This is to certify that the
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Productivity analysis of microtunneling pipe installation using
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Yu Luo

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PRODUCTIVITY ANALYSIS OF MICROTUNNELING PIPE INSTALLATION USING SIMULATION

By

Yu Luo

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ABSTRACT

PRODUCTIVITY ANALYSIS OF MICROTUNNELING PIPE INSTALLATION USING SIMULATION

By

Yu Luo

Microtunneling is a construction method in the family of trenchless technology, which is used to install underground utilities with minimum impacts on ground surface. Microtunneling is a complex operation that requires the integration of several systems, a variety of supporting equipments and experienced personnel, and is heavily influenced by subsurface conditions. The use of this technology is increasing as the underground infrastructures become more complicated and denser. As a result, the need to better understand the operations involved becomes crucial to improve planning, cost estimating, resource selection, and productivity. Simulation can be used to study microtunneling operations before they are actually performed, thereby identifying problems at the different stages of the project. Simulation can be used to aid in the decision-making process to control costs and shorten project duration. The objective of this research is to analyze and to evaluate the factors that affect the productivity in microtunneling operations. For this purpose, an actual microtunneling project was selected. Based on the data collected from the project, this research developed a CYCLic Operations NEtwork (CYCLONE) model with highlight on the impact of variations in soil compositions on the productivity of the operation. Simulations were repetitively conducted with different soil compositions. The results were used in a regression analysis to find a function of productivity and soil compositions. Various combinations of resource utilization were also simulated with the model to optimize the productivity.

This Thesis Is Dedicated To My Wife Huixia For Her Love, Affection,

And Encouragement To Successfully Complete The Graduate Study,

And

To My Parents For Their Encouragement And Continued Support

Throughout My Entire Education

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1 INTRODUCTION

1.1 Overview

The development of underground infrastructure, environmental concerns and economic trends are influencing society resulting in the advancement of technology for more efficient and cost-effective utility installation, maintenance, repair and renewal (Allouche et al. 2003). Trenchless methods can be classified under two main categories which are new pipeline construction, and pipeline renewal (Najafi, 2005). This research focuses on microtunneling, one of the many methods and the fastest growing method in new pipeline installation category.

Microtunneling was spawned in Japan in the early 1970s and eventually spread to Europe before landing in the United States. Growth was slow throughout its first decade in the U.S., going from about 10,000 ft pipeline installation in 1986 to about 55,000 ft in 1994. The use of microtunneling in the United States really took off in 1995 at the height of the Greater Houston Wastewater Program. That year saw a two-fold increase in installed footage from the year before, going from 55,000 ft in 1994 to more than 110,000 ft in 1995 (Figure 1.2). Today, more than 1 million ft of pipe has been installed in the United States by microtunneling (Rush 2004). The advantage of microtunneling is it can be performed in a highly urban environment with a low risk of injury and less potential for settlement and resulting damage to structures and roads.

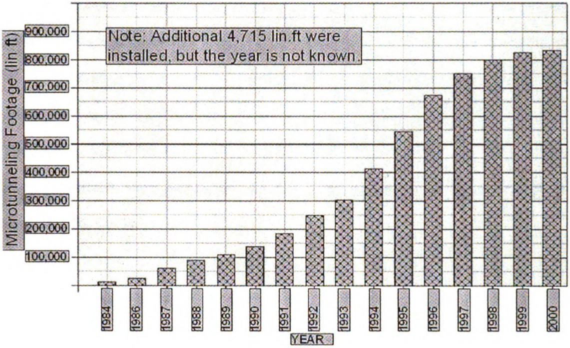


Figure 1.1 -Cumulative Microtunneling Footage in the USA and Canada as of March 2000 (Source: Trenchless Technology Center, Louisiana Tech University)

To better understand microtunneling operations, variety of research methods have been approached. Among them, a full-scale field test was conducted at Louisiana Tech University in June 1992. The main purpose was to investigate the capability of a microtunneling propulsion system called “LLB” (Laying pipes of Low Bearing force) to install a polyvinyl chloride (PVC) pipe in a range of soil conditions.

Highlights of the test included use of PVC pipe and microtunneling in four different types of lab selected soil conditions. Traditionally, the types of usable pipes for microtunneling have been limited, because the jacking force is directly exerted on the pipe itself, making it necessary to have a sufficient strength of the pipe to resist that force. This excluded a wide variety of pipe materials with excellent corrosion and hydraulic characteristics but low end-bearing strength, such as polyvinyl chloride (PVC) from microtunneling operation. Since a major portion of costs for microtunneling is the cost of thick-wall pipe to resist axial jacking loads, utilization of less expensive pipes would make microtunneling more cost competitive with open-trench construction (Nido et al. 1999). The LLB system developed by Kidoh Construction Company of Osaka, Japan, is aimed to enable microtunneling machines to install a wide variety of less expensive, thin-wall pipes (Najafi, 1993).

The field test included construction of the test bed with four types of soils, construction of drive and receive shafts, conducting testing operation and evaluation of results. The field test was focused on jacking force acting on the pipe and longitudinal and circumferential deflection of the pipe after installation. However, procedures of the microtunneling operation and associated data as activity cycle times, production rates, joint installation method, and soil friction factors were reported, which provided an opportunity for a thorough study on the productivity of microtunneling operation with PVC pipe and in variety of soil conditions.

1.2 Problem and Need Statement

Microtunneling is a complex operation that requires the integration of several systems, a variety of supporting equipment and experienced personnel. The uses of microtunneling methods for underground pipeline installation is increasing as this technology can significantly minimize the social and environmental impacts related to the traditional open-trench method of conduit construction. At the same time, microtunneling has proven to be a cost-effective means of new subsurface infrastructure construction. This cost-effectiveness is apparent in both the direct costs of the construction and reduced social costs, and increases in intangible benefits (Bhavani, 2004). Furthermore, utilization of thin-wall pipe in microtunneling will potentially decrease the cost and increase competitiveness. As a result, the need to better understand the operations involved becomes crucial for improved planning, estimating and resource selection (Nido et al. 1999).

Computer simulation can be used to study microtunneling operations before they are actually performed. For the repetitive nature of microtunneling operation, data collected from the site can be input to well designed simulation model to repeat the operation in computer thousands of times, which will be impossible in real world. The big amount of data generated from simulation can magnify any inefficiency of resource used in the operation to easily identify problems at different stages of the project. The model can be modified to include possibilities of soil compositions and simulate corresponding productivity. Therefore, the statistical relationship between soil composition and microtunneling productivity can be studied.

1.3 Goal and Objectives

The main goal of this study is to analyze and to evaluate the factors that affect the productivity of microtunneling operation, thereby to refine the microtunneling process and optimize productivity. In addition, the relationship between different soil conditions and microtunneling productivity will be studied. In order to analyze microtunneling technology an actual project was chosen, the data was collected at the Louisiana Tech University LLB Microtunneling Field Test Project in Ruston, Louisiana. The operation analysis will be performed using simulation based on the CYCLONE methodology. Specifically, the research has following objectives:

1. Portray the process of microtunneling operation, identify resources,
2. Develop the model for simulation,
3. Analyze the production cycle data and find statistical distributions,
4. Input the distribution data in the model and run simulation with WebCYCLONE,
5. Compare the simulated productivity results with actual observations at the project, and modify the model if necessary,
6. Perform sensitivity analysis by varying resource assignments, to measure their effects on the operation's productivity and find the optimization,
7. Enhance CYCLONE model with consideration of soil compositions,
8. Run simulation with variety of soil compositions to obtain corresponding productivity and
9. Study of the correlation between soil composition and microtunneling.

1.4 Methodology

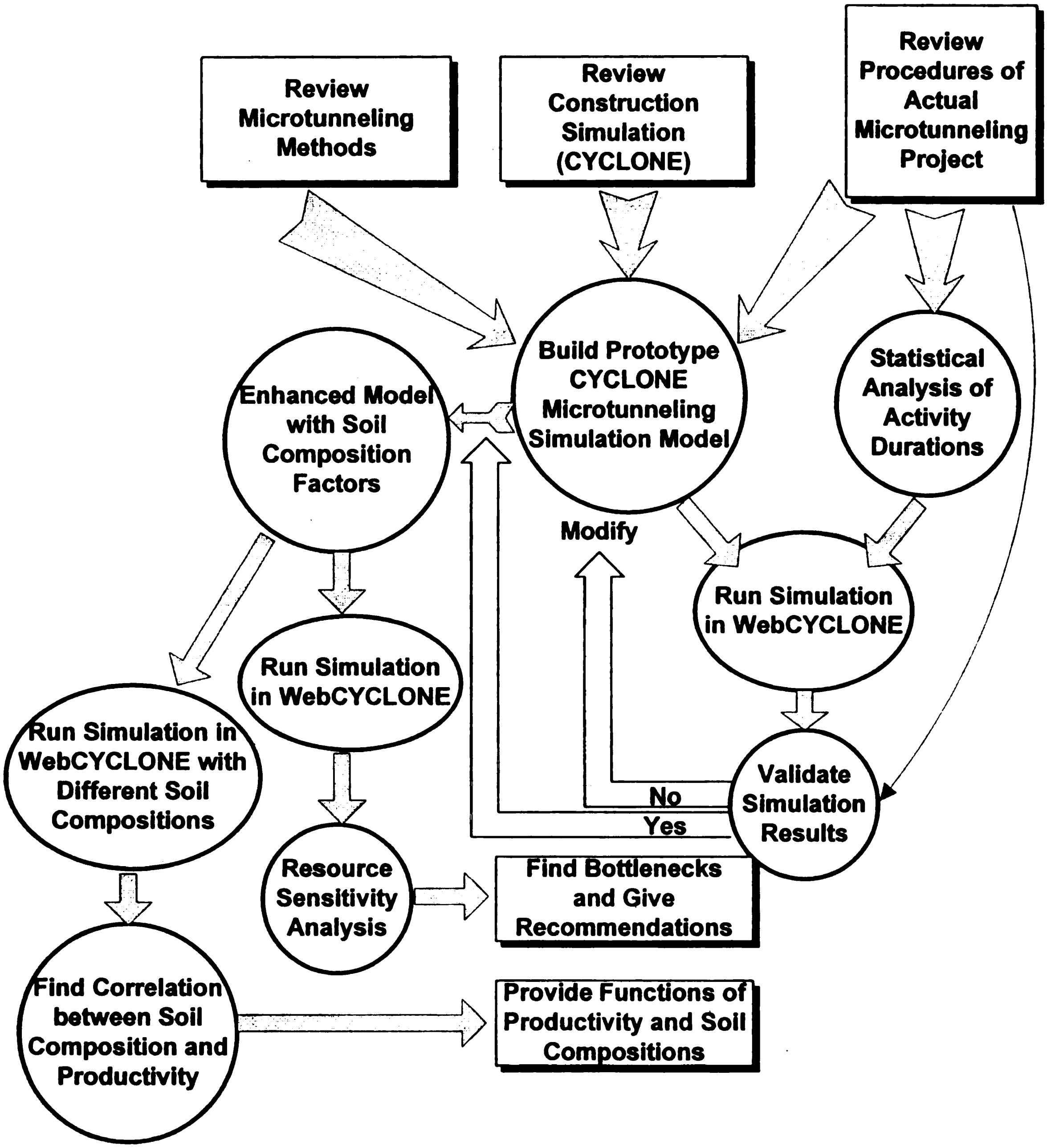


Figure 1.2 -Flowchart of the Thesis Study

As illustrated in Figure 1.2, this study consists of several steps. At first, overviews on microtunneling methods in general and the candidate project in specific, and construction simulations are presented. Upon finishing reviews, a prototype simulation model with

CYCLONE methodology is developed, which need inputs from the project procedures and collected duration data. The candidate project data collected on site need to be analyzed statistically to find distributions before running simulation in WebCYCLONE software. Prototype model and data distributions input together with resource initialization are coded to run WebCYCLONE simulations. Productivity results from multiple simulations are averaged and validated with actual cycle duration measured from the project. According to the comparison of simulation result and actual data, the model may be adjusted and simulations need to be redone to validate the model.

After validation of the prototype model, the same structure and logic are used with enhancement of soil compositions to build a new model. The enhanced model is coded together with soil condition specified activity duration distribution data into WebCYCLONE simulations. Resource sensitivity analysis is conducted on the simulation results to find bottlenecks on productivity and optimize the operation. Recommendations on streamlining the candidate project in specific and microtunneling operations in general are presented.

In addition, the enhanced model is modified to reflect different soil compositions faced by the microtunneling operation. The productivities simulated with corresponding soil compositions are studied with statistical regression analysis to find any correlations between them. Microtunneling productivity as a function of soil composition is stated in the conclusion of the thesis.

1.5 Scope and Limitations of the Thesis

The scope of this thesis research is limited to the microtunneling productivity study through operational simulation of the LLB microtunneling propulsion system field test, which includes details of simulation model developments, statistical analysis of activity duration data, simulation results validation, sensitivity analysis, soil composition alternatives study with simulation. In addition, background information on microtunneling operation, construction simulation, and soil classifications are presented.

The simulation will be conducted on the cyclic parts of the microtunneling process, including from pipe section preparation to pipe section jacked in place. In mobilization and demobilization stages, activities including digging shafts, hauling MTBM, setting up control console etc. will not be modeled into the simulation due to the non-cyclic nature.

In the candidate project, the microtunneling equipment and PVC pipe installed were both sponsored by manufacturers for scientific research purpose with no monetary charge. Due to the missing cost data of MTBM and pipes, total cost of the microtunneling operation is not considered in the scope of this study. Therefore, productivity optimization will not consider cost factors.

The function of productivity and soil compositions is based on the actual soil samples used in the project. The correlation is highly related to the microtunneling equipment, pipe installed, and soil conditions of the project. It can be considered a general rule, but is not intended to predict productivity in any microtunneling project. Such a goal needs more complete database from variety of microtunneling projects and requires further study.

1.6 Organization of the Thesis

This study consists of six chapters. The first chapter provides a brief introduction to the topic and research proposal statement. The second chapter presents an overview of four closely related topics of existing literature, which include microtunneling operation in general, pipe materials used in microtunneling, soil classifications and properties, the simulation candidate project description, and construction simulation methodologies. The third chapter contributes the simulation models with and without soil factor enhancement. The fourth chapter presents statistical analysis of activity duration data distributions as input of the simulation. The fifth chapter validates and discusses results from simulations, and conducts resource sensitivity analysis to identify resource bottlenecks. Microtunneling operations in different soil conditions are simulated and correlations between productivity and soil composition are in the fifth chapter also. The sixth and final chapter presents the conclusion of the research and recommendations for optimizing the microtunneling operation productivity. Such information can provide an effective tool to assist project managers in making well-informed decisions. Potential future studies will also be suggested.

Appendices include microtunneling glossary, actual duration data collected from the project, codes of two simulation models, and data from simulation results. A list of referenced materials is presented at the end of this study.

2 LITERATURES AND PROJECT REVIEW

The literature review chapter comprises of five sections. The first section reviews the microtunneling methods. The second briefly reviews pipe materials used in microtunneling. The third describes soil classifications and their properties. After background introduction, the simulation candidate project is described in section four. Necessary information for model development can be found in this section. The fifth is the background and brief history of construction simulation, along with popular simulation methodologies introduction. The last section summarizes the literature review.

2.1 Microtunneling Methods

The term microtunneling is used to describe methods of horizontal earth boring which are highly sophisticated. Microtunnel Boring Machines (MTBM's) are laser guided, remotely controlled boring machines which permit accurate monitoring and adjusting of the horizontal and vertical alignment as the work proceeds so that the pipe can be installed on precise line and grade (Iseley and Tanwani, 1992). This method is uniquely suited for the installation of gravity sewer lines where a high degree of accuracy is required.

American Society of Civil Engineers (ASCE, 2001) defines microtunneling as a trenchless construction method for installing pipelines with all following features utilized.

1. Remote controlled – The microtunneling boring machine (MTBM) is operated from a control panel, normally located on the ground surface. The system

simultaneously installs pipe as spoil is excavated and removed. Personnel entry to the tunnel is not required for routine operation.[1]

2. Guided – The guidance system usually refers to a laser beam projected onto a target in the MTBM, capable of installing gravity sewers or other types of pipelines to the required tolerance, for line and grade.[1]
3. Pipe jacked – The process of constructing a pipeline by consecutively pushing pipes and MTBM through the ground using a jacking system for thrust.[1]
4. Continuously supported – Continuous pressure is provided to the face of the excavation to balance groundwater and earth pressures.[1]

2.1.1 Method Description

Microtunneling is a trenchless construction method for installing conduits below ground in a wide range of soil conditions, while maintaining close tolerances to line and grade from the drive shaft to the reception shaft. The microtunneling process is a cyclic pipe jacking process.

Based on the mode of operation, the microtunneling method can be subdivided into two major groups: 1) slurry method and 2) auger method. In the slurry type method, slurry is pumped to the face of the MTBM. Excavated materials mixed with slurry are transported to the driving shaft, and discharged at the soil separation unit above the ground. In an auger type method, excavated materials are transported to the drive shaft by the auger in a casing pipe, and then hoisted to ground surface by a crane. However, since slurry

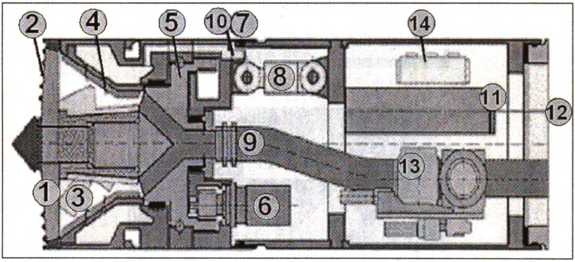
[1] ASCE Standard Construction Guidelines for Microtunneling

microtunneling is more versatile by protecting the tunnel face by slurry pressure (specially under water table and unstable ground), the auger type MTBM is not common in the United States. Because the simulation candidate project used slurry type MTBM, only slurry type microtunneling is reviewed in detail. Both microtunneling systems consist of the following six major components:

1. Microtunnel boring machine (MTBM),
2. Automated spoil transportation and rate of excavation controls,
3. Pipe jacking equipment suitable for the direct installation of the product pipe,
4. Remote control system,
5. Active direction control, and
6. Jacking pipe

2.1.1.1 Slurry Microtunneling Boring Machine (MTBM)

In this method, a rotating cutting head excavates soil mechanically. The rotation of the cutting head can be eccentric or centric, and the speed of rotation (RPM) can be constant or variable. Cutter heads are bi-rotational. The head normally rotates in clockwise direction when looking from the rear of the machine. Reverse rotation can provide more flexibility in overcoming obstructions and difficult ground condition. The spoil excavated at the face is extruded through small parts located at the rear of the MTBM face into the mixing chamber. The main functions of this chamber are to mix the spoil with clean water from the separation system and control hydrostatic head imposed on the MTBM face by a body of water or groundwater. When the spoil and water are mixed to slurry with suitable pumping consistency, typically less than 60% solids, the slurry is transported to the solids separation system hydraulically (Iseley et al. 1999). Figure 2.1 illustrates the inside structure of slurry type MTBM. Drives of up to 1200 ft have been completed in full-face solid granite by MTBM with rock strengths exceeding 20,000psi. Virtually, all ground conditions can be completed with large slurry MTBM.



