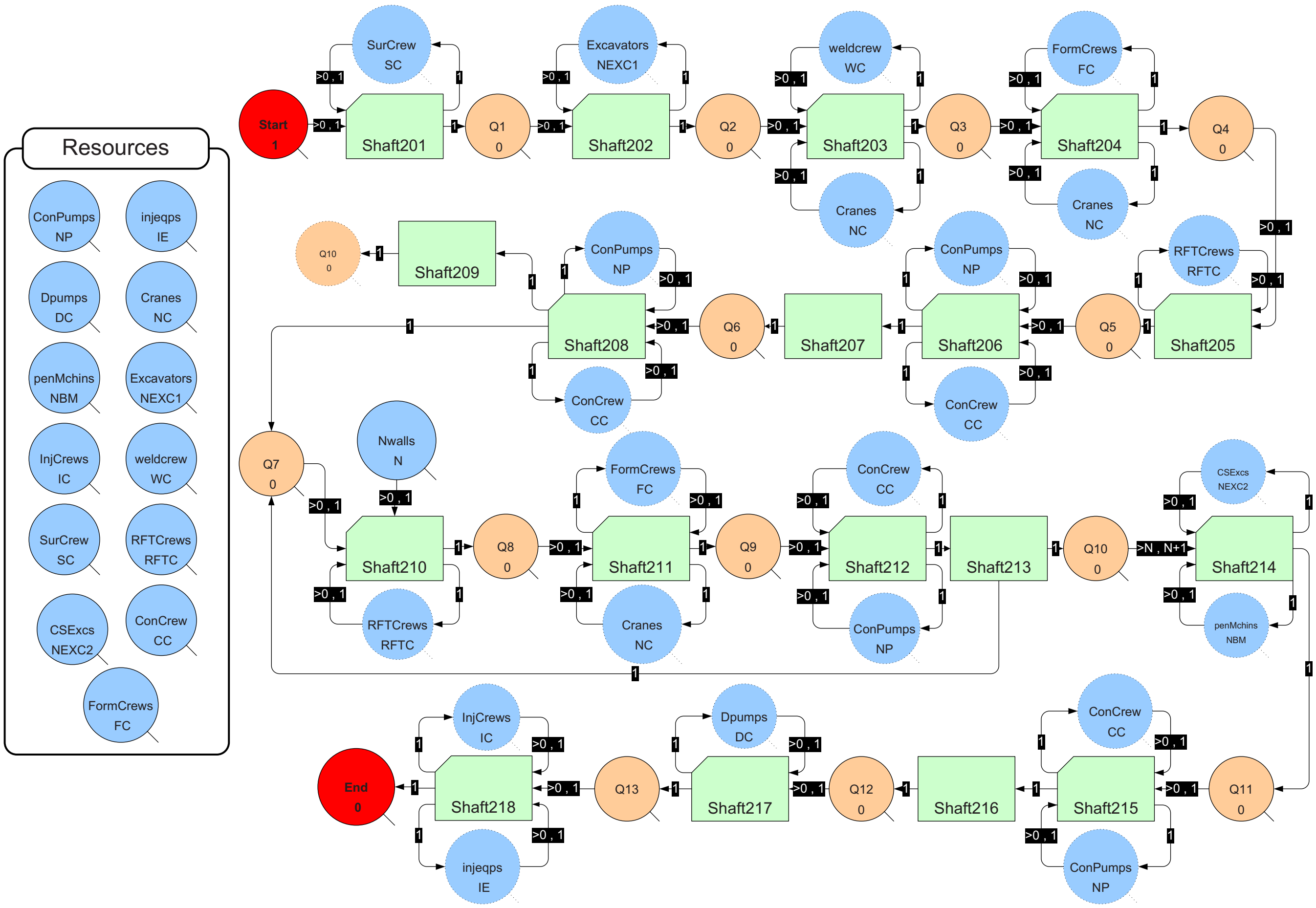

Fig. 9. Simulation model for shafts construction using traditional forms

data, and it exports the results of the tool. This is performed by analyzing and breaking down microtunneling projects into zones that consist of a number of shafts and microtunnels' segment. The module provides three techniques for construction of microtunneling using pipe-jacking: manual excavation, mechanical excavation, and slurry mechanical excavation. Also, it provides three techniques for construction of shafts using: traditional forms, slip forms and precast concrete segments. Microtunneling projects are broken down into zones, taking into consideration the following aspects:

1. Used construction method;
2. Assigned resources in each zone are independent of the other zones (e.g., resources might be assigned differently for each construction location even for the same construction method); and
3. Construction sequence and logic.