1. Cutting wheel	8. Steering cylinder
2. Extraction tool	9. Conveyor pipe
3. Crusher space	10. Supply pipe
4. Nozzles	11. ELS target
5. Main bearing	12. Laser beam
6. Rotation drive	13. Bypass
7. Shield articulation seal	14. Valve block

Figure 2.1 -Typical Slurry Type MTBM (Najafi, 2005)

Some pictures of slurry type MTBMs are shown in Figure 2.2, 2.3, and 2.4.

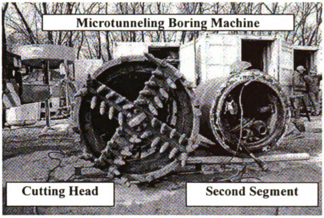


Figure 2.2 - MTBM (Najafi, 2005)

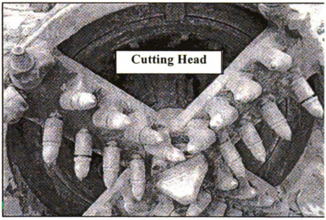


Figure 2.3 - Cutting Head (Najafi, 2005)

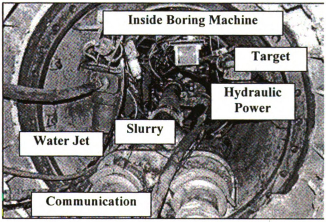


Figure 2.4 - Inside of MTBM (Najafi, 2005)

2.1.1.2 Jacking System

The main jacks are mounted in a jacking frame and are located in the drive (starting) shaft. A jacking frame is shown in Figure 2.5. The jacking frame successively pushes the MTBM along with a string of connected pipes toward a receiving shaft. The jacking capacity of the system must be sufficient to push the MTBM and the string of pipes through the ground. Calculations must be made in advance to determine 1) face excavation forces, 2) frictional forces, and 3) weight of the MTBM and pipes. The jacking equipment installed must have capacity greater than the calculated theoretical jacking load to allow for a safety factor. The hydraulic cylinder extension rate must be synchronized with the excavation rate of the MTBM, which is determined by the soil conditions. Figure 2.6 shows a 42 in steel casing with 20 ft long section that is being jacked.

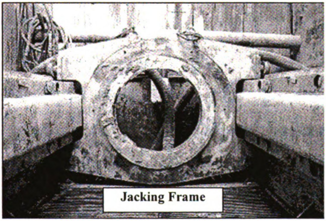


Figure 2.5 - Jacking Frame for Microtunneling (Najafi, 2005)

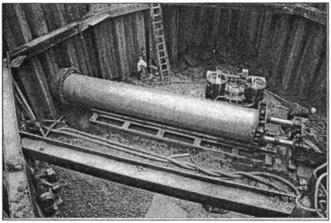


Figure 2.6 - Steel Casing Being Jacked (Najafi, 2005)

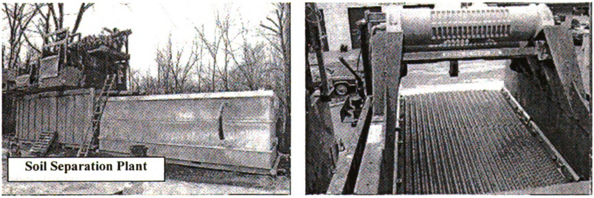
Intermediate jacking stations are usually provided for diameters larger than 900 millimeters (36 inches) and when the calculation of the total jacking force needed to complete the installation exceeds 80 percent of the capacity of the main jacks or the designed working compressive loads allowed for the pipe. The jacking system must develop a uniform distribution of jacking forces on the end of the pipe by the use of spreader rings and packing.

If the calculated jacking forces on the pipe are expected to exceed the pipe design strength with a 2.5 to 1 safety factor, a pipe lubrication system can be utilized. An approved lubricant is injected at the rear of the MTBM and, if necessary, through the pipe walls to lower the friction developed on the surface of the pipe during jacking.

The jacking capacity ranges from approximately 100 tons to over 1,000 tons. The jacking capacity is mainly determined by the length and diameter of the bore and the soil. The soil resistances are generated from face pressure, friction, and adhesion along the length of the steering head and pipe string. The jacking system determines two major factors of microtunneling operation: the total force or hydraulic pressure and penetration rate of pipe. The total jacking force and the penetration rate are critical to control the counterbalancing forces of the MTBM.

2.1.1.3 Automated Spoil Transportation

The spoil is mixed into the slurry in a chamber located behind the cutting head of the MTBM. This mixed material is transported through the slurry discharge pipes and discharged into a separation system. This system is a closed-loop system because the slurry is recycled. The velocity of the flow and the pressure should be carefully regulated because the slurry chamber pressure is used to counterbalance the groundwater pressure. The machine can be sealed off from external water pressure, allowing underwater retrieval. Slurry is a mixture of bentonite (a clay material) in a powder form and water. The bentonite is used to increase the density of water so that it can transport heavy spoil particles. These heavy particles are filtered from the slurry at the separation units. The filtered slurry is sent to storage tanks, which will be recirculated through the system. Figure 2.7 (a) shows the soil separation system. One of the three screens for the separation system is shown in Figure 2.7 (b).



(a) Soil Separation System (b) Screen for Soil Separation System

Figure 2.7 - Soil Separation System (Najafi, 2005)

The system is capable of any adjustment required to maintain face stability for the particular soil condition encountered on the project. The system monitors and continuously balances and ground water pressure to prevent the loss of slurry and/or ground water.

In a slurry spoil transportation system, the ground water pressure is managed by the use of the variable speeds slurry pumps, pressure control valves and a flow meter. A slurry bypass unit is included in the system to allow the direction of flow to be changed and isolated as necessary.

A separation process is provided when using the slurry transportation system. The process is designed to proved adequate separation of the spoil from the slurry so that the clean slurry can be returned to the cutting face for reuse. The type of separation process used is dependent upon the size of the tunnel being constructed, the soil type being excavated, and the space available for erecting the plant.

2.1.1.4 Guidance and Remote Control System

A remote control system is provided to allow for the operation of the system without the need for personnel to enter the microtunnel. The control equipment must integrate the system of excavation and removal of soil and its simultaneous replacement by a pipe. As each pipe section is jacked forward, the control system will synchronize all of the operational functions of the system.

The laser is the most commonly used guidance system for microtunneling. The laser gives the line and grade information for the pipe installation. The laser is installed in the driving shaft and gives a fixed reference point. The laser target and a closed circuit television (CCTV) camera are installed in the MTBM. There should not be any obstruction along the laser beam pathway from the driving shaft to the laser target. There are two types of laser targets: the passive system and the active system. In the passive system, a target grid is mounted in the steering head. The CCTV monitors this target and the information obtained by this CCTV is transferred back to the operator's control panel. The operator can make any steering correction based on the information. In the active system, photosensitive cells are installed on the target and these cells convert information into digital data. Those data are electronically transmitted to the control panel and give the operator digital information of the location. Both active and passive systems are commonly used. Figure 2.8 shows the laser used for the Soltau microtunneling system. The target mounted in the MTBM is shown in Figure 2.9.

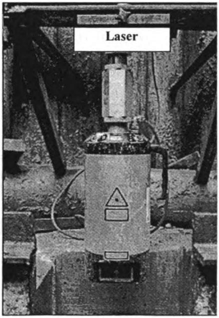


Figure 2.8 - Laser for Guidance of MTBM (Najafi, 2005)

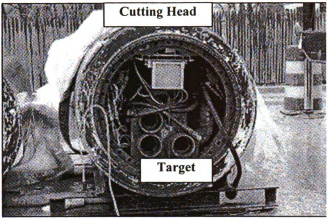


Figure 2.9 - Target Mounted in the MTBM (Najafi, 2005)

Operation boards are usually located in a standard container with 8 by 20 ft dimensions. Operation board consists of control panel, computer and monitor, and a printer. Through the operation board, all the microtunneling operations such as tunneling machine, main jacks, interjack stations, direction and speed of the cutting wheel, and bentonite lubrication equipment, etc. can be controlled. An example of operation board of Soltau Microtunneling is shown in Figure 2.10. The screen of the computer in operation board is presented in Figure 2.11.

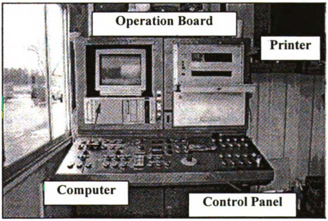


Figure 2.10 - Operation Board of a MTBM (Najafi, 2005)

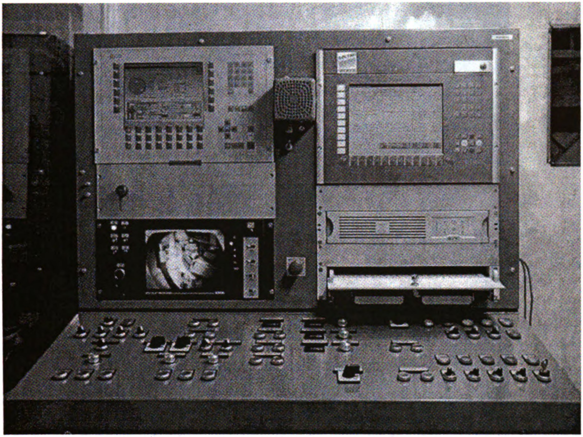


Figure 2.11- Computer Screen (Najafi, 2005)

In addition to the computer monitor, two other monitors are used in the microtunneling operation. One is for communication purpose, and the other one is for monitoring the inside of MTBM. A small camera with microphone is installed at the top of sheet pile at driving shaft, which provides the overview of the operation. The operator in the cabin can see and hear the tunneling site so that he/she can control the equipment based on input from the crews on the site. Another small camera is installed inside the MTBM. This camera provides a view inside the MTBM. These two monitors are shown in Figure 2.12 and 2.13.

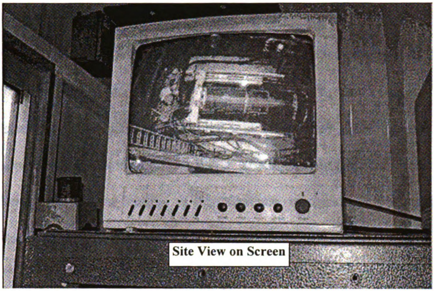


Figure 2.12 - Monitor for Communication (Najafi, 2005)

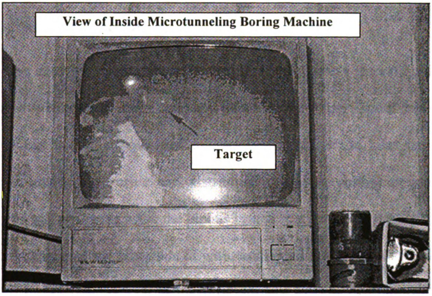


Figure 2.13 - Monitor Showing a View Inside the MTBM (Najafi, 2005)

2.1.1.5 Active Direction Control

Line and grade is controlled by a guidance system that relates the actual position of the MTBM to a design reference, by a laser beam transmitted from the jacking shaft along the centerline of the pipe to a target mounted in the shield. The MTBM is capable of maintaining grade to within ±25 millimeters (±1 inch) and line to within ±38 millimeters (±1.5 inches). The line and grade tolerances are subject to project and ground conditions.

The active steering information is monitored and transmitted to the operation console. The minimum steering information available to the operator on the control console usually includes the position relative to the reference, role, inclination, attitude, rate of advance, installed length, thrust force, and cutter head torque.

2.2 Jacking Pipe Materials Used in Microtunneling

2.2.1 General Requirements

In general, pipe used for microtunneling must be round, have a smooth, uniform outer surface, and with watertight joints that also allow for easy connections between pipes. Pipe lengths must be within specified tolerances and pipe ends must be square and smooth so that jacking loads are evenly distributed around the entire pipe joint and such that point loads will not occur when the pipe is jacked in a reasonably straight alignment. Pipe used for microtunneling is capable of withstanding all forces that will be imposed by the process of installation, as well as the final in-place loading conditions. The driving ends of the pipe and intermediate joints are protected against damage as specified by the manufacturer. The detailed method proposed to cushion and distribute the jacking forces is specified for each particular pipe material. In detail, microtunneling pipe should meet the following general requirements:

1. Circular shape with a flush outside surface (including at the joints)

2. Strength sufficient to withstand both installation loads and the in-place, long term service loads
3. Dimensional tolerances on length, straightness, roundness, end squareness, and allowable angular deflection
4. Durability for the service exposure (internal and external corrosion resistance)
5. Joints capable of the specified level of water-tight performance and transfer of jacking loads between pipes

In microtunneling operation, any pipe showing signs of failure may be required to be jacked through to the reception shaft and removed. The pipe manufacturer's design jacking loads should not be exceeded during the installation process. The ultimate axial compressive strength of the pipe must be a minimum of 2.5 times the design jacking loads of the pipe (Najafi, 1993).

2.2.2 Material Types

At present time the following seven pipe materials specially manufactured for microtunneling operations are available:

1. Ductile iron (DI)
2. Fiberglass-reinforced polymer mortar (RPM)
3. Polymer concrete (PC)
4. Polyvinyl chloride (PVC)
5. Reinforced concrete (RCP)

6. Steel
7. Vitrified clay (VCP)[2]

Pipe installation by microtunneling is most widely done in sewer and drainage applications. The pipes most often jacked in these nonpressure applications include PC, RCP, RPM, and VCP. All of these pipe materials have a substantial microtunneling installation history in sewer applications. Steel pipe, although rarely used in sewers, is routinely installed by jacking and microtunneling for casings and various other structural applications. New methods of joining steel pipe and new coating and lining technology will likely broaden the application of steel pipe to include pressure systems. Microtunneling of pressure pipes was limited before 1998. Materials suitable for this application include DI, RCP, reinforced concrete cylinder pipe, RPM, and steel pipe.

In addition, the newest microtunneling pipe is solid-wall PVC, first installed in the USA in 1997 (ASCE, 2001). The simulation condidate project conducted in Louisiana Tech University, which will be studied in this thesis, unusually installed PVC sewer pipes with special microtunneling equipments in the USA.

2.2.3 Material Selection

Pipe Materials used in microtunneling should be selected base on many factors, including

1. Pipeline operating conditions (pressure – operating, test, transient, and vacuum),

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[2] ASCE Standard Construction Guidelines for Microtunneling

2. Pipeline service environment (fluid, temperature, and corrosivity),
3. External loads (soil loads, surface live loads, and water head),
4. Pipe inside diameter required,
5. Jacking machine (type and diameter), anticipated jacking loads, and drive lengths,
6. Pipe deformation and rebound (during jacking) for plastic/elastic materials,
7. Pipe hydraulic characteristics,
8. Pipe performance capabilities,
9. Pipe availability, reliability, and durability,
10. Life cycle cost.

The following are typical lengths of pipe sections for the different pipe materials (Table 2.2).

Table 2.1 -Typical Lengths Of Pipe Sections Used In Microtunneling (ASCE, 2001)

Material Type	Standard	Available
DI	19.5'	Varies
PC	8'/10' and 1m/2m/3m	3'/6'
PVC	2'/4'/6'	Varies
RCP	7.5' to 24'	Varies
RPM	10'/20'	4'/5'/6.5'/8'
Steel	8'/10'/20'/40'	Any
VCP	4'/6'/8'/10' and 1m/2m/3m	2'/5'

As material costs comprise about half of the total cost of the microtunneling operation (Nido et al. 1999), cost is major concern of pipe selection. Compared to other types of pipe materials available for microtunneling such as reinforced concrete, steel and glassfiber reinforced plastic mortar pipe (GRP), PVC sewer pipe has less unit cost (Najafi, 1993). This is the motivation that the simulation candidate project selected PVC sewer pipe, which is not commonly used in microtunneling.

2.3 Soil Conditions

The most favorable ground condition for slurry microtunneling is wet sand. However, a wide selection of MTBM cutter heads are available that provide the capability to handle a range of soil conditions, including boulders and solid rock. Typically, boulders of 20 to 30 percent of the machine diameter can be removed by microtunneling by crushing the boulders into particle sizes of 1 in and smaller. Table 2.3 presents applicability of slurry microtunneling for different soil conditions.

Table 2.2 -Applicability of Slurry Microtunneling for Different Soil Conditions (Najafi, 2005)

Type of Soil	Applicability
Soft to very soft clays, silt & organic deposits	Yes
Medium to very stiff clays and silts	Yes
Hard clays and highly weathered shales	Yes
Very loose to loose sands (above water table)	Yes
Medium to dense sands (below the water table)	Yes
Medium to dense sands (above the water table)	Yes
Gravels & cobbles less than 2-4 in. diameter	Yes
Soils with significant cobbles, boulders and obstructions larger than 4-6 in. diameter	Marginal
Weathered rocks, marls, chalks and firmly cemented soils	Yes
Significantly weathered to unweathered rocks	No

2.3.1 Soil Classifications

In order to study the impacts of different soil compositions on microtunneling operation using simulation, the subsurface conditions must be classified. Soil classification systems are for the purpose of identifying soils in a systematic manner to determine suitability for use in specific applications based on past experience.

- **Noncohesive and cohesive soils**: If an inherent physical characteristic of the mass of soil grains is that on wetting and/or any subsequent drying, the soil grains stick together so that some force is required to separate them in the dry state, the soil is cohesive. If the soil grains fall apart after drying and stick together only when wet because of surface tension forces in the water, the soil is cohesionless, or noncohesion (Bowles, 1984).

- **Soil Texture**: Soil texture may be defined as the visual appearance of a soil based on a qualitative composition of soil grain sizes in a given soil mass (Bowles, 1984). Large soil particles with some small particles will give a coarse-appearing or coarse-textured soil. A conglomeration of smaller particles will give a medium-textured material, and a conglomeration of fine-grained particles yields a fine-textured soil. It can be observed, however, that lumps of fine-grained materials will give a coarse texture, so we must also relate texture to the state of elemental soil particles. Texture based on visual appearance is often used in soil classification of cohesionless materials such as coarse sand, medium coarse sand and gravel, fine sand, etc. Texture is not used for cohesive soils, since the soil state is a factor in the texture (i.e., lumps can be pulverized).