The processes that are followed by microtunnel analyzer module to perform a planning session for a microtunnel can be summarized as follow:

1. Define general data for the project such as: number of working hours per day, number of working days per week, project start date, number of zones in the project, and indirect cost of the project;
2. Define shafts data and their associated construction method(s) such as: tasks' duration, available resources, labors and equipments rates, and materials costs;
3. Define the microtunnel construction method in each zone and its associated data such as: tasks' duration, available resources, labors and equipments rates, materials costs, and number of simulation runs. The module allows the use of 10 probability distributions to estimate tasks' duration: beta, erlang, exponential, gamma, normal, pert, pertpg, scaled beta, triangular, and uniform;
4. Trigger simulation module to estimate the duration and resources utilization for each zone. Then, simulation data are sent to tunnel analyzer module in order to calculate project execution time and cost; and
5. Export outputs in a form of cost, duration, and utilization of resources.

Fig. 6 shows a flowchart of the processes that are followed by microtunnel analyzer module. It is worth to note that project cost is estimated based on labors and equipments utilization, materials costs, and indirect costs. While project duration is calculated, depending on the relationship between shafts and microtunnels zones, shafts duration and zones' duration.

Simulation Module

The simulation module is responsible for estimating duration and utilization of resources in each shaft and microtunnel segment in the project. It utilizes STROBOSCOPE as a general purpose simulation engine (Martinez 1996). It is implemented using Microsoft Visual Basic 6.0 to control and facilitate data flow from/to STROBOSCOPE simulation engine. Six simulation modules have

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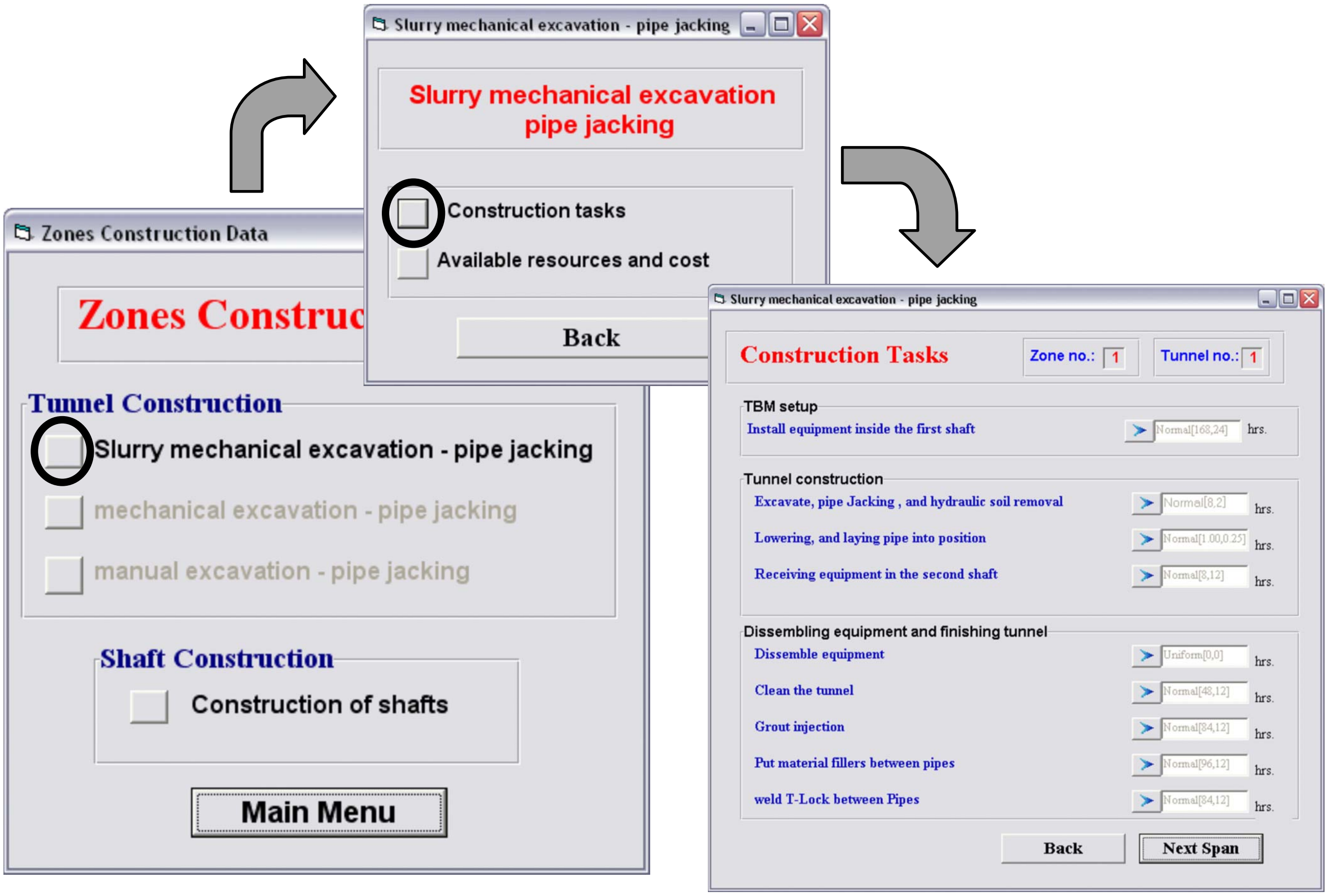