2.3.2 Soil Classification Common Systems

Soils may be classified in a general way as cohesionless or cohesive, or as coarse- or fine-grained. These terms are too general to provide either a repeatable or reproducible identification of similar soils.

A number of classification systems have been proposed in the past. Table 2.4 illustrates several of the classification systems that have been used.

Table 2.3 –Soil Classification Systems (Bowles, 1984)

Sieve number:		4		200	
Unified	Cobbles	Gravel	Sand	Silt	Clay
Size, mm	76.1	4	0.074	0.002	

In the Louisiana Tech University microtunneling project, only the Unified Soil Classification (USC) System was used for selecting soils. The USC System, which was originally developed for military airfield construction during World War II and subsequently published with wide acceptance resulting, is most widely used system (and internationally) for foundation engineering such as dams, buildings, and underground construction.

In the USC system, those physical properties of use in predicting suitability of a soil as a construction material for fill as in earth dams and levees, for use in building sites as fill, for road fills, and similar are

- Percentages of gravel, sand, and fines – requiring a sieve analysis

- Shape of the grain size distribution curve – may require plotting the sieve analysis data
- Plasticity (WL, WP, and IP) – requiring Atterberg limits

2.3.3 The Unified Soil Classification (USC) System

This system, originally developed for in airfield construction, was reported by Casagrande (1948). It had already been in use since about 1942, but was slightly modified in 1952 to make it apply to dams and other construction.

The principal soil groups of this classification system are given in Table 2.5. As shown in the table under the column heading "Group Symbols," the soils are designated by group symbols consisting of a prefix and suffix. The prefixes indicate the main soil types and the suffixes indicate the subdivisions within groups as follows:

Table 2.4 –Principal Soil Groups in USC (Bowles, 1984)

Soil type	Prefix	Subgroup	Suffix
		Well graded	W
Gravel	G	Poorly graded	P
Sand	S	Silty	M
		Clay	C
Silt	M		
Clay	C	$W_L < 50$ percent	L
Organic	O	$W_L > 50$ percent	H
Peat	Pt		

A verbal description should accompany the classification symbols, e.g., brown, coarse, well-graded sand with trace of gravel, SW. The ASTM D-2487 should be consulted for any requirements for classifying the soil. In general, soils that have the same classifications tend to have the same engineering behavior (Bowles, 1984).

Table 2.5–Descriptions of Group Symbols in USC (Bowles, 1984)

Group Symbols	**Typical Names**
GW	Well-graded gravels, gravel-sand mixtures; little or no fines.
GP	Poorly graded gravels, gravel-sand mixtures; little or no fines.
GM	Silty gravels, poorly graded gravel-sand-silt mixtures.
GC	Clayey gravels, poorly graded gravel-sand-clay mixtures.
SW	Well-graded sands, gravelly sands; little or no fines.
SP	Poorly graded sands, gravelly sands; little or no fines.
SM	Silty sands, poorly graded sand-silt mixtures.
SC	Clayey sands, poorly graded sand-clay mixtures.
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity.
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.
OL	Organic silts and organic silt-clays of low plasticity.
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.
CH	Inorganic clays of high plasticity, fat clays.
OH	Organic clays of medium to high plasticity.
Pt	Peat, muck, peat-bog, etc.

A soil is well graded or nonuniform if there is a wide distribution of grain sizes present, i.e., if there are some grains of each possible size between the upper and lower gradation limits. A soil is poorly graded, or uniform, if the sample is mostly of one grain size or is deficient in certain grain sizes. A beach sand is an example of a uniformly graded soil.

The Unified Soil Classification System defines a soil as:

1. Coarse-grained if more than 50 percent is retained on the No. 200 sieve

2. Fine-grained if more than 50 percent passes the No. 200 sieve

The coarse-grained soil is either:

1. Gravel if more than half of the coarse fraction is retained on the No. 4 sieve
2. Sand if more than half of the coarse fraction is between the No.4 and No. 200 sieve size

The coarse-grained soil is shown in Table 2.7.

Table 2.6 –Coarse-grained Soils (Bowles, 1984)

GW, GP or SW, SP	≤ 5% passes No. 200 sieve
GW-GM, GP-GM, GW-GC, GP-GC or SW-SM, SP-SM, SW-SC, SP-SC	5 < Percent passing No. 200 sieve ≤ 12
GM, GC or SM, SC	> 12 percent passes No. 200 sieve

Classification of coarse-grained soils depends primarily on the grain-size analysis and particle size distribution. A major classification change with a small increase or decrease in the percent passing the No. 4 or No. 200 sieve is another reason why a verbal description is included along with the symbols, i.e., very sandy gravel, very gravelly sand, etc.

Only the sieve analysis and the Atterberg limits are necessary to classify the soil in USC system. A sieve analysis is performed and a plot of the grain-size distribution curve is made. When less than 12 percent passes the No. 200 sieve, it is necessary to obtain C_C and C_U to establish whether the soil is well or poorly graded. When more than 12 percent of the material passes the No. 200 sieve, the uniformity coefficient C_U and the coefficient of curvature C_C have no significance and only the Atterberg limits are used to classify the soil.

2.3.4 Soil Selection in the Candidate Project

The main goal in determining the four different soil types to be used in the project was to obtain a consistent soil so that the effects of different types of soil on LLB microtunneling system could be determined (Najafi, 1993). Although encountering such a soil variety would be probably rare in actual practice for a single microtunneling operation, it was assumed that the results of the microtunneling test could be used for simulation of impacts of similar types of soils so that the performance of the microtunneling LLB system could be predicted for different subsurface conditions. Moreover, the simulation result could add knowledge of different subsurface conditions' impacts on general microtunneling productivity and cost. Therefore, in order to simulate soil materials mostly encountered in real situations, samples of sand, clay, silt, and clayey gravel were selected.

Eleven different soil samples were tested for possible use in the microtunneling project. These included sands, silts, clays, gravels, and various combination of each. Out of these 11 samples, three most desirable for optimum compaction were selected for backfilling in 14,6-meter (48-foot) lengths in the test trench. Each sample was tested for particle size distribution and Atterberg limits so that it could be properly classified (Najafi, 1993).

The soil specimens were prepared for the appropriate tests in accordance with either ASTM D-2217 (Standard Practice for Wet Preparation of Soil Samples for Particle-size

Analysis and Determination of Soil Constants) or ASTM D-421 (Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants).

Particle-Size Analysis. Each of the samples was subjected to a particle-size analysis in accordance with ASTM D-422 (Standard Method for Particle-Size Analysis of Soils). A representative ample was taken from each of the 11 samples. A sieve analysis was conducted on the portion retained on the #10 sieve, while the portion passing the #10 sieve was subjected to hydrometer analysis. After the hydrometer analysis was completed, the specimen was washed over a #200 sieve, and the retained material was dried overnight and subjected to a sieve analysis.

Atterberg Limits Testing. In order to classify the samples containing clay and silt, it was also necessary to conduct tests to determine the Atterberg limits of the samples. The procedures used for finding these limits were in accordance with ASTM D-4318 (Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils). The liquid limit of each sample was found by preparing a representative portion of that sample passing the #40 sieve and testing it in a standard liquid limit device. The plastic limit of each sample was found by rolling a portion of the sample into $\frac{1}{8}$-inch thick threads as required by the standard test. The plasticity index was then found by subtracting the plastic limit from the liquid limit.

Each of the 11 samples was subjected to tests to that it could be properly classified according to the USC system. Table 2.20 is a list of the results of the classification procedures conducted on each of the samples.

Table 2.7 – Soil Classifications in the Candidate Project (Najafi, 1993)

Sample Number	Group Symbol	Group Name
#1	SP	Poorly graded sand
#2	SC	Clayey sand
#3	SP	Poorly graded sand
#4	CL	Sandy lean clay
#5	GP	Poorly graded gravel
#6	CL	Sandy lean clay
#7	SM	Silty sand
#8	CL	Lean clay
#9	CL	Lean clay with sand
#10	SP	Poorly graded sand
#11	GC	Clayey gravel with sand

To select the four samples of sand, clay, silt, and gravel, to be used in the project, sample #7, a grayish brown, very fine material, was chosen as the silt to be used; a combination of samples #8 and #9, which were taken from the jobsite at different depths, was chosen as the best clay sample to used; sample #10, a light brown material, as chosen as the sand to be used; sample #11, a sample of pit-run gravel, a mixture of 19- to 25.4- mm ($\frac{3}{4}$- to 1- inch) top size gravel, sand, and clay, was obtained and chosen as the gravel to be used.

2.4 Simulation Candidate Project Description

2.4.1 Project Location and Soil Profile

For this study, data was collected on the Louisiana Tech University LLB Microtunneling Field Test Project, located in Ruston, Louisiana. This project was conducted in order to evaluate workability of the LLB system in actual field conditions. As a technology transfer project, details of the test were finalized between the LLB system manufacturer-Kidoh Construction Company, Iseki Inc., and Trenchless Technology Center at Louisiana Tech University. A 58.52 meters (192 feet) long test bed was constructed on the Louisiana Tech University campus. An excavation of 43.89 meters (144 feet) in length and 2.13 meters (7 feet) wide and 3.05 meters (10 feet) deep was constructed. It was backfilled with equal sections of clay, silt, sand, and clayey gravel. An additional 14.6-meter (48-foot) section of the test bed was undisturbed stiff clay. The length of each section of the test bed was chosen to be the equivalent of six 2.438-meter (8-foot) pipe sections. The depth of installation was uniformly 2 meters (6.6 feet), which is the minimum requirement for slurry microtunneling method to provide enough pressure to prevent slurry loss. The ground water level was found to be 1.5 meters (5 feet). Figures 2.14 to 2.16 illustrate the test bed construction.

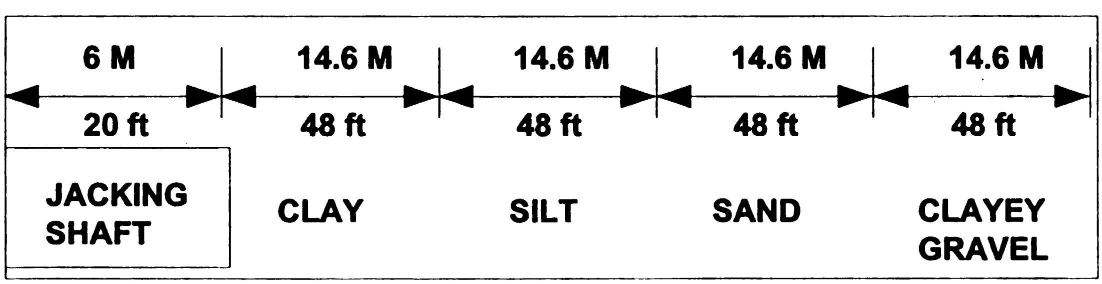


Figure 2.14 – Test Bed Plan (Najafi 1993)

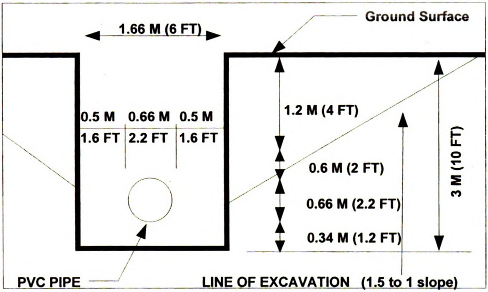


Figure 2.15 – Test Bed Cross Section (Najafi 1993)

Figure 2.16 –Test Bed Construction (Najafi 1993)

2.4.2 Jacking Forces

The jacking forces in this project varied from a range of 9 tf to 14 tf when jacking through clay, from 10 tf to 20 tf when jacking through silt, from 11 tf to 21 tf when jacking through sand, from 23 tf to 41 tf when jacking through clayey gravel. Detailed jacking force information was obtained for 24 of the PVC pipe drives.

2.4.3 Microtunneling Pipes

The project consists of the installation of 58.5 meters (24 drives) of OD 620 mm PVC sanitary sewer pipe using Iseki Unclemole (TCC 500) microtunneling machine. PVC is a suitable product for sewer system construction. Some of the advantages of PVC pipes include the following: 1) light weight and easy to handle, 2) good impact resistance and toughness, 3) excellent resistance to a wide range of corrosive environments found in sewage and soil, 4) good hydraulic flow characteristics, 5) easy to work with, 6) economical, 7) durable, 8) availability of different joint systems which are extremely reliable against leakage, 9) excellent abrasive resistance, 10) excellent dimensional control, and 11) not biologically degradable (Najafi, 1993). The use of PVC sewer pipe has decreased infiltration and exfiltration and accompanying tree-root problems. The surface of the pipe is very smooth and resists buildup of deposited materials and other solids.

Compared to other types of pipe materials available for microtunneling such as reinforced concrete, steel and glassfiber reinforced plastic mortar pipe (GRP), PVC sewer pipe has less unit cost (Najafi, 1993). However, in the past, the following factors were the main obstacles to the utilization of PVC pipe in microtunneling:

1. Axial thrust load limitations,
2. Higher cost of thick-wall PVC pipe to resist the thrust load, and
3. Lack of a suitable joint compatible for microtunneling.

In the LLB system, the above obstacles have been removed with a method of transmission of the thrust force by the addition of a liner casing and gripper system. This system transfers the face resistance of the machine to the liner casing inserted in the pipe. Also, the circumferential frictional resistance of the product pipe transfers to the gripper systems which are installed at certain intervals along the length of the pipe. These gripper systems expand with air pressure and connect the liner casing with the inner surface of the pipes to transmit the thrust force of the liner casing to the pipes. Therefore, the maximum thrust force exerted to the product pipes is equal to the circumferential frictional resistance of the portion of product pipes between the gripper locations. Consequently, with utilization of the LLB system, pipes with relatively low compressive strength can be installed with microtunneling methods.

In addition to reducing the thrust force on the plastic pipe, the gripper system also has the following characteristics:

1. There is minimal possibility of damaging pipes because the contact is made by pneumatically inflated rubber tubes.

2. Conventional microtunneling methods require product pipes of special wall thicknesses. The LLB system does not have these requirements.
3. The grippers can be installed at desired locations depending on the level of circumferential resistance of the pipes.
4. Long-distance thrusting with minimal restriction to pipe compressive strength is possible with LLB system.

Some of the characteristics to consider when selecting a pipe for microtunneling operations are stiffness, smoothness of the pipe and joint design, joint watertightness, dimensional consistency, weight, resiliency and absorbency. After reviewing the available options of different PVC products for water and sewer construction, Vylon PVC Sewer Pipe manufactured by Lamson Vylon Pipe, Cleveland, Ohio, was selected for this evaluation program. The Vylon pipe provided suitable characteristics and eliminated both of the major obstacles other PVC pipes experience when used for microtunneling, that is, cost and suitable joint.

The Vylon pipe utilizes a new joint system developed by Lamson Vylon Pipe for microtunneling. The joint provides a smooth outside and inside transition from one pipe section to another, making the pipe suitable for microtunneling application. This connection permits the pipe and joint system to mate up with the machine. Additionally, and air-tight seal is formed at the joint with a multi-fin gasket wrapped around a fiberglass insert ring. For economy, Vylon utilizes a profile wall. Vylon's I-Beam design reduces the amount of PVC required when compared to the same size solid-wall pipe, yet maintains smooth surface inside and outside.

The pipe sections selected for use in the project were each 2.438 meters (8 feet) in length and weighed approximately 29.76 kg/m (20 pounds per foot). The Vylon PVC sewer pipe is manufactured according to ASTM F-794 for pipe requirements and ASTM D-3212 for joint requirements. A special adapter was designed and manufactured by Iseki Poly-Tech for the pipe/microtunneling machine connection. This connection provided the necessary tolerance for the PVC jacking pipe and LLB propulsion system. This adapter was located at the tail of the boring machine and provided the necessary tool to transfer face resistance of the boring machine to the liner casing while the PVC pipe mated up with the adapter.

2.4.4 Microtunneling Equipment

An Iseki Unclemole machine (TCC 500) was used for this program. The Iseki Unclemole is a small-bore tunneling machine designed to meet the demand for a wide range of ground conditions. This machine has an actual outside diameter (OD) of 655 mm (25.787 inches) and can construct a borehole equivalent to 660 mm (25.984 inches) in diameter. The Unclemole is basically a mechanical earth pressure counter balance (MEPB) shield that utilizes slurry to counterbalance hydrostatic head and to transport excavated material. The Unclemole uses a unique built-in cone-shaped crusher to crush cobbles and gravel up to 30 percent of the outside diameter of the shield into small particles for transportation as slurry. Figure 2.18 illustrates the mechanism of the cone-shaped crusher.

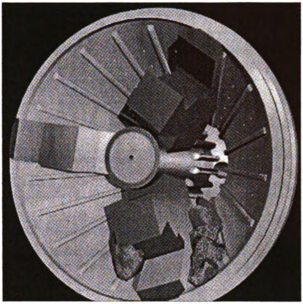


Figure 2.17 – Cone-shaped Build-in Crusher (Herrenknecht 2000)

The Unclemole was modified to accommodate the LLB system and Lamson Vylone pipe. The necessary microtunneling equipments were provided by Iseki Poly-Tech, including boring machine, jacking equipment and guide rails, charging and discharging slurry pumps with necessary pipes and hoses, laser transit, desandman, entrance ring, hydraulic unit and control panel. The desandman is a slurry container which has a vibratory screen and hydrocyclone to separate slurry from spoil material. A list of equipment provided by Iseki Poly-Tech for this evaluation program is provided in Table 2.9.

Table 2.8 –List of Microtunneling Equipment Provided for the Project (Najafi, 1996)

<table>
<tr><th>Description</th><th>Quantity</th><th>Net Weight (kg)</th><th>Size</th></tr>
<tr><td>Tunnel Boring Machine, TCC-500 (I-C)</td><td>1</td><td rowspan="2">1,040</td><td>600 mm diameter, 2,390 mm length</td></tr>
<tr><td>Thrust Jacking Equipment, 3-Stage Molemeister, M3-150T-30 (I)</td><td>1</td><td>Width 1,300 mm, Length 4,400 mm</td></tr>
</table>

Table 2.8 (cont'd)

Load Meter	1		Diameter 670 mm, Length 170 mm
Air Bleeding Valve, SAP02-000J	1		29 x 14 x L53
Check Valve, S6AT-KI-0	1		28 x 24 x L80
Thrust Ring Assembly	1		
Operation Board, B05-I, including Power Cables, Operation Cables and TV Cable	1	1,040	W 1,000 x H 1,270 x L 700
Power Pack, MP-7.5k-320 A	1		
Straub Coupling, Connecting Pipes, Hydraulic Hose, Power Cables, Operation Cables, Jack Speed Cable	1 set	80	
Adapter Ring	1		Diameter 646 mm, Length 630 mm
Special Collar	1		Diameter 640 mm, Length 950 mm
Pit By-Pass Unit, TRW-2	1	1,100	
Entrance Ring	1		
Slurry Pump, SC-28WES, 5.5 kw-4p	1		
Inventor Pump, SC-28WES 5.5 kw-4p	1		
Flexible Hose	8		
Distribution Boards, ELCB 200A, MCCB30A x 3-100A and ELCB 200A, MCCB75A x 3 + 50A	2		
Flow Meter, Pipe, Flexible Hose, Elbow Pipe, Victualic Joint, etc.	1 set	270	
Operation Cable, Laser Theodolite (LTL-20DP), Diagonal Eye Piece, Funnel Viscosimeter	1	210	
PC Bar Φ 26 x 2.4 m, Slurry Pipes 2B x 0/0 x 2 m	1 set	1,100	
Air Gripper, K211740 (Φ584 x L 2460)	3	2,550	
Casing Pipe (Φ595 x L 2460)	1 set	2,800	
Spacer, Pipe, Connecting Pipe, etc.	1 set	110	
Slurry Disposal Plant, Model: "Desandman" IM-2	1	6,370	465 x 231 x 3060 centimeters

2.4.5 Other Equipments

The other equipment items utilized for the microtunneling operation were as follows:

1. A 10-ton crane for hoisting microtunneling equipment in and out of jacking pit (the same crane was used to hoist pipe sections and liner casings);
2. An office trailer (to house the control panel);
3. An electric generator to provide required power for operation of the microtunneling equipment (75 KVA, 200V/60HZ, three phase);
4. An air compressor to provide necessary air pressure to inflate gripper system (the maximum air pressure needed was 7 kgf/cm^2 or 100 psi);
5. An 11.35-cubic meter or 3000-gallon water truck to fill up desandman after slurry discharge;
6. A 6-cubic yard dump truck hauling spoils from spoil tank;
7. A welding and cutting equipment to install the steel framing, guide rails, entrance ring, and miscellaneous welding and cutting works;
8. A backhoe CAT 225 DLC loading spoils from spoil tank to the truck (on part-time basis to excavate drive and receiving pits and slurry pond);
9. A water pump (3 inch-gasoline operated, to pump underground and slurry water from drive pit).

2.4.6 Labor Crews

The following manpower was necessary for installing the pipe and the evaluation program. This manpower (except item 8 is for the data collection) is normally required for a typical microtunneling project:

1. Microtunneling machine operator;
2. Crane operator;
3. Loader operator;

4. Truck drivers (2);
5. Technician;
6. Laborers (2);
7. Supervisor (for desandman operation, setting up laser, checking air gripper installation and loadings, boring operation including connection and dismantling of cables and hoses);
8. Data collectors (3).

2.4.7 Project Site Layout

The typical section layout of construction site for slurry type microtunneling has several components. Two shafts are required for the microtunneling operation: a driving shaft and a reception shaft. A MTBM is set up on the guide rail of the jacking frame in the driving shaft. The main jack pushes the machine, and excavation starts. After the machine is pushed into the ground, the first segment of the pipe is lowered. As main jack pushes the pipe, the MTBM simultaneously excavates soil (Ueki et al. 1999).

The site layout is a critical factor defining simulation model, because it reflects the resource cycle patterns of the project. Project site layout should allow adequate space for microtunneling operation, ease of material delivery, and keep components of each resource cycle in spatial adjacent manner to minimize time waste. The resource cycle components include labor, material and equipment. At the project level, each resource is usually involved in different cycles. The layout needs to consider multiple involved resources and facilitate all resource cycles.

Adequate working space needs to be provided at the drive shaft to accommodate the required equipment and materials for the microtunneling operation. The space requirement is determined by the drive shaft size, which can range from 16 ft by 33 ft to 50 ft by 100 ft, depending on pipe diameter and length and equipment dimensions. Adequate working space typically would range from 20 ft to 40 ft wide and from 75 ft to 150 ft long.

Typical microtunneling project layouts are from experience. A small microtunneling system can be arranged as showing in Figure 2.19. Due to the location of the small projects, which are usually in urban areas, the working space is constrained, epically on longitude direction when construction is on roadway. The space constraints become a critical issue when shafts are positioned along high traffic volume roads. In most cases, only one traffic lane should be closed for microtunneling operation, which is one of major advantages of microtunneling.

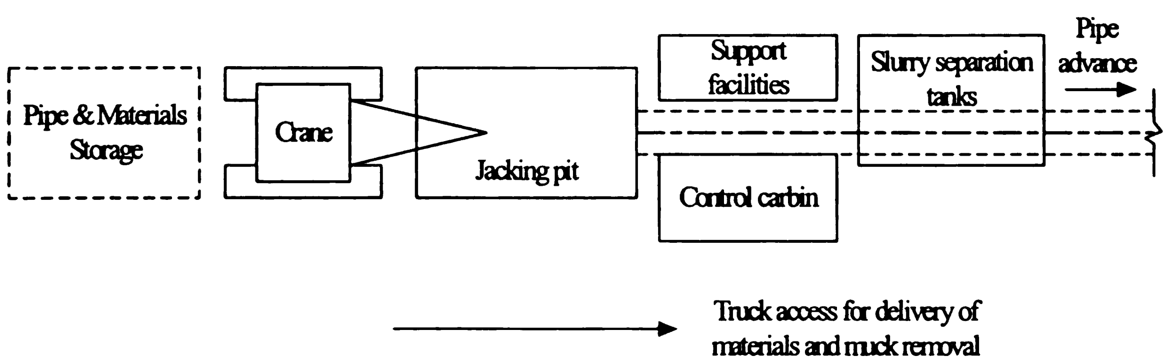


Figure 2.18 –Typical Layout for Small Microtunneling System (Abbott 2005)

In larger microtunneling projects, which commonly install large diameter pipelines in inurbane areas, the space constrain is less an issue because of the location of projects and larger equipment requirements. Figure 2.20 illustrates a typical larger microtunneling project layout around driving shaft area. The construction site is accessible from two sides, which reflects more delivery material needs.

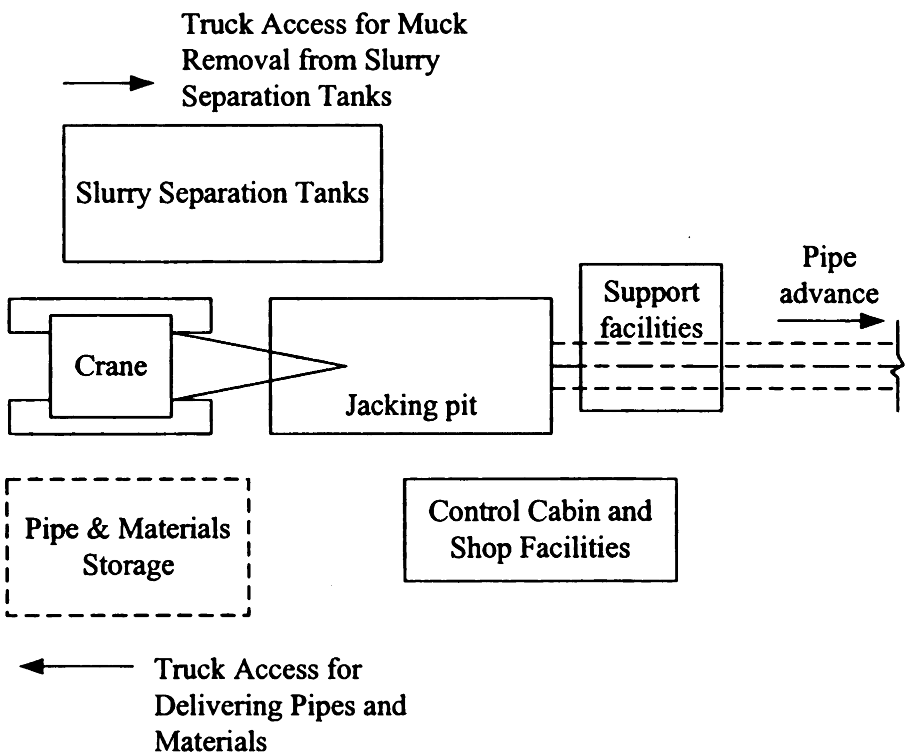


Figure 2.19 - Typical Layout for Large Microtunneling System (Abbott 2005)

In the project in Ruston, Louisiana, the microtunneling operation was conducted in a test area on campus. Congestion was not a serious issue in such a test project as in urban area. In order to generalize the simulation model, the site layout of the candidate project is slightly modified to reflect common pattern of microtunneling operations. Figure 2.21 shows the site layout of the project.

Equipments' lay out was next to the 58.52 meters (192 feet) long test bed on the Louisiana Tech University campus. Driving and receiving shafts were located at both ends of the test bed.

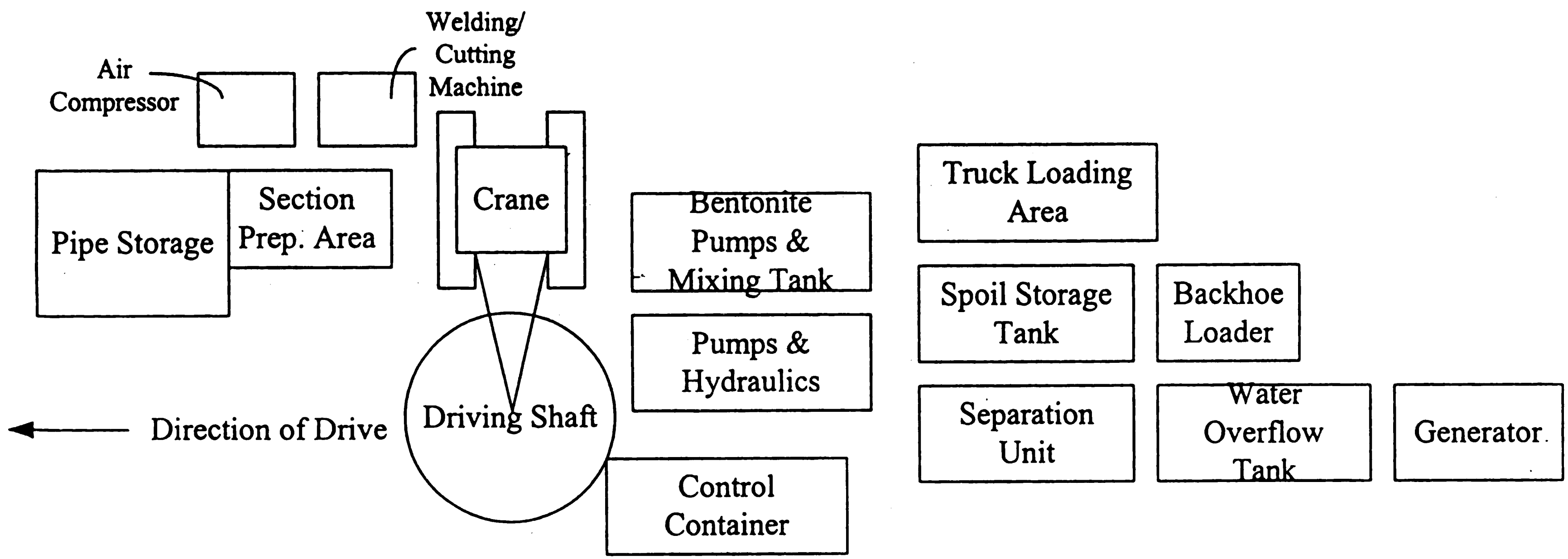


Figure 2.20 –Site Layout of the Candidate Microtunneling Project

2.5 Construction Simulation

2.5.1 Computer Simulation Overview

Computer simulation is a valuable management tool that is well suited to the study of resource-driven processes. It gives the analyst an insight into resource interaction and assists in identifying which factors in a problem domain are important. Simulation allows the modeler to experiment with and evaluate different scenarios. Normally, such experimentation and study would be too costly to be carried out in the real world.

Real world systems are so complex that some these systems are virtually impossible to model and solve mathematically (Banks and Carson II, 1984). In these instances, numerical and computer-based simulation can be used to imitate the behavior of the system over time. A model is defined as a representation of a system for the purpose of studying the system. Although Mihram and Miharam (1974) and many other simulationists stated that it is not necessary to consider all the details of a system because thereby a model is a substitute and a simplification of a system, the model should be sufficiently detailed to permit valid conclusions to be drawn for the real system. The simulation model building process involves many steps. Problem formulation, setting up of objectives, model design and building, data collection, programming and validation, and implementation are the major steps. The art of modeling is enhanced by an ability to abstract the essential features of a problem, to select and modify basic assumptions that characterize the system, and enrich and elaborate the model until a useful approximation results. However, the model complexity need not exceed that required to accomplish the purpose for which the model is intended (Banks and Carson II, 1984).

Computer simulation is defined as the process of designing a mathematical-logical model of a real world system and experimenting with the model on a computer (Pristker 1986). Early simulation users were required to build a model by writing programming code, mainly in FORTRAN, and experimenting by directly manipulating the computer program. This was followed by the invention of simulation specific programming environments where users write simulation specific code or access a provided function library. "Modeling" is the term used to describe the process of specifying a given simulation model. In the next phase of development, a host of systems were introduced that allowed for alternative model development. This meant that modelers no longer had to write code directly. Graphical modeling made it possible to define the simulation model by creating, manipulating and linking a number of available basic building blocks. This meant that users no longer had to be proficient in programming. A detailed account of the history of simulation concepts and systems is detailed in Kreutzer (1986).

Computer simulation can be classified as either deterministic or stochastic depending on its uncertainty content (Wilson 1984). Since construction operations are subject to a wide variety of fluctuations, changes, interruptions, and uncertainties, most simulation applications use probabilistic simulation methods in simulating construction operations. The input modeling, model design, and output modeling are critical issues in simulation modeling for any given situation. AbouRizk (1990) conducted in-depth research on modeling input data for the simulation of construction operations. There are many problems faced by the model designers and users when creating simulation models. When a real system is converted into a simulation model, several logical assumptions are applied. Sometimes these assumptions do not represent the correct nature of the real system. Uncertainty and unpredictable events in a real system are usually modeled using statistical distributions to reflect the actual occurrence of those events. A lack of historical data and its applicability to a statistical distribution may fail to successfully model such random events. Because of the high uncertainty involved in construction operations and the unavailability of historical quantitative data, various researchers have hypothesized the determination of activity durations for most construction operations. AbouRizk et al. (1994) divided certain input parameters for "certainty portions" and "uncertainty portions" based on the uncertainty content of the input parameters: deterministic analysis to estimate the certainty potion and probability and conceptual analysis to estimate the uncertainty portion.

Construction simulation can be of great assistance to decision makers in analyzing various construction operations and alternatives. Simulation of construction operations allows analysts and construction industry personnel to experiment with different construction technologies, and estimate their possible consequences and impact on scheduling and costs. Although simulation has been considered a very powerful tool for construction, its application to real life construction projects has been minimal (Ruwanpura 2001). The use of computer simulation for planning construction projects has been limited to academia and a few large contractors who can afford to employ dedicated simulation professionals (Hajjar 1999).

2.5.2 Construction Simulation

Possibly due to the uniqueness of constructed facilities and the perceived lack of repetition, the concept of studying work processes did not receive much attention until the late 1960s. At this time, work sampling and various graphical techniques related to bar charting were considered. It was recognized that although projects are typically unique, many construction processes are repetitive (e.g. earth hauling, tunneling, road construction, glass installation on a tall building, etc.) and amenable to closer investigation. Due to the comparatively short "half life" of construction processes, sophisticated analytical methods were viewed as being too complex for most situations.

With the emergence of the desktop computer, application of more sophisticated methods has become more accessible. In particular, simulation of construction processes to establish anticipated levels of production and solve some of the problems related to the randomness of construction operations has become a more widely accepted as a tool available for use in planning and estimating.

Random number techniques to solve stochastic problems encountered in construction have been used to establish ranges of expected cost (e.g. range estimating), evaluate project time duration (PERT simulation), and model and evaluate expected production of various construction processes. One of the earliest applications of random number methods was in a gaming context. AI, Parti, and Bostleman developed a construction bidding game in the late 60s which in various configurations is still used at several universities for teaching purposes (Au et al, 1969).

Following this, the CONSTRUCTO project management game was developed at the University of Illinois by Halpin to integrate the effects of weather and labor productivity into the management of projects in a network format (Halpin, 1976). A similar simulation was developed by Borcherding (1977) of the University of Texas. Recently, the concepts of the bidding game and the project management format have been integrated into an educational game (Superbid) by AbouRizk at the University of Alberta, Edmonton (AbouRizk, 1992)

In order to be accepted in the construction environment, simulation has to be presented in a very simple and graphical context. Contact with construction professionals indicates that formats which appear to be too theoretical or analytical tend not to be accepted of utilized. Therefore, ideally simulation systems should be pictorial of schematic emphasizing graphical input and graphical output. The early systems designed to study construction operations utilized simple bar charting concepts.

With the advent of simulation methods in construction, simple networking concepts were introduced as a modeling framework for studying construction operations. The earliest of these methods was the so-called "link node" model adapted by Teicholz (1963). After that, Halpin (1973) developed the CYCLONE format at the University of Illinois that has become the basis for a number of construction simulation systems. CYCLONE simplified the simulation modeling process and made it accessible to construction practitioners with limited simulation background.

2.5.3 Simulation Modeling

There are many ways of modeling a given problem and these generally fall into two categories: continuous and discrete-event. Continuous or time-dependant algorithms are often represented with a system of equations or mathematical models and then solved for steady state performance using differentiation, integration, or approximation. In discrete event simulation utilizes "next event processing" of activities based on logical relationships between process components and availability of resources (AbouRizk, 1998).

Users can typically change the behavior of a simulation model after it is constructed. This is the concept of the reusability where the model can be used for a multitude of scenarios. The degree to which users can change the pre-defined simulation behavior is dependent on the development strategy utilized. Simulation systems can generally be classified according to this feature as follows (Ulgen et al, 1991):

1. Fully documented simulation models,
2. Parameterized simulation models,
3. Special purpose simulation program generators, and
4. General-purpose simulation program generators.