Fig. 10. Tasks screen of slurry mechanical excavation

been coded and developed to represent methods of construction for shafts and microtunnel segments (see Table 1). These simulation models were built based on the sequence of construction and adopting the elements of STROBOSCOPE simulation language. Fig. 7 illustrates the interaction between microtunnel analyzer module and simulation module which is performed as follows:

1. Simulation module receives project data from microtunnel analyzer module, then, it depicts the model(s) that represents the construction method(s) for each zone from models that are stored in simulation module's library. Subsequently, each model is fed by its data (general data, tasks' duration, available resources, and number of runs) to generate simulation model(s) that represents the project under consideration;
2. STROBOSCOPE is triggered to run the generated model(s) in order to get the total duration and utilization of resources for each zone; and
3. The output data are transferred to microtunnel analyzer module to perform the calculations of total project duration and total cost.

Slurry mechanical excavation is one of the most common techniques that is used in construction of microtunneling for its high advancement rate, full control on tunnel construction by the control chamber, highest level of safety for the personnel, and least impact to the surface structures. It involves three processes with nine tasks. Fig. 8 depicts the simulation model for construction of pipe-jacking microtunnels using slurry mechanical excavation. The first process, named site setup, involves one task called "Install equipment inside the first shaft." This activity starts by drawing one resource from each of the following: crane1 *queue*, TBM queue, and *dummy queue* named "start." At finish, it returns the drawn resource from crane1 queue, and sends one resource to *dummy queue* named "Q1." The details for the second and third processes are illustrated in Tables 2 and 3.

Shafts construction using traditional forms is one of the techniques that is used in construction of microtunnels' shafts. It involves four processes with 18 tasks. Shafts construction using traditional forms is one of the techniques that is used in construction of microtunnels' shafts. It involves four processes with 18 tasks as listed in Table 4. Fig. 9 depicts the simulation model of shafts construction using traditional forms. Detailed description of the remaining simulation models can be found elsewhere (Abdallah 2008).

Tool Implementation

This section presents the implementation of the proposed tool. The developed program is used to provide an easy graphical user interfaces for contractors to: enter data for STROBOSCOPE simulation engine and estimate project duration and cost. The system runs in Microsoft Windows 98, ME, 2000, or XP. Entering data for microtunnel projects is performed in five steps: project general data, zones' relationships, project zones information, zones construction data, and indirect costs. Project general data includes project start date, number of zones, number of working hours and days, and number of tunnel zones. Zones' relationships indicate the type of relationships between zones; either finish to

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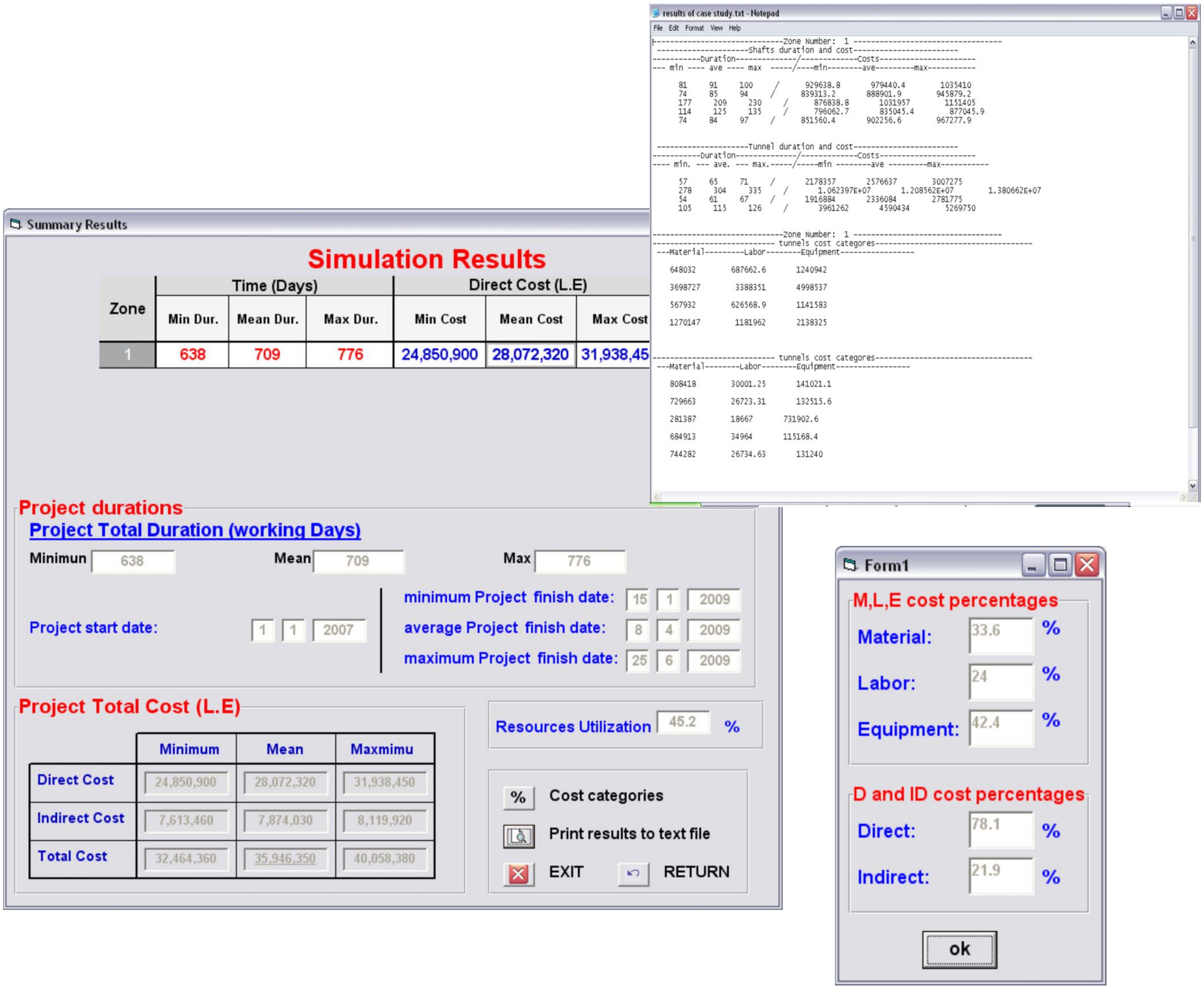

Fig. 11. Results screen for microtunnels tool

start or start to start. Tunnel zones information defines the construction technique for microtunnel segments. Whereas, zones construction data defines tasks durations, available resources and resources' rates. Fig. 10 shows tasks' durations assigned for microtunnel construction using slurry mechanical excavation. Fig. 11 shows the output of the proposed tool.