With fully documented simulation models, users are required to modify the simulation models by manipulating them at the same level used to originally develop them. This assumes end users are knowledgeable with the way the simulation system works. Parameterized simulation models allow for model re-use by exposing a set of parameters that users can modify each time the model is simulated. The values of the parameters can be used to modify routing strategies, resource values and entity attributes. With special-purpose program generators (SPSPG), users are able to create models by selecting from a list of available domain specific constructs and defining their parameter values as well as their relation to other elements. Examples of such systems include WITNESS and SIMFACTORY (Mathewson 1989), Ap2Earth (Hajjar et al. 1998). The advantages of special purpose simulation program generators are outlined in AbouRizk and Hajjar (1998). General-purpose simulation program generators (GPSPG) are like SPSPG; only expert users can add new modeling constructs to the system.

Halpin (1977) popularized the use of simulation in construction research with his invention of a system called CYCLONE (CYCLic Operation NEtwork). CYCLONE allowed the user to build models using a set of abstract but simple constructs. The system became the basis for a wide range of construction simulation research efforts with the objective of enhancing the basic system functionality and most construction simulation work was motivated by the success of CYCLONE (AbouRizk, 1998). This included MicroCYCLONE (Halpin, 1978), INSIGHT (Paulson et al., 1978), UM-CYCLONE (Ioannou, 1989), and RESQUE (Chang and Carr 1987). STROBOSCOPE (Martinez and Ioannou, 1994) was another development based on CYCLONE which allowed for dynamic simulations based on the definition of entity and resource attributes using programming - like syntax. DISCO (Huang et al., 1994) developed to allow the use of graphical-based modeling for CYCLONE models.

Simphony is another simulation platform for building general and special purpose simulation tools, which was developed in the University of Alberta. It is a Microsoft Windows based computer system developed with the objective of providing a standard, consistent, and intelligent environment for both the development and utilization of special purpose simulation (SPS) tools (Hajjar and AbouRizk, 1999). AbouRizk and Hajjar (1998) also defined SPS as "*a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications, and reporting are completed in a format native to the domain itself.*" A detailed introduction can be found in Hajjar and AbouRizk (1999).

MicroCYCLONE is chosen as the base for this simulation study, due to the accessibility and ease of use. Specifically, a web based version of MicroCYCLONE, namely, WebCYCLONE maintained by Purdue University is used to run simulations. The use of WebCYCLONE requires coding of the model in a format set by MicroCYCLONE and upload to the website. The interface of WebCYCLONE is shown in Figure 2.22. MicroCYCLONE is a microcomputer based simulation program designed specially for modeling and analyzing site level processes which are cyclic in nature. In broader terms, it can be used to model construction operations which involves the interaction of tasks with their related durations, and the resource unit flow routes through the work tasks are the basic rationale for the modeling of construction operations.

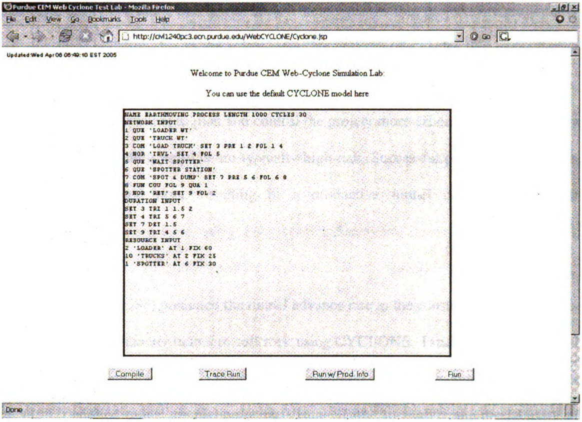


Figure 2.21 -A glance at WebCYCLONE User Interface

2.5.4 Tunneling and Microtunneling Simulation Tools and Applications

Similarities exist between tunneling and microtunneling construction methods. Microtunneling is considered as tunneling with special features (ASCE, 2001). As having much longer history, researches have been approached on all aspects of tunneling. The significant amount of previous tunneling simulation projects can nourish the development of microtunneling simulation, which is rarely found.

In general, the term "tunneling" can be used to describe a wide range of underground excavation operations. Tunnels can be used to serve a variety of functions, including subways, utility corridors, and sewer lines. Tunnel construction projects are particularly suitable for simulation due to the many repetitive construction cycles that occur during construction. Simulating the process of tunnel advancement can guide the engineers, planners, and constructors to plan and control the project more efficiently. It is generally accepted that tunneling projects are typically high-risk. Successful project planning can save both cost and time, resulting in a productive tunnel construction project (Ruwanpura, 2001).

Touran and Asai (1988) predicted the tunnel advance rate in the construction of a several-mile-long, small-diameter tunnel in soft rock using CYCLONE. Tanaka (1993) presented a tunnel simulation using CYCLONE for shielded tunnel boring machines. AbouRizk et al. (1997) applied tunnel simulation using Visual SLAM to analyze the productivity of construction activities for a tunnel constructed under a river to validate a productivity claim. Olufa et al. (unpublished) presented a library-based simulation modeling development with an implementation in shielded tunnel construction projects in University of Alberta. They used an object-oriented simulation programming language called MODSIM to simulate the tunneling projects. Salazar (1987) presented a simulation model based on the event scheduling approach to generate probabilistic descriptions of the advance rate of tunnel excavation and the corresponding demand for resources. It used linked lists to dynamically schedule construction activities as the excavation takes place through difficult ground conditions and provided two case studies comparing two tunneling methods to illustrate the model. Abd Al-Jalil (1998) developed a decision support system- Decision Aids in Tunneling (DAT) to predict the performance of Tunnel Boring Machine (TBM) based excavation systems in hard rock geological conditions. These tunnel simulation models have catered to particular situations and cannot be used for other types of tunnel or microtunnel construction projects.

Ruwanpura et al. (2000b and 2000c) discussed the independent studies conducted by two graduate students Hajjar (1997) and Ruwanpura (1998) of the University of Alberta as part of their course work, to model TBM-based tunnel construction using Visual SLAM (Pritskar 1994). However, both models were not flexible enough to model for any given tunnel construction project using a TBM, and were not validated using a construction project. In both cases, they concluded that simulation could be a very useful tool for project planning. As an improvement, Ruwanpura (2001) developed a special purpose simulation (SPS) template for tunnel construction operation, which included a modeling technique to predict the soil types in the tunnel path in City of Edmonton, Alberta, Canada. The prediction of soil types in the tunnel path was realized by using Markov Chain probabilistic theory on historical geological bore data from City of Edmonton.

Research on microtunneling using simulation is very limited. Nido et al. (1999) simulated an actual microtunneling project in Montgomery County, Ohio, using CYCLONE methodology. The analysis highlighted the impact of variations in soil compositions on the productivity of the operation and on the utilization of labor resources. The project selected for simulation used centrifugally cast fiberglass mortar pipes, which is significantly more expensive than PVC pipe used in the Louisiana Tech University LLB Microtunneling Field Test Project. Since the pipe cost constitutes a big portion of microtunneling cost, the effect on cost reduction by using PVC pipe is one of the goals of this simulation research. Nido et al. selected an actual microtunneling project with predominantly variety of clays encountered along the path, based on which simulation was conducted to analyze the impact of variations in soil compositions on the productivity. The soil compositions were limited by the actual geological conditions on the job site; therefore, the simulation could not reveal potential impacts of a wide range of soil conditions. However, in the Louisiana Tech University LLB Microtunneling Field Test Project, to simulate soil materials mostly encountered in real situation, samples of sand, clay, silt, and gravel were selected artificially. Although encountering such a soil variety would probably be rare in actual practice for a single microtunneling operation, it was assumed that the results of the microtunneling test could be used for similar types of soils so that the performance of the LLB system could be predicted for different subsurface conditions (Najafi, 1993). This feature of the data collected will enhance the simulation analysis.

2.6 Summary of Literature Review

The literature review in this chapter indicates that simulation can be used for study on the productivity of cyclic microtunneling operation. Backgrounds and elements need for an operational simulation on microtunneling have been reviewed. Various aspects of microtunneling methods in general and the candidate project in specific were descried in details. The possibility of the application of CYCLONE simulation on microtunneling was discussed. Also, pipe materials used in microtunneling and soil condition classifications were documented to develop a broad-based understanding of the method. The literature review indicates that there is a good possibility to develop a successful CYCLONE model if the microtunneling operation procedures are well understood. In following chapters, simulation models will be developed based on operation procedure and duration data analysis.

3 CYCLONE METHODOLOGY AND APPLICATION

Previous chapters dealt with the literature review that gave the necessary background for pursuing this thesis. This chapter presents the methodology used in this research for microtunneling productivity analysis. The productivity simulation models are built with CYCLONE (*CYCL*ic *O*perations *NE*twork) techniques. A detailed description of CYCLONE methodology is presented in this chapter, along with the model development.

3.1 Cyclone Methodology

For the analysis of the microtunneling operation productivity of the candidate project, Web-Cyclone, a web-based simulation program that is based on the CYCLONE methodology, was selected for modeling and simulation of the process. The CYCLONE (*CYCL*ic *O*perations *NE*twork) methodology is a modeling technique that allows the graphical representation and simulation of discrete systems that deals with deterministic or stochastic variables. Construction processes simulation using the CYCLONE methodology, abstracts the reality into a graphical representation by dividing the process into discrete pieces or work task and by representing how these interact. It focuses on resources and their interactions. The purpose and ideal objective of computer simulation is to optimize system performance, in the thesis research, is to study to improve and estimate microtunneling productivity.

Steps involved in CYCLONE simulation are:

- Defining the system (well defined boundaries)
- Modeling the system (system of equations, graphical modeling)

- Input & Output Analysis
- Validation/Verification

To define the Network model:

- Define work task composing a process
- Establish logical relationship between the work tasks
- Work task use resources and require time to be completed, this fact is accounted into the model by supposing that entities flow thorough the network, are delayed by work tasks, wait for processing, etc. When they are served (or used) by each work task they continue flowing through the network.

The basic modeling elements used in the CYCLONE methodology are shown in Table 3.1. The precedence rules of CYCLONE elements are shown in Table 3.2. Resources can be in one of two states – active (denoted by a square element) or idle (represented by a circle element). Resources will move between these two states, as they "traverse" from one activity to another. A flow unit traverses a CYCLONE network with the following effects:

- Waits in **QUEUE** nodes for processing
- Initiates (or signal) the processing of a work task
- Generate other entities where they traverse a **QUEUE-GEN** node
- Get consolidated with other flow units when they pass a **CONSOLIDATE Function**

- Register productions where they pass a function **COUNTER**

Table 3.1 –CYCLONE Modeling Elements (Division of Construction Engineering and Management Simulation Homepage, Purdue University, 2005)

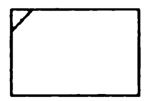
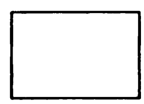
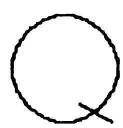
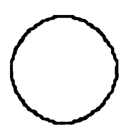
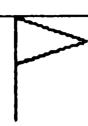
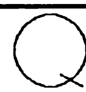
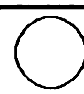
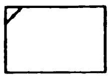
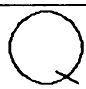
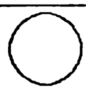
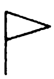
Name	**Symbol**	**Function**
Combination (COMBI) Activity		This element is always preceded by Queue Nodes. Before it can commence, units must be available at each of the preceding Queue Nodes. If units are available, they are combined and processed through the activity. If units are available at some but not all of the preceding Queue Nodes, these units are delayed until the condition for combination is met.
Normal Activity		This is an activity similar to the COMBI. However, units arriving at this element begin processing immediately and are not delayed.
Queue Node		This element precedes all COMBI activities and provides a location at which units are delayed pending combination. Delay statistics are measured at this element.
Function Node		It is inserted into the model to perform special function such as counting, consolidation, marking, and statistic collection.
Accumulator		It is used to define the number of times the system cycles.
Arc	→	Indicates the logical structure of the model and direction of entity flow.

Table 3.2 –CYCLONE Elements Precedence Table (Division of Construction Engineering and Management Simulation Homepage, Purdue University, 2005)

					
	*N*	*I*	*I*	*I*	*I*
	*N*	*I*	*I*	*I*	*I*
	*M*	*N*	*N*	*N*	*N*
	*N*	*I*	*I*	*I*	*I*
	*N*	*I*	*I*	*I*	*N*

- M = required or mandatory
- I = immaterial
- N = nonfeasible

Active states or work tasks can either be unconstrained (NORMAL modeling element – represented by a rectangle) or constrained (i.e., certain initial conditions must be satisfied). The constrained active states are named COMBI (depicted by a hatched rectangle) modeling elements. "The NORMAL and COMBI work tasks have user-defined time delay functions that represent the time period during which resource entities are delayed while processing through these work tasks. The idle state represented by the QUEUE node, has the potential for storing in a waiting state or queue format the resource entities held up by system requirements pending the satisfaction of COMBI work task ingredients or initializing logic" (Halpin et al., 1992). The sequence of work tasks undertaken by the resource entities together with their idle states indicates the level of the use of resource.

Two basic resource flow patterns are commonly used. The slave entity pattern is produced whenever a resource entity is used by a single active work task, such that the resource entity cycles between the active state and the idle state. When a resource entity is shared between two or more work tasks, the resulting flow pattern is called a butterfly pattern. In such cases, once the resource entity is in the idle state, its subsequent active work state may depend on other factors, such as the availability of other resources, the priority system adopted for the work tasks in the construction operation, etc. Units can be generated into the system by defining a GENERATE function (abbreviated as GEN) which is associated with a selected QUEUE node. When a work task is initiated after a specified number of cycles of the system or system subcomponent, a CONSOLIDATE function (abbreviated as CON) is defined. The GENERATE function is a discrete event multiplier, while the CONSOLIDATE function can be considered a discrete event divider.

3.2 Microtunneling Operation Procedures

The microtunneling procedures for the simulation candidate project are as follows:

1. Excavate and prepare the driving shaft.
2. Set up the control container and any other auxiliary equipment beside the jacking shaft.
3. Set up the jacking frame and the hydraulic jacks.

4. Lower the MTBM (Unclemole) into the driving shaft and set it up on the guide rails.
5. Set up laser guidance system.
6. Set up the slurry lines and hydraulic hoses on the MTBM as illustrated in Figure 3.1.

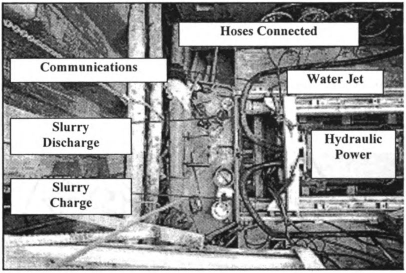


Figure 3.1 - Slurry Lines and Hydraulic Hoses (Najafi, 2005)

7. The main jack pushes the MTBM.
8. After the MTBM is pushed into the ground, the slurry lines and hydraulic hoses are disconnected from the jacked section (or MTBM).
9. The hydraulic jacks are retracted.
10. A new pipe section is brought from the storage and liner casing with two slurry steel pipes, air hose and cables are placed inside the pipe as shown in Figure 3.2. Air grippers are installed on certain sections as shown in Figure 3.3.

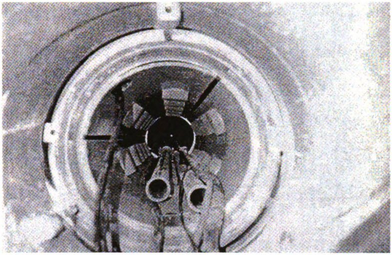


Figure 3.2 –Inside View of PVC Pipe Showing Liner Casing, Slurry Pipes, Bentonite Hoses and Cables (Najafi 1993)

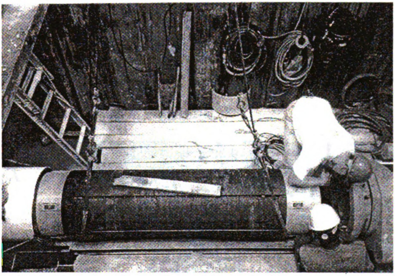


Figure 3.3 – Air Gripper Used in the Project (Najafi 1993)

11. The pipe section is attached to crane and lowered into the driving shaft as shown in Figure 3.4.

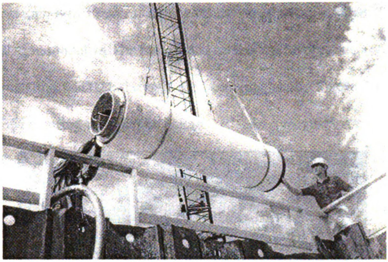


Figure 3.4 – Lower Pipe Section into Driving Shaft (Najafi 1993)

12. Connect the slurry lines and hydraulic hoses in the new pipe segment to the ones in the previously jacked segment (or MTBM).
13. Jack the new pipe section, while removing the spoil, adding lubrication, and filling water as shown in Figure 3.5.

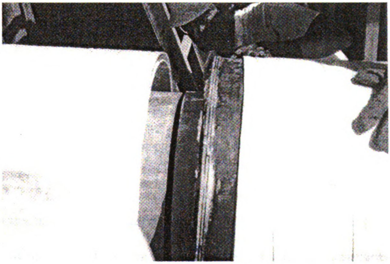


Figure 3.5 – PVC Pipe Joint Being Pushed in (Najafi 1993)

14. Excavate and prepare the receiving shaft.

15. Repeat step 8 to 12 as required until the pipeline is installed. The CYCLONE simulation model will be built based on this cyclic process.
16. Remove the MTBM through the receiving shaft. Figure 3.6 illustrates the MTBM entering the receiving shaft.

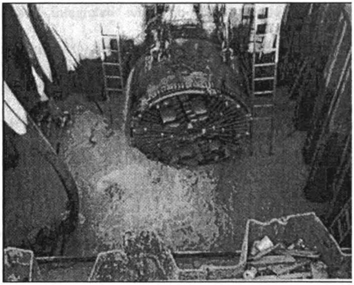


Figure 3.6 - MTBM at the receiving shaft (Kerr Construction Inc.)

17. Remove jacking frame and other equipment from the driving shaft.
18. Grout the annular space between the exterior pipe surface and the tunnel.
19. In case of sewer applications, install manholes at the shaft locations.
20. Remove shoring, lining, or casing from the shaft and backfill them.

The major procedures in the candidate project are also applied in slurry type microtunneling in general. Therefore, possibility exists that the simulation model based on the specific project can be generalized to other slurry type microtunneling projects with modification.

Microtunneling is a complex operation process, which includes multiple types of resource cycling and interacting in the overall system. Due to the limited supply of resources, interactions between various resource cycles create the major limitation on productivity of microtunneling operation. To optimize the productivity, single resource cycles must be modeled first and integrated with the logic among them to truly reflect the microtunneling operation. On the both levels of modeling, the CYCLONE model building procedure need to be followed, which involves four basic steps:

1. Define resources;
2. Identify work tasks in the process (work tasks with which resources are involved);
3. Determine the logic of the processing of resources;
4. Build a model of the process.

The next section will follow the four steps to identify flow units and resources in each resource cycles.

3.3 Flow Unit and Recourses Identification

The resource identification stage is extremely important since it will dictate the degree of detail of the finished model. In order to portray the resources in the model, important activity duration information must be measured in the field. The most important resources were identified as the following: the pipe sections, the jacking system, two labor crews (called Labor A and Labor B), the lubrication mixture, the water in the spoil removal system and the spoil that was removed from the borehole (these resources will be called leading resources thereafter). Other resources were identified, but they were considered as secondary resources, these included construction equipment such as backhoe, crane, dump trucks, water truck, air grippers for the PVC pipes, and the ingredients for the lubrication (bentonite and polymer).

The most important resource in the system is the pipe section. A pipe section is defined as a 8 feet long section of PVC sewer pipe. The pipe sections are brought to the site and are placed on a storage place showing on Figure 3.1, as they are unloaded from the truck. When needed, the Labor A rolls one section to the base of the crane where it will be prepared for installation. This preparation includes the placing of a liner casing with two slurry steel pipes, air hoses and cables inside the PVC pipe section. Air grippers need to be installed on every four sections. Then, the prepared section will be attached to the crane and lifted, lowered into the shaft and laid on the guardrail. Labor B crew sets up the pipe for installation. The setup activity includes installing slurry pipes, air hose and cables, joining the thrust ring with the liner casing and the PVC pipe, and installing laser guidance. Once the pipe has been set up, the jacking of the section may begin. After the pipe section has been fully jacked, slurry lines and the hydraulic lines may be dismantled. At this point, one production cycle is complete. For the models developed in this study, the production unit was defined as the jacking of one 8 feet long section of PVC sewer pipe. The installation of each section was deemed to be completed after the slurry and hydraulic lines have been dismantled from the jacked section. Figure 3.1 illustrates the resource cycle for pipe section.

Air gripper installation as a secondary resource is required on certain pipe sections in the preparation activity. Due to the material characteristic of PVC pipe used in the project, air grippers have to be installed on some pipe sections for the air hoses in order to adapt the PVC pipe to the microtunneling system. The project used air grippers on section number 4, 9, and 14 in 24 sections installed, which was based on the engineer's experience. Assumption is made to model air gripper installation on every 5 sections. Based on the notes in Appendix B, after installations, approximately 67% of times the air grippers are ready to use, and 33% of times it needs to be adjusted, which occupies resources (Labor A, Supervisor) for certain time. Fig. 3.8 illustrates the air gripper installation on the pipe section that is necessary.

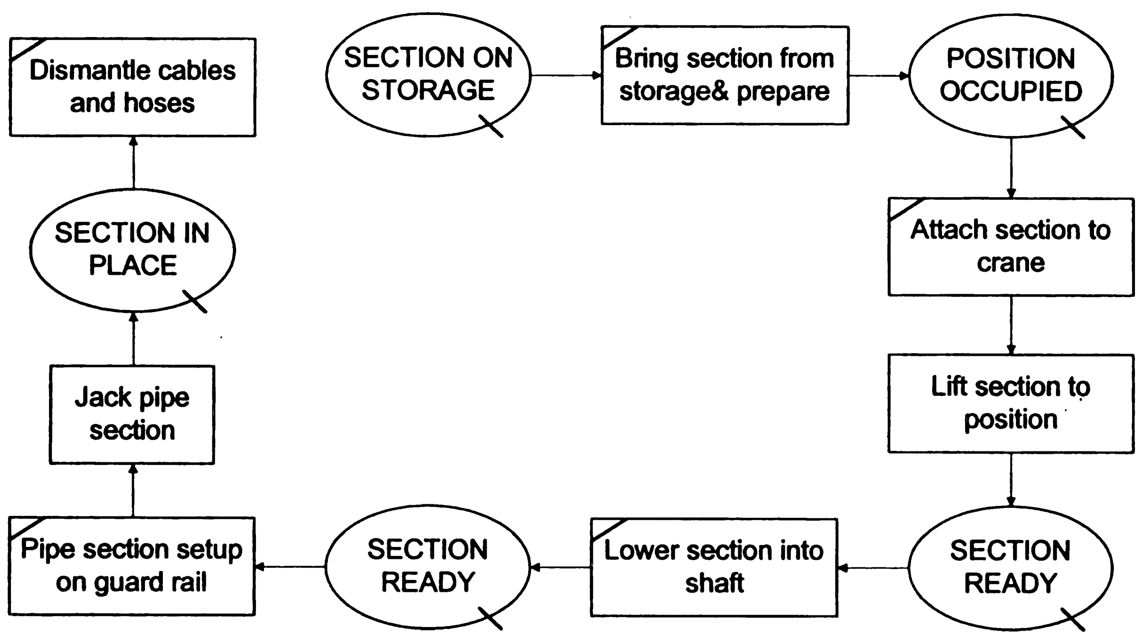


Figure 3.7 –Pipe Section Resource Cycle

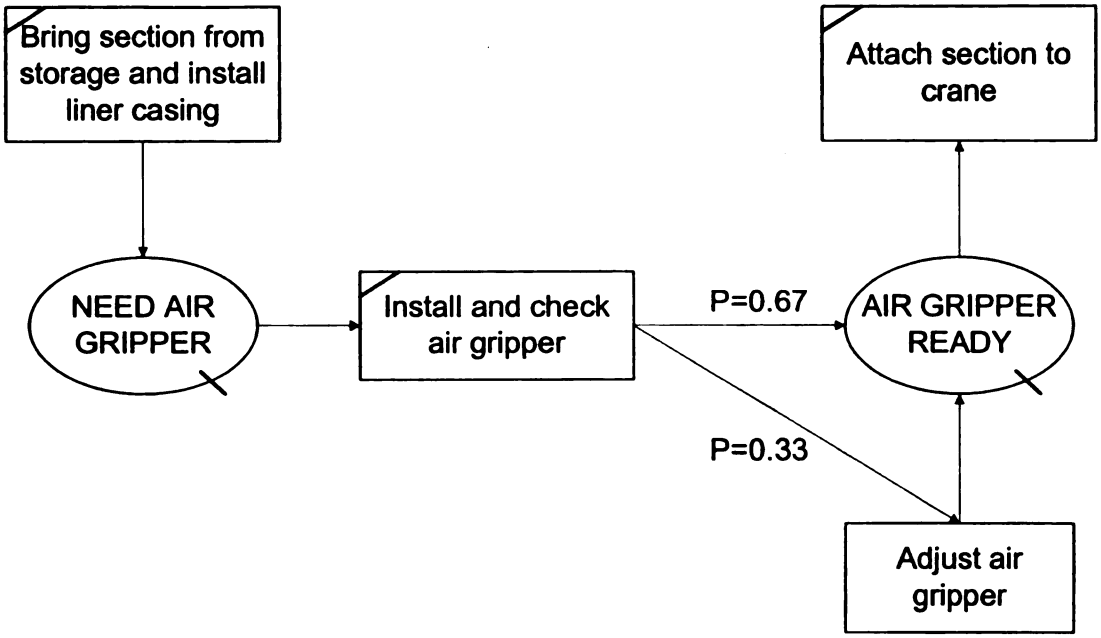


Figure 3.8 – Air Adaptor Installation on Pipe Section Resource Cycle

The jacking system is another leading resource; its cycle is shown in Figure 3.9. The jacking process is the main component of the microtunneling operation. The cycle begins when jacking frame completely retracted and ready to accept a pipe section, this state is called jacking system idle. After a pipe section is setup then the jacking system "jacks" (or pushes) the pipe. After the jacking pipe takes place then the slurry and hydraulic lines are dismantled and jack frames are retracted once again ready to begin another cycle. The jacking system consists of: the jacking frame, one worker who is always inside the shaft cleaning and observing the jacks, the MTBM and its operator who also controls the jacks, the spoil separation unit. Production unit was defined as jacking system went through one cycle from retracted status to next retracted status.

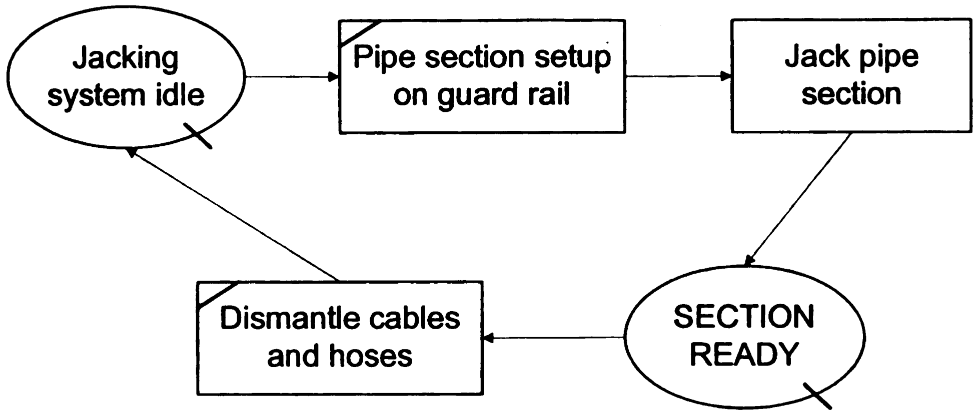


Figure 3.9 –Jacking System Resource Cycle

The "Labor A" resource is defined as a one-worker crew. This worker is assigned to various activities as shown in Figure 3.10. This worker does not directly interact with the jacking system cycle since he does not perform any jacking related activity. This worker is involved in the mixing of the lubrication, attaching the pipe section to the crane and preparing the section for installation.

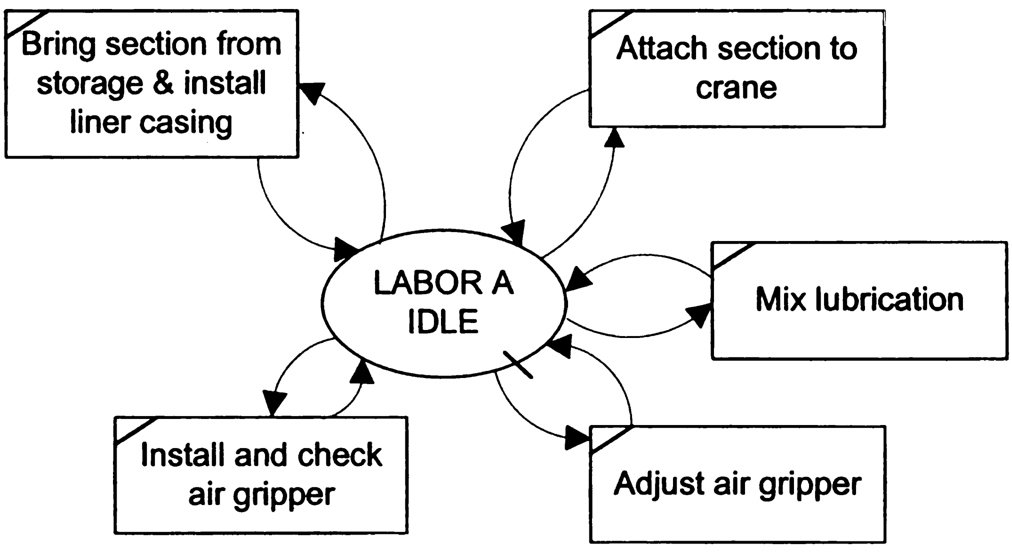


Figure 3.10 –Labor A Resource Cycle

The next resource is called "Labor B". Labor B is defined as a two-worker crew with one labor and one technician, who are involved mainly in jacking related activities like setting up the pipe in the shaft, dismantling the slurry and hydraulic lines and lowering the section into the shaft. This crew is also involved in the task of discharging and refilling the desandman (Figure 3.11). The crew members have to work together.

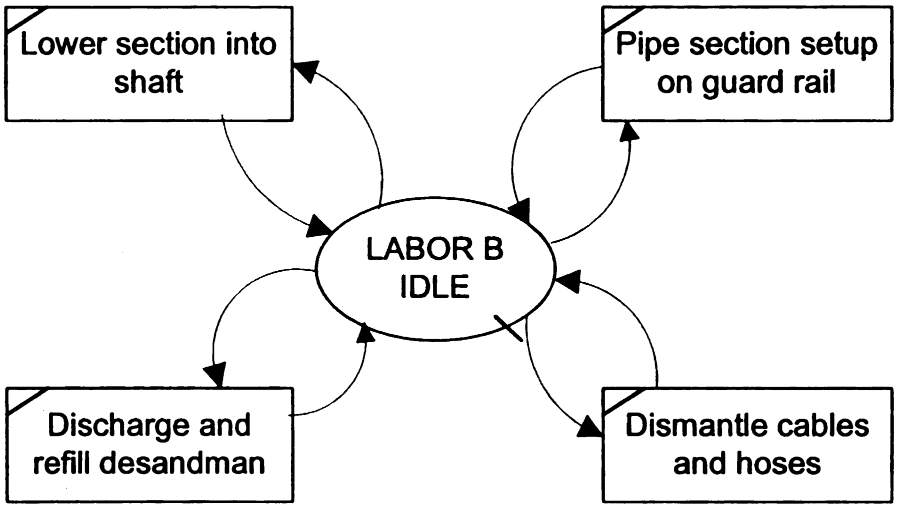


Figure 3.11 –Labor B Resource Cycle

The lubrication cycle (Figure 3.12), starts with the lubrication in its storage tank. This resource is used to set up the pipe in the jacking frame. It is also required through the entire jacking process until the slurry lines and hydraulic lines are dismantled. After five cycles, the lubrication is consumed and more is needed, so the ingredients (polymer liquid, bentonite powder and water) must be mixed in the mixing tank and then stored. The flow unit is defined as one lubrication mix process is finished and ready for use.

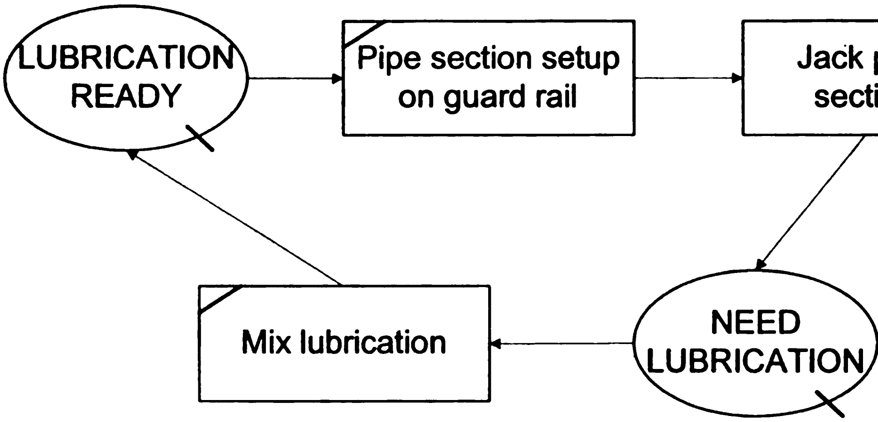


Figure 3.12 –Lubrication Resource Cycle

The slurry (water based) in the system is a very important resource, as shown in Figure 3.13. Slurry is needed in all phases of the jacking process, from the setting up of the pipe, through the jacking itself until the slurry and hydraulic lines are dismantled. Slurry can be recirculated through the system only a certain number of times, which is a function of the composition of the soil being excavated. The flow unit is one time of discharging the desandman and refilling water for use.

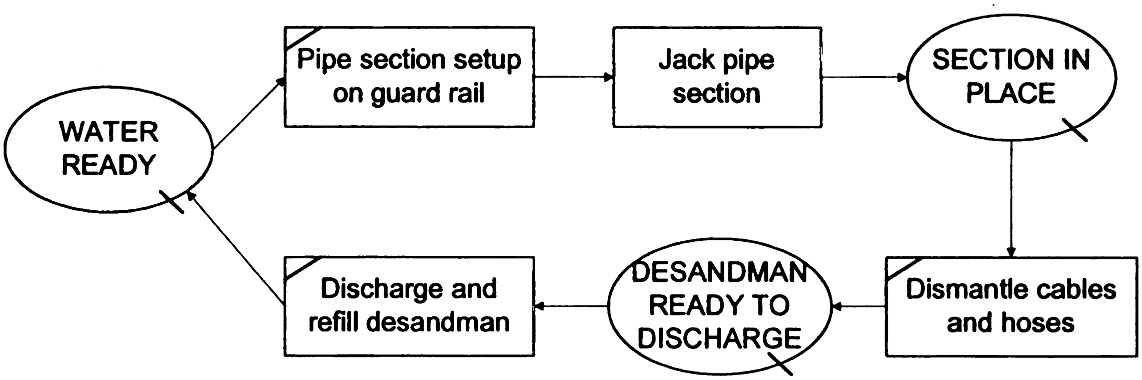


Figure 3.13 –Water Resource Cycle

During the pipe jacking process spoil is removed through the slurry return lines in the form of a slurry suspension (Figure 2.7). It is then separated from the water and dumped into the storage tank before it is loaded into dump trucks for hauling to disposal sites, as depicted in Figure 3.14. Flow unit is the spoil tank is emptied once.

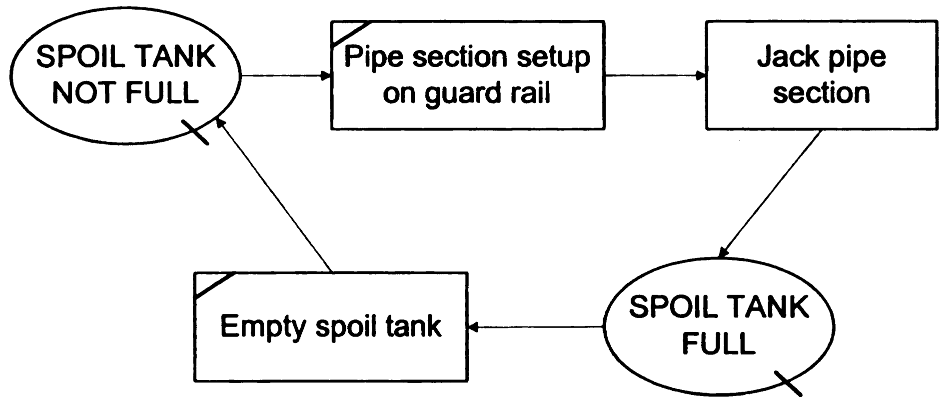


Figure 3.14 –Spoil Cycle

After leading resource cycles have been defined, secondary resources need to be identified. One of them is the supervision provided by Kidoh staff from Osaka, who is responsible for checking air gripper installation, pipe section setup on guardrail including laser setup and connection of cables and hoses, desandman operation, and dismantling cables and hoses. Figure 3.15 shows the resource cycle of supervision. One supervisor is assumed and he must be available at the beginning of each activity which need to be supervised. The supervisor can only present at one activity a time.