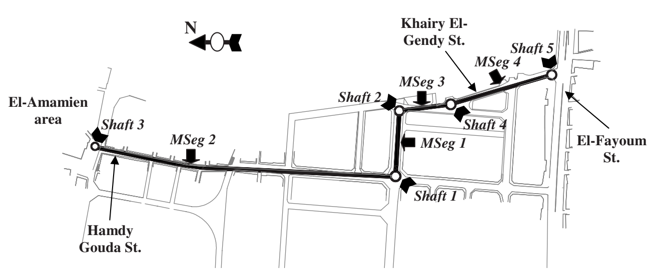

Fig. 12. Layout of Dar El-Salam microtunneling

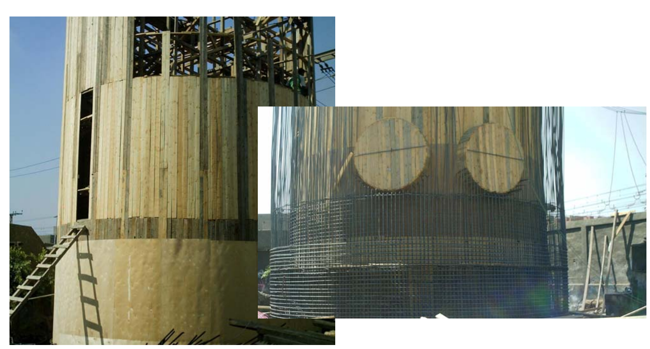

Fig. 13. Execution of traditional forms shafts in El-Salam microtunneling

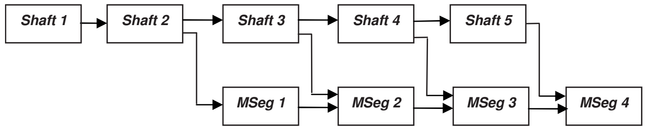

Fig. 14. Construction sequence of shafts and microtunnel segments

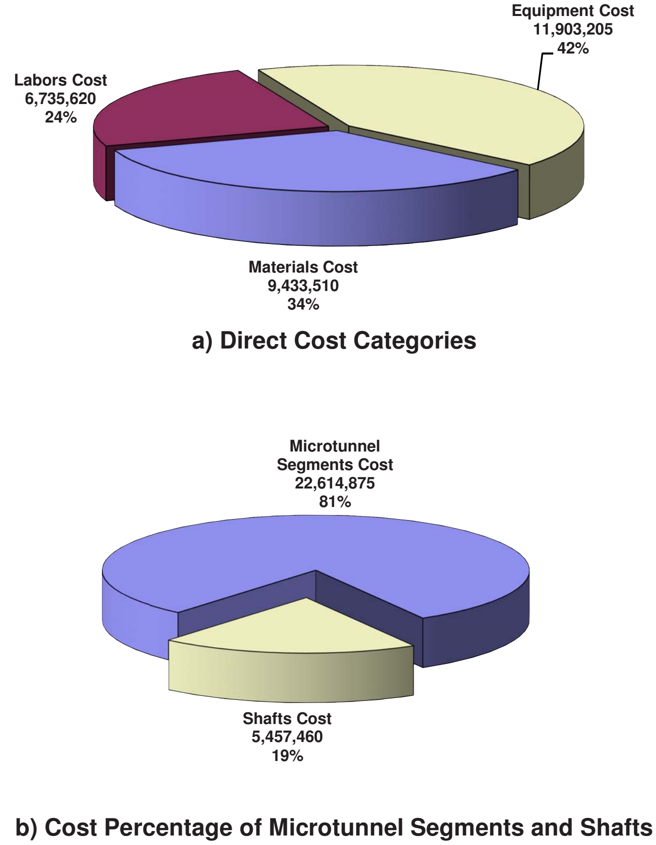

Fig. 15. Cost breakdown of Dar El-Salam microtunnel

Application Example

Case Description

This case study considers the construction of Dar El-Salam (Cairo, Egypt) branch for wastewater which was constructed, adopting microtunneling. It conveys wastewater from El-Fayoum Street to El-Amamien area. It goes through Khairy El-Gendy Street and Hamdy Gouda Street (see Fig. 12). The tunnel has a total length of 692 m and 2,500 mm diameter. The total contract value of this microtunneling branch is 45 million L.E. and it was planned to be executed in three years. The contract scope included the construction and finishing works of Dar El-Salam branch and surveying works for surrounding structures before and after construction. Dar El-Salam branch consists of five shafts and four microtunnel segments. The lengths of the four microtunnel segments; *MSeg 1*, *MSeg 2*, *MSeg 3*, and *MSeg 4* are 77.5, 402, 70, and 142.5 m, respectively. Shafts number 1 and 4 are jacking shafts while the remaining shafts (2, 3, and 5) are receiving shafts. The construction of shafts was executed using slip forms for Shafts Number 1, 2, and 5 and traditional form method for Shafts Number 3 and 4. The four microtunnels segments are constructed using slurry mechanical excavation. The execution of microtunnel segment and shafts of Dar El-Salam microtunneling is depicted in Figs. 1 and 13, respectively.

Case Modeling