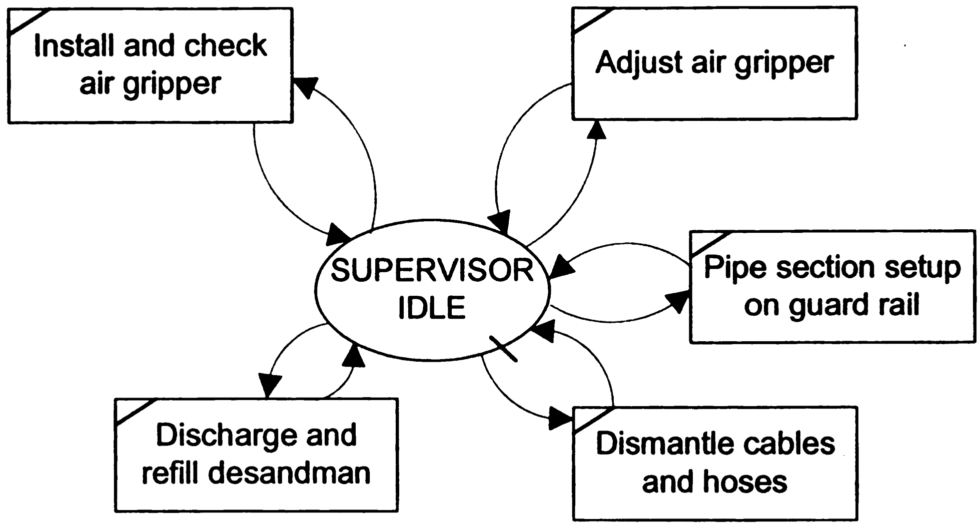


Figure 3.15 – Supervisor Resource Cycle

The crane cycle is another secondary resource cycle, as shown in Figure 3.16, the crane returns when pipe section is setup on guardrail, and ready to be attached next pipe section. Flow unit is defined as a cycle that from attaching pipe to crane idle completes.

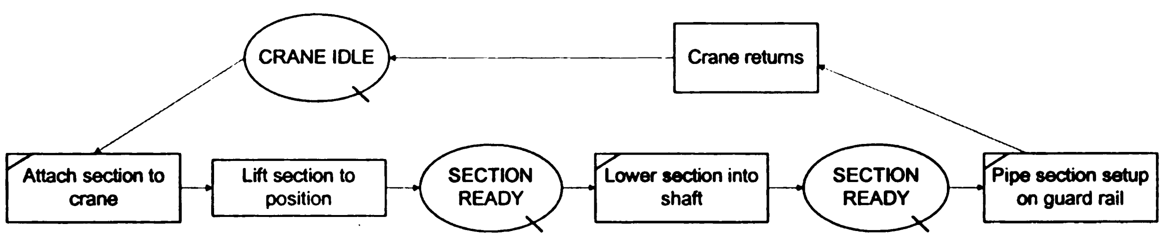


Figure 3.16 – Crane Resource Cycle

There are other secondary resources not forming independent cycles, such as backhoe, crane, dump trucks, water truck, and the ingredients for the lubrication. Those secondary resources will be included in next section of integrating independent resource cycles into one microtunneling simulation model.

3.4 Integration of Independent Resource Cycles

The second step in building the model is the integration of the independent resource cycles. When all the flow unit cycles have been identified, they can be integrated at the COMBIs for development of the comprehensive process model. Those COMBIs that appear in different resource cycles will be joints on the comprehensive process model connecting the independent resource cycles. Such a model structure reflects logic nature behind the operation process. For instance, COMBI Pipe Section Setup on Guard Rail appears in eight independent resource cycles. Resources including pipe section, labor B, supervisor, water, lubrication, spoil tank, jacking system, cables, hoses, and laser must be ready before pipe section can be setup on guard rail.

Basically we need the following information in order to simulate the actual process:

1. When can a work task be scheduled to start?
2. What resources are necessary for its processing?
3. Time consumed by processing the resource

Item 1 and 2 are discussed in this section, which explains the structure and logic of the model. Time consumed by processing the resource will be studied in chapter 4, Statistical Analysis of Observed Duration Data.

Figures 3.17 and 3.18 present the complete prototype CYCLONE model for microtunneling operation without consideration of soil impacts. The purpose of this prototype model is for validation of the modeling structure and logics. After building and validating this prototype model, enhancements of different soil composition impacts will be included in next section.

The complete description of the prototype simulation model elements is shown in Table 3.3 to 3.6.

Figure 3.17 –Combination Elements in Prototype Model

COMBI elements	
Element number (Priority)	**Description**
1	Discharge and refill desandman
2	Mix lubrication
3	Dismantle cables and hoses
4	Empty spoil tank (desandman)
5	Setup pipe section on guard rail
6	Lower section into shaft
7	Adjust air gripper
8	Install and check air gripper
9	Attach section to crane
10	Bring section from storage and install liner casing

In order to prioritize activities sharing the same resource, thorough analysis has been conducted to follow the microtunneling practice. In CYCLONE modeling, lower numbered COMBI elements receive priority (Halpin et al. 1998). For example, resource Labor A is responsible for five activities in priority of: *Mix lubrication*, *Adjust air gripper*, *Install and check air gripper*, *Attach section to crane*, and *Bring section from storage and install liner casing*. Slurry is ranked first because it is the most important among five, without lubrication the operation could be jeopardized and fail. Other four activities are prioritized following a general rule: later positioned activity in the cycle takes higher priority. The logic of the rule is that there is only one situation later and earlier positioned activities fight for the resource: later activity deals with previous pipe section while the early activity deals with next pipe section. For instance, *Bring section from storage and install liner casing* must happen before *Attach section to crane*, but they share resource Labor A, which means normally two activities won't occupy Labor A simultaneously. However, the only possibility comes when Labor A is to attach pipe section to crane, the next section need to be brought and prepared. Obviously, Labor A should attach section to crane first in order to keep the whole operation running and come back to bring more sections and prepare. Thus, if any two of these activities need Labor A at the same time, higher numbered activity has to wait for lower numbered activity finish and release Labor A to idle status.

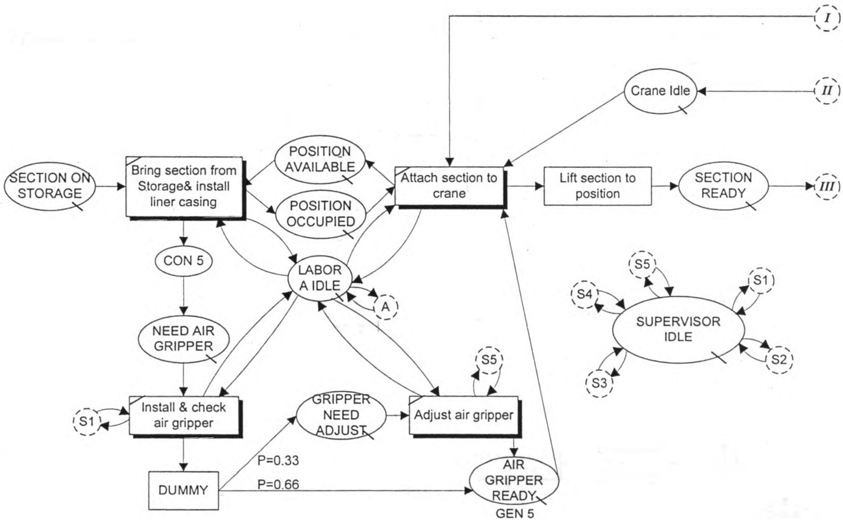


Figure Error! No text of specified style in document. –Prototype CYCLONE Model for the Observed Microtunneling Operation

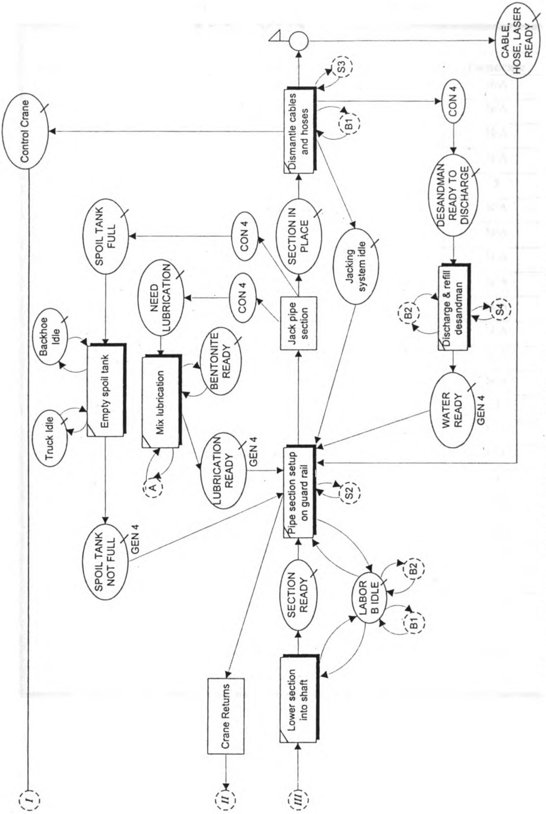


Figure 3.19 –Prototype CYCLONE Model for the Observed Microtunneling Operation (Continued)

Figure 3.18 – Queue Elements in Prototype Model

QUEUE elements		
Element number	**Description**	**Generate**
11	Section on storage	N/A
12	Position available	N/A
13	Labor A idle	N/A
14	Supervisor idle	N/A
15	Air gripper ready	5
16	Crane idle	N/A
17	Crane control	N/A
18	Labor B idle	N/A
19	Truck idle	N/A
20	Backhoe idle	N/A
21	Lubrication ready	N/A
22	Bentonite ready	N/A
23	Jacking system idle	N/A
24	Water ready	4
25	Need air gripper	N/A
26	Air gripper need adjust	N/A
27	Spoil tank not full	4
28	Position occupied	N/A
29	Section ready	N/A
30	Section ready	N/A
31	Spoil tank full	4
32	Need slurry	N/A
33	Desandman ready to be discharged	N/A
34	Section in place	N/A
35	Cables, hoses, and laser ready	N/A

Figure 3.19 –Function Elements in Prototype Model

FUNCTION elements		
Element number	**Description**	**Consolidate**
36	CON 5	5
37	CON 4	4
38	CON 4	4
39	CON 4	4
99	COUNTER	N/A

Number generated by QUEUE element is multiplying resource units exit after one unit enters the QUEUE. Consolidate is the number to be consolidated before the entity exits this node. If combined on one flow route, consolidate and generate can model regularly happened activities. For example, when *Jack pipe section* is finished, one unit is released to function node 37 to consolidate 4, which will stay in the function node until four pipe sections are jacked and lubrication need to be added. Then, the four consolidated units trigger one time of mixing lubrication. After lubrication ready, the QUEUE node generates four units available for *Pipe section setup on guard rail*, which will provide adequate lubrication for next four pipe sections.

Figure 3.20 – Normal Elements in Prototype Model

NORMAL elements	
Element number	**Description**
40	Lift section to position
41	Crane returns
42	Jack pipe section
43	DUMMY

3.5 Resources Initialization

After building the model, in order to perform the simulation, the resources must be initialized. This is the third step of the model building process. Table 3.7 provides the information regarding initialization for all the resources. The resources have been initialized such that at the beginning of the simulation all the pipe sections are on the storage, the crane is available, supervisor, crew Labor A and B are free, air gripper is not needed for the first four sections, trucks and backhoe are free, spoil tank, water, and lubrication are ready for the first four sections, bentonite is ready to make lubrication, jacking system, cables, hoses, and laser are ready. Hence before the jacking begins, a section must be brought from storage and prepared, lowered into the shaft, and finally set up on the jacking frame.

Figure 3.21 –Resource Initialization

Resource Initialization			
Queue	**Description**	**Quantity**	**Type**
11	Section on storage	30	Pipe section
12	Position available	1	Position
13	Labor A idle	1	Labor
14	Superintendent idle	1	Supervisor
15	Air gripper ready	1	Signal
16	Crane idle	1	Crane
17	Crane control	1	Signal
18	Labor B idle	1	Labor
19	Truck idle	1	Truck
20	Backhoe idle	1	Backhoe
21	Lubrication ready	1	Signal
22	Bentonite ready	1	Bentonite
23	Jacking system idle	1	Jacking system
24	Water ready	1	Signal
27	Spoil tank not full	1	Signal
35	Cables, hoses, and laser ready	1	Signal

3.6 Modeling Assumptions

Certain assumptions were made in order to build this prototype model. These assumptions are as follows:

- The manner in which the resources have been initialized assumes that at the beginning of the simulation all pipe sections are on the storage, therefore the driving shaft is empty.
- One complete production cycle is finished after one pipe section (8 feet long) is fully jacked, the slurry and hydraulic lines have been dismantled from that section and the jacking frame is fully retracted.

- Labor A (1-labor crew) and labor B (1 labor and 1 technician crew) work independently.
- One tank of mixed lubrication lasts for the duration of the jacking of four pipe sections (CON 4, node 37).
- The spoil tank must be emptied after tunneling for 4 consecutive pipe sections (CON 4, node 38) averagely in four types of soil conditions.
- The water in the system must be changed after tunneling for 4 consecutive pipe sections (CON 4, node 39) averagely in four types of soil conditions.
- The air gripper must be installed on every five pipe sections. It is checked for and must be adjusted 33% (P = 0.33 between node 43 and 26) of the times it is checked.
- The time required to retract the jacks is included in the slurry and hydraulic lines dismantling activity (COMBI node 3).
- The time required to set up laser is included in the pipe section setting up activity (COMBI node 5); the time required to take off laser is included in the slurry and hydraulic lines dismantling activity (COMBI node 3).
- Before the setting up of a pipe section in the shaft can take place the following tasks must be finished (in order of priority): changing the water in the system (if necessary), mixing of lubrication (if necessary), slurry and hydraulic must be dismantled from the previous section, jacks must be retracted, laser must taken off, and the Labor B crew must be available.
- MTBM breakdown and obstruction that may halt the operation are not considered.

3.7 Model Enhancement with Soil Composition Changes

After the building of a prototype model, duration data for activities was analyzed to find distributions for the simulation, which is discussed in Chapter 4. The model was coded with duration distributions and loaded onto WebCYCLONE for simulation. The results were compared with observed productivity for validation in Chapter 5. The simulation results were satisfactory, which means the structure and logic of the prototype model was valid for enhancements with soil composition changes.

Enhancements to include changes in the operation due to different soil composition are introduced as shown in Figure 3.19 and 3.20. Three enhancements were included. After pipe section is setup on guard rail, a dummy activity was introduced to split the flow unit into four ways according to probability on each route. Four routes represent four types of soils used in the candidate project. The probability of each route is set equally to 0.25, because the testing bed was constructed of four segments of different soils with the same length. By changing the probabilities on each route, various combination of soil compositions can be simulated to find the correlation between productivity and soil condition, which will be discussed in Chapter 6. The second enhancement will be presented in Chapter 4, which is finding the different duration time distribution in four types of soils.

The other change was on the water resource cycle. Because the slurry pump used in the candidate project was not compatible of handling clay soil, the desandman was discharged more frequent when pipe in clay soil, which is reflected in the model structure. The desandman need to be discharged every two pipe sections jacked in clay soil, while every six pipe sections jacked in other three kinds of soils. The average times of discharging desandman remains six in 24 pipe sections installation.

To match the structure of changed consolidate nodes, QUEUE Water Ready (node 24) is no longer generate 4 units as in the prototype model. Instead, after dismantling cables and hoses in any type of soils, one unit flows to QUEUE Water Ready (node 24) and Con 2 or Con 3. Before certain number is consolidated, the COMBI Discharge and Refill Desandman (node 1) will not be triggered, so the QUEUE Water Ready (node 24) provides unit for COMBI (node 5) Pipe Section Setup on Guard Rail for jacking activity. Once the consolidation reaches the preset number, one unit will be released to trigger COMBI Discharge and Refill Desandman (node 1). Because of the dual direction of unit flow between QUEUE (node 24) and COMBI (node 1) and higher priority of COMBI (node 1), any unit in QUEUE (node 24) Water Ready will flow back to COMBI (node 1) to discharge and refill desandman and put COMBI (node 5) Pipe Section Setup on wait until desandman is ready. This structure change models the water resource cycle in different soils.