First, the general data of the project is defined including working hours per day and working days per week which are 12 h and 6 days, respectively. The sequence of construction for the five shafts and the four microtunnel segments (*MSeg*) is shown in Fig. 14. Tasks involved in the construction of the four microtunnel segments are represented according to the sequence of work described before, i.e., for MSeg 1, the duration for dismantling MTBM is considered zero as it is used for construction of MSeg 2. Also, the duration for installing MTBM components and site setup is less than MSeg 1 as machines already installed in *Shaft 1*. Site setup durations are considered the same for MSeg 3 and MSeg 4. Table 5 lists the duration of tasks that are involved in the construction of microtunnel segments. It is worth to note that the construction of wall in *Shaft 3* and *Shaft 4* are divided into four parts. Tables 6 and 7 list tasks' durations of shafts involved in Dar El-Salam branch. Subsequently, the available resources and their respective rates are user defined to calculate the direct costs of Dar El-Salam microtunnel. The indirect costs are entered to the tool in two forms: time dependent and time independent indirect cost. Table 8 lists indirect cost items that are considered in the case under consideration.

Table 5. Duration of Microtunnel Segments' Tasks

		Duration			
Process	Task description	MSeg 1	MSeg 2	MSeg 3	MSeg 4
TBM setup	Install equipments inside the first shaft	$N[14,2]d$	$N[9,1]d$	$N[14,2]d$	$N[9,1]d$
Microtunnel construction	Excavate, pipe-jacking, and hydraulic soil removal	$N[8,2]h$	$N[8,2]h$	$N[8,2]hr$	$N[8,2]h$
	Lowering and laying pipe into position	$N[60,15]m$	$N[60,15]m$	$N[60,15]m$	$N[60,15]m$
	Receiving equipment in the second shaft	$U[8,12]h$	$U[8,12]h$	$U[8,12]h$	$U[8,12]h$
Dissembling and finishing	Dissemble equipments	—	$N[14,2]d$	—	$N[14,2]d$
	Clean the tunnel	$N[4,1]d$	$N[20,5]d$	$N[4,1]d$	$N[7,2]d$
	Grout injection	$N[7,1]d$	$N[35,5]d$	$N[7,1]d$	$N[13,2]d$
	Putting material fillers between pipes	$N[8,1]d$	$N[40,5]d$	$N[7,1]d$	$N[15,2]d$
	Welding T-lock between pipes	$N[7,1]d$	$N[35,5]d$	$N[7,1]d$	$N[13,2]d$

Note: $U[N1,N2]$: U: uniform distribution, $N1$: lower limit, $N2$: upper limit; $N[N1,N2]$: N: normal distribution, $N1$: average duration, $N2$: SD; d: days, h: hours, m: minutes.

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Table 6. Tasks Duration for Shafts using Slip Forms

Process	Task description	Duration		
		Shaft 1	Shaft 2	Shaft 5
Construction preparation	Survey to locate shaft position	$U[2,3]h$	$U[2,3]h$	$U[2,3]h$
	Excavate the required depth and putting of aggregate layer	$N[8,2]d$	$N[7,2]d$	$N[7,2]d$
Wall construction	Set and weld cutting edge segments	$N[8,1]d$	$N[7,1]d$	$N[7,1]d$
	Slip formwork for the wall part above the cutting edge	$N[8,1]d$	$N[7,1]d$	$N[7,1]d$
	Steel work for the wall above the cutting edge	$N[4,1]d$	$N[4,1]d$	$N[4,1]d$
	Concrete pouring of the wall part above the cutting edge	$U[10,12]h$	$U[9,11]h$	$U[9,11]h$
	Concrete curing of the wall part above the cutting edge	$N[7,0]d$	$N[7,0]d$	$N[7,0]d$
	Concrete pouring for collar	$U[8,12]h$	$U[7,11]h$	$U[7,11]h$
	Concrete curing for collar	$N[7,0]d$	$N[7,0]d$	$N[7,0]d$
	Jacking the slip form, steel work, concrete pouring, and concrete curing for the wall	$N[16,2]d$	$N[14,2]d$	$N[14,2]d$
	Concrete curing for the last wall part and removal of forms	$N[4,0]d$	$N[4,0]d$	$N[4,0]d$
Caisson sink and plug construction	Excavation and caisson sink	$N[30,2]d$	$N[30,2]d$	$N[30,2]d$
	Concrete pouring of plug	$N[12,2]h$	$N[12,2]h$	$N[12,2]h$
	Concrete curing for plug	$N[1,0]d$	$N[1,0]d$	$N[1,0]d$
	Dewatering for the surplus (if exist)	$N[10,2]h$	$N[10,2]h$	$N[10,2]h$

Note: $U[N1,N2]$: U: uniform distribution, $N1$: lower limit, $N2$: upper limit; $N[N1,N2]$: N: normal distribution, $N1$: average duration, $N2$: SD; d: days, h: hours, m: minutes.

Case Analysis

Once the case data are feed to the system, it simulates Dar El-Salam microtunnel segments and shafts. The system retrieves simulation module outputs to perform time and cost calculations. Simulation module provides minimum, mean, maximum duration for each microtunnel segment and shaft, in addition to resources' utilization. The system estimated the mean direct and indirect costs to be 28,072,335 and 7,874,030 L.E., respectively. The mean total cost was estimated to be 35,946,365 L.E. The mean expected total duration of the project is 709 working days which is equivalent to 828 calendar days. Table 9 shows (shortest, mean, and longest) duration, (minimum, average, and maximum) project cost of the four microtunnel segments and five shafts. Table 10 shows the shortest, mean, longest duration, minimum, average, and maximum project cost categories of Dar El-Salam wastewater branch. The system generates a text output file that includes a detailed description of each microtunnel segment and shaft. Also, the file includes the materials, labors, and equipments costs for

Table 7. Tasks Duration for Shafts using Traditional Forms

Process	Task description	Duration	
		Shaft 3	Shaft 4
Construction preparation	Survey to locate shaft position	$U[2,3]h$	$U[2,3]h$
	Excavate the required depth and putting of aggregate layer	$N[1800,0]d$	$N[8,2]d$
Wall construction	Set and weld cutting edge segments	—	$N[8,1]d$
	Shuttering inner forms of the wall and outer part above the cutting edge	—	$N[8,1]d$
	Steel work for the wall part above the cutting edge	—	$N[4,1]d$
	Concrete pouring of wall part above the cutting edge	$U[10,12]h$	$U[10,12]h$
	Concrete curing of wall part above the cutting edge	$N[2,0]d$	$N[7,0]d$
	Concrete pouring for collar	—	$U[8,12]h$
	Concrete curing for collar	—	$N[7,0]d$
	Steel work for the next wall part	$N[5,1]d$	$N[5,1]d$
	Shuttering forms for the next wall part	$U[1,2]d$	$U[1,2]d$
	Concrete pouring of the next wall part	$U[10,12]h$	$U[10,12]h$
	Concrete curing of the next wall part	$N[7,0]d$	$N[7,0]d$
Caisson sink and plug construction	Excavation and caisson sink	—	$U[25,30]d$
	Concrete pouring of plug under water (if exist)	—	$N[12,2]h$
	Concrete curing of plug	—	$N[1,0]d$
	Dewatering for the surplus (if exist)	—	$N[10,2]h$

Note: $U[N1,N2]$: U: uniform distribution, $N1$: lower limit, $N2$: upper limit; $N[N1,N2]$: N: normal distribution, $N1$: average duration, $N2$: SD; d: days, h: hours, m: minutes.

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Table 8. Indirect Cost Items of Dar El-Salam Microtunnel

Category	Indirect cost Items	Rate/Amount
Time dependent indirect cost (L.E./day)	Site staff salaries	1,840
	Site offices	180
	Field services	180
	Land renting	95
	Site equipments	1,100
	Main office administration	180
	Site operation	95
	Others	0
	Total	3,670L.E./day
Time independent indirect cost (L.E.)	Mobilization	260,000
	Field offices	260,000
	Field services	260,000
	Roadways	524,000
	Construction camp	260,000
	Consultant	524,000
	Sales and taxes	1,300,000
	Insurance	260,000
	Bank expenditures	524,000
	Others	1,100,000
	Total	5,272,000L.E.

each microtunnel segments and shaft in the project. It should be noted that equipment represents a sizable portion with respect to the remaining direct cost components (labor and materials) as shown in Fig. 15(a). This is attributed to the high cost of MTBM that is used in construction of microtunnels. Microtunnel segments cost represents 81% of the direct cost while the remaining 19% represents the direct cost needed for the construction of shafts [see Fig. 15(b)].

Conclusions

Microtunneling construction is characterized by complexity, repetitive operations, difficult construction environment, and different construction techniques. These characteristics lead to uncertainty in the estimated duration and cost. This paper presented a tool that aids contractors in planning of microtunneling projects using computer simulation. The proposed tool estimates duration and cost required for construction of microtunnels. It provides three methods for construction of microtunnels using pipe-jacking techniques: manual excavation, mechanical excavation, and slurry mechanical excavation. Also, it provides three methods for construction of microtunneling shafts: traditional forms, slip forms, and precast concrete segments. The paper provided an overview of the tool components: microtunnel analyzer module and simulation module. Microtunnel analyzer module is considered the planning unit of the proposed tool. It analyzes and breaks down microtunneling projects into zones that consist of a number of shafts and microtunnels' segments according to used construction method, assigned resources, and construction sequence. The simulation module is responsible for estimating duration and utilization of resources in each shaft and microtunnel segment in the project. It utilizes STROBOSCOPE as a general purpose simulation engine. Six simulation modules have been coded and developed to represent methods of construction for shafts and microtunnel segments. A case study of Dar El-Salam branch wastewater microtunnel was presented in order to demonstrate the important features of the proposed tool and its capabilities in the planning of microtunneling.

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Table 9. Durations and Costs of Microtunnel Segements and Shafts

Type	ID	Shortest duration (days)	Mean duration (days)	Longest duration (days)	Minimum direct cost (L.E.)	Average direct cost (L.E.)	Maximum direct cost (L.E.)
Microtunnel segement	1	59	66	74	2,280,020	2,705,880	3,266,110
	2	282	304	331	11,284,250	12,620,760	14,374,780
	3	53	60	69	2,010,830	2,399,315	2,887,835
	4	101	114	124	4,232,920	4,888,920	5,539,290
Shafts	1	80	90	97	1,010,610	1,064,620	1,122,040
	2	79	85	96	918,510	969,525	1,044,765
	3	177	208	231	1,163,820	1,363,285	1,531,180
	4	116	125	132	1,024,360	1,073,450	1,120,315
	5	77	86	96	925,590	986,580	1,052,140

Table 10. Cost and Duration of Dar El-Salam Microtunnel

Shortest duration (days)	Mean duration (days)	Longest duration (days)	Cost type	Minimum cost (L.E.)	Average cost (L.E.)	Maximum cost (L.E.)
638	709	776	Direct	24,850,910	28,072,335	31,938,455
			Indirect	7,613,460	7,874,030	8,119,920
			Total	32,464,370	35,946,365	40,058,375

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