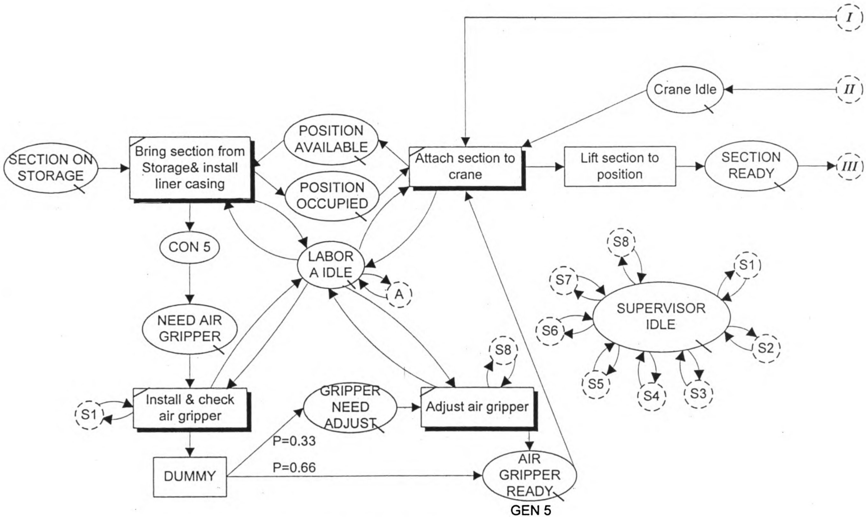


Figure 3.24 – CYCLONE Model Considering Soil Types

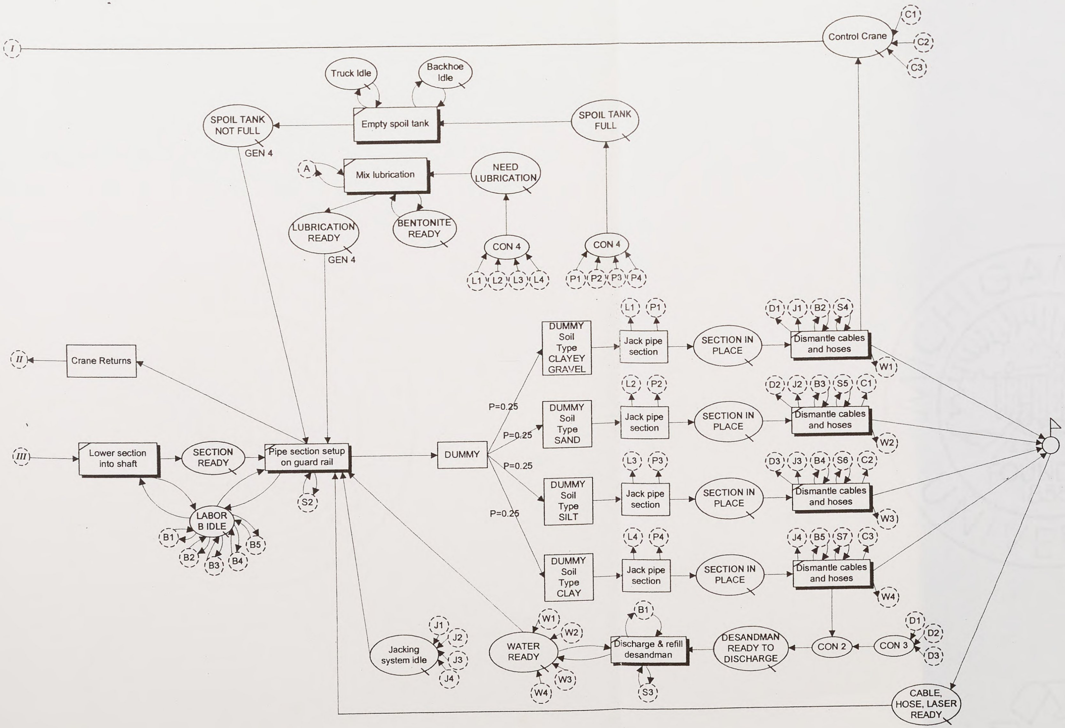


Figure 3.25 – CYCLONE Model Considering Soil Types (Continued)

4 STATISTICAL ANALYSIS OF OBSERVED DURATION DATA

In order to conduct simulations in WebCYCLONE with built model, task duration data obtained from the candidate project need to be analyzed. Each task element should be accompanied with a duration set number that defines the duration category of the task and the population from which the duration of the task will be sampled. MicroCYCLONE / WebCYCLONE recognizes two categories of tasks based on duration-stationary tasks and nonstationary tasks. From data collected during the operation, only duration-stationary tasks are defined. Figure 4.1 illustrates the time consuming process of the simulation program and the works presented in Chapter 3 and 4.

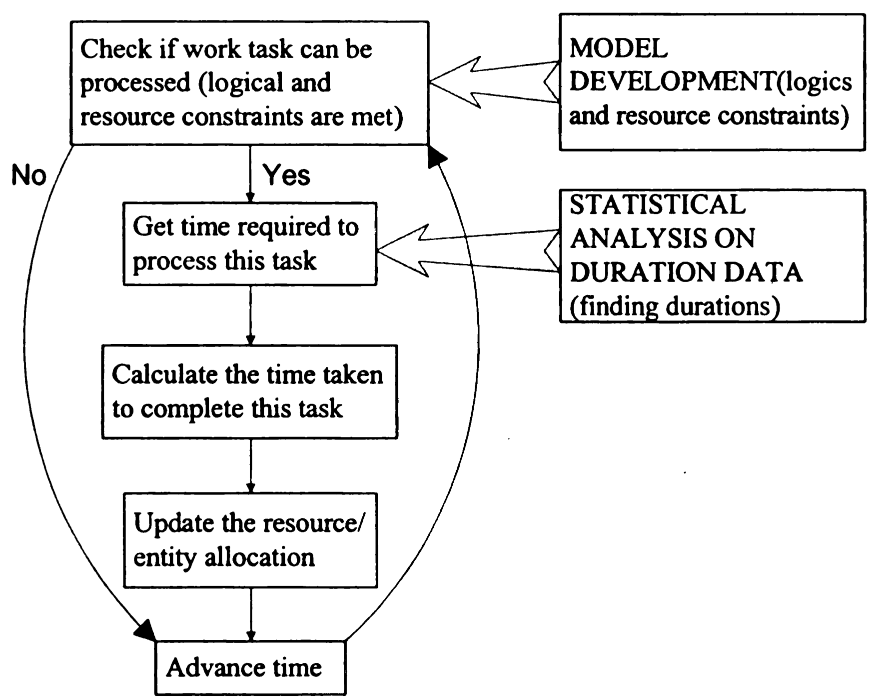


Figure 4.1 – Time Consuming of the WebCYCLONE Simulation Program

4.1 Data Collected from the Project

Appendix B shows the duration data collected from the candidate project. 24 sets of data are recorded for activities:

- Durations of COMBI (node 1) Discharge and Refill Desandman,
- COMBI (node 3) Dismantle Cables and Hoses,
- COMBI (node 5) Pipe Section Setup on Guard Rail,
- COMBI (node 7) Adjust Air Gripper,
- COMBI (node 8) Install and Check Air Gripper,
- COMBI (node 10) Bring Section from Storage and Install Liner Casing,
- And NORMAL (42) Jack Pipe Section.

The distributions of recorded activity durations will be found using goodness-of-fit testing on CDFs (Cumulative Density Function). Activity duration of jacking pipe section will be further analyzed to find distributions in four types of soil conditions. All the analyses are done with R1.9.0. R, which is a free version of S-plus and can be downloaded from http://www.r-project.org/.

Non-record activity durations such as crane returning, attaching pipe to crane are not critical in the project, and are assumed as having same distributions as other recorded slurry microtunneling project (Nido et al. 1999).

4.2 Introduction to Statistical Distributions in WebCYCLONE

The statistical distributions for the duration time random variables recognized by the input module of WebCYCLONE program are:

- Exponential distribution,
- Triangular distribution,
- Uniform distribution,
- Log normal distribution,
- And Beta distribution.

1. Exponential distribution: $\exp(\theta)$

The probability density function (PDF) of the exponential distribution $\exp(\theta)$ is

$f(x) = \frac{1}{\theta} e^{-x/\theta}, \quad x > 0, \quad \theta > 0$, where θ is the scale parameter.

Both the mean and the standard deviation of $\exp(\theta)$ equal to θ.

The cumulative distribution function (cdf) is the probability that the variable takes a value less than or equal to x. That is $F(x) = \Pr(X \le x)$. Therefore, the cdf of exponential distribution $\exp(\theta)$ is $F(x) = 1 - e^{-x/\theta}, \quad x > 0, \quad \theta > 0.$

The exponential pdf is always convex, and is stretched to the right as θ increases in value. The following in Figure 4.2 are the plots of the probability density functions of $\exp(0.5)$, $\exp(1)$ and $\exp(2)$.

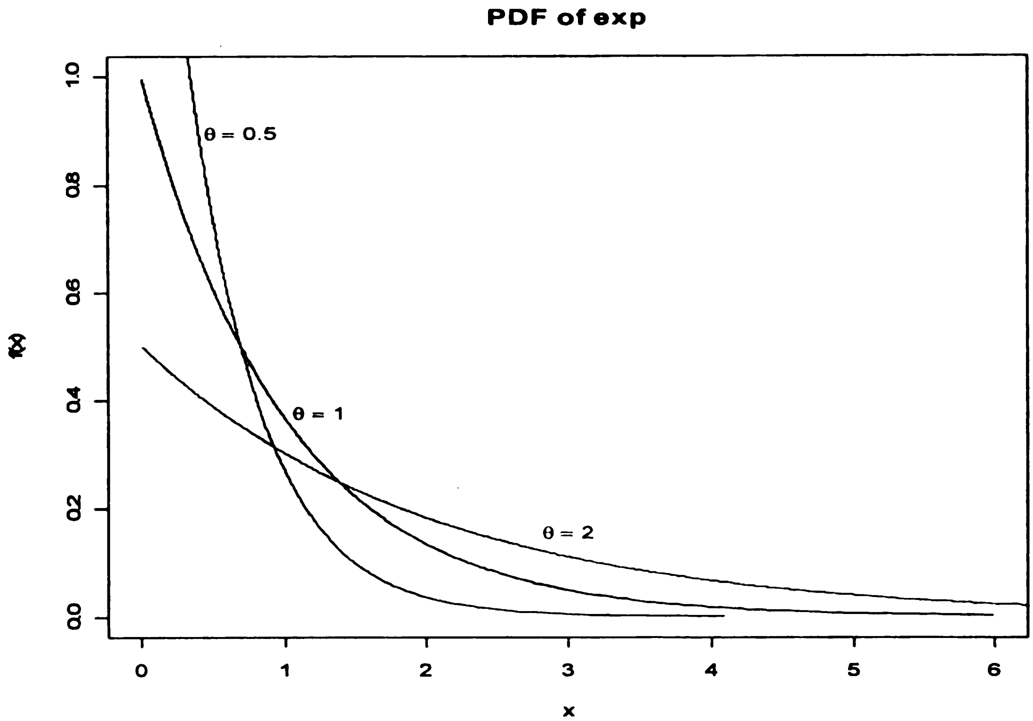


Figure 4.2 –PDFs of Exponential Distribution (Shao, 2003)

2. Triangular distribution: $\text{Triangular}(a, \theta, b)$

The probability density function (pdf) of the Triangular distribution $\text{Triangular}(a, \theta, b)$ is

$$f(x) = \begin{cases} \dfrac{2(x-a)}{(b-a)(\theta-a)}, & a \le x \le \theta \\ \dfrac{2(b-x)}{(b-a)(b-\theta)}, & \theta \le x \le b \end{cases}$$

, and its cdf is

$$F(x) = \begin{cases} \dfrac{(x-a)^2}{(b-a)(\theta-a)}, & a \le x \le \theta \\ 1-\dfrac{(b-x)^2}{(b-a)(b-\theta)}, & \theta \le x \le b \end{cases}$$

,

where a represents the lower bound (the least possible value), b represents the upper bound (the highest possible value), and θ is the mode (the most common value). The distribution is called right triangular distribution when $\theta = b$, and left triangular distribution when $\theta = a$. The mean of Triangular(a, θ, b) equals to $\frac{1}{3}(a+b+\theta)$, and the standard deviation equals to $\sqrt{\frac{a^2+b^2+\theta^2-ab-a\theta-b\theta}{18}}$.

The distribution is skewed to the left when the mode is close to the minimum, and is skewed to the right when the mode is close to the maximum. It is a simple distribution that as its name implied, has a triangular shape. Below in Figure 4.3 are the plots of the pdfs of four triangular distributions with varying parameters.

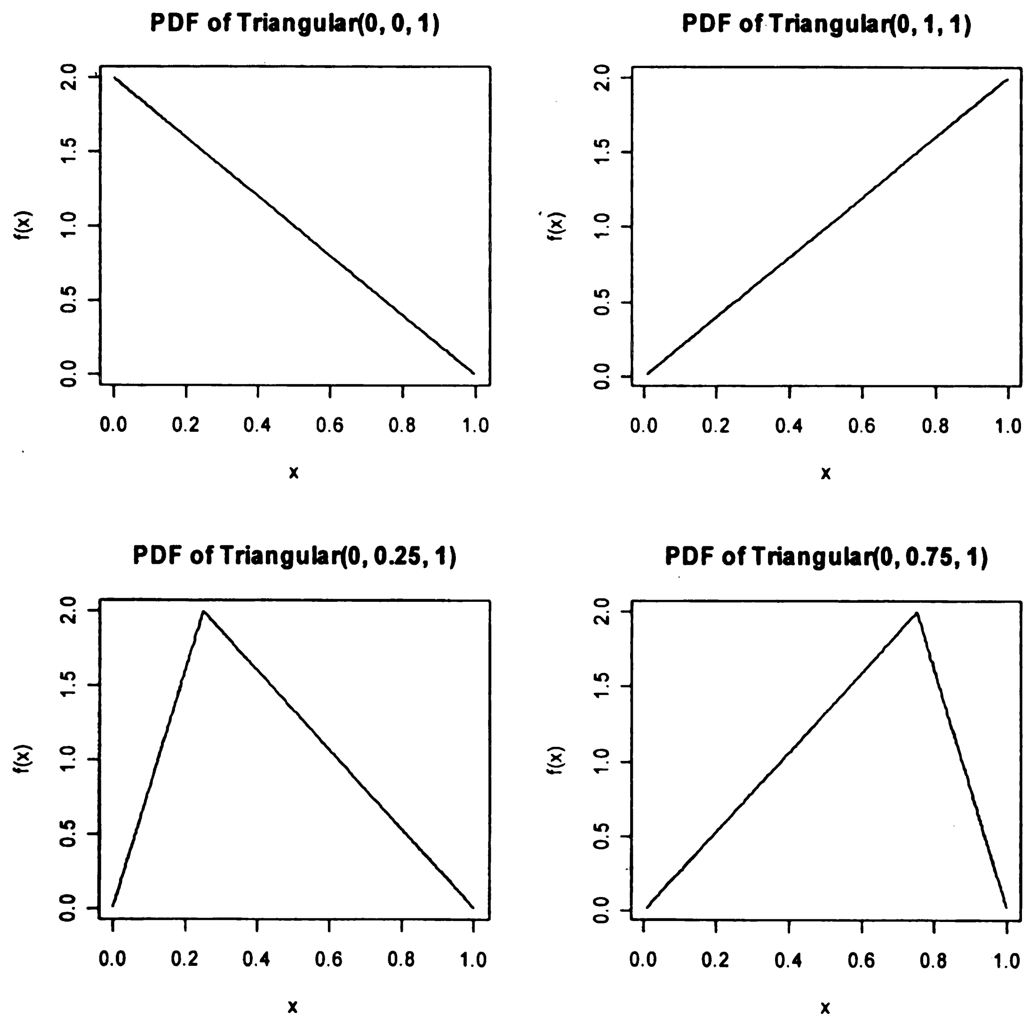


Figure 4.3 –PDFs of Triangular Distribution

3. Uniform distribution: $U(a, b)$

The probability density function (pdf) of the uniform distribution $U(a, b)$ is $f(x) = \frac{1}{b-a}, \quad a \le x \le b$, where a is the location parameter representing the lower bound (the least possible value), and $b-a$ is the scale parameter with b representing the upper bound (the highest possible value). The mean of $U(a, b)$ equals to $\frac{1}{2}(a+b)$, and the standard deviation equals to $\frac{b-a}{\sqrt{12}}$.

The following in Figure 4.4 is the plot of the probability density function of $U(0,1)$.

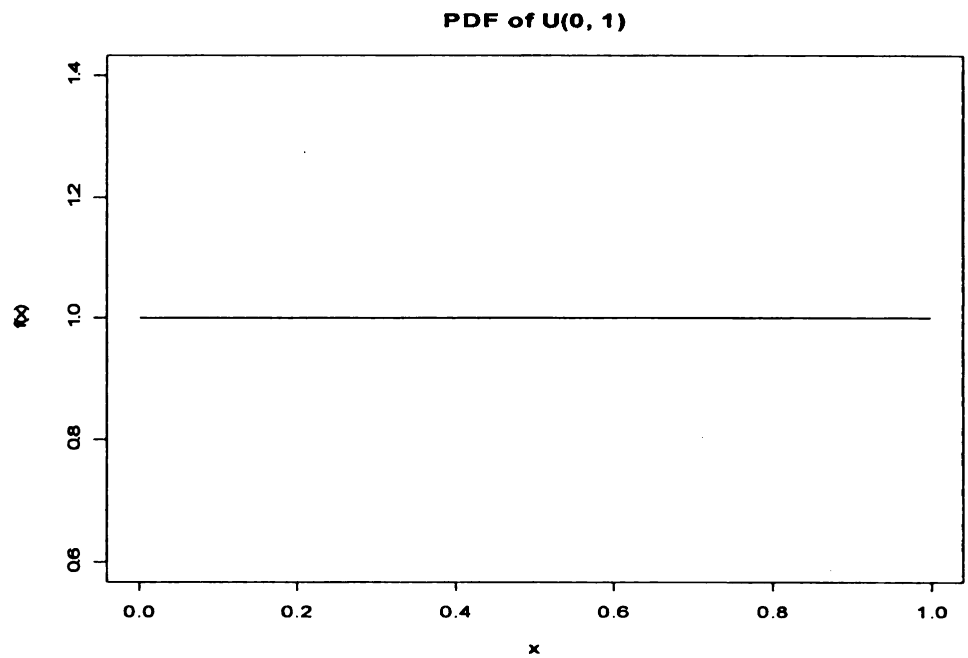


Figure 4.4 –PDF of Uniform Distribution

The uniform distribution measures data for which the probability of occurrence is the same for all possible values of x.

4. Lognormal distribution $\log normal(\theta, \lambda, \sigma^2)$

A variable X is lognormally distributed if $Y = \log(X)$ is normally distributed, where "$\log$" denotes the natural logarithm. The probability density function (pdf) of the lognormal distribution $\log normal(\theta, m, \sigma)$ is

$$f(x) = \frac{e^{-[\log((x-\theta)/\lambda))^2/(2\sigma^2)]}}{(x-\theta)\sigma\sqrt{2\pi}}, \quad x \geq \theta; \ \ \lambda > 0, \ \ \sigma > 0,$$

where θ is the location parameter, λ is the scale parameter, and σ is the shape parameter. The case where $\mu = 0$ and $\lambda = 1$ is called standard lognormal distribution. The mean of $\log normal(\theta, \lambda, \sigma^2)$ equals to $\theta + \lambda e^{0.5\sigma^2}$. The standard deviation of $\log normal(\theta, \lambda, \sigma^2)$ equals to $\lambda\sqrt{e^{\sigma^2}(e^{\sigma^2} - 1)}$.

The lognormal distribution is a distribution skewed to the right, and the degree of skewness increases as σ increases, for a given (θ, λ). Therefore, lognormal distribution is used to model continuous random quantities when the distribution is believed to be skewed, such as certain income and lifetime variables. The following in Figure 4.5 is the plot of the standard lognormal probability density function for four values of σ.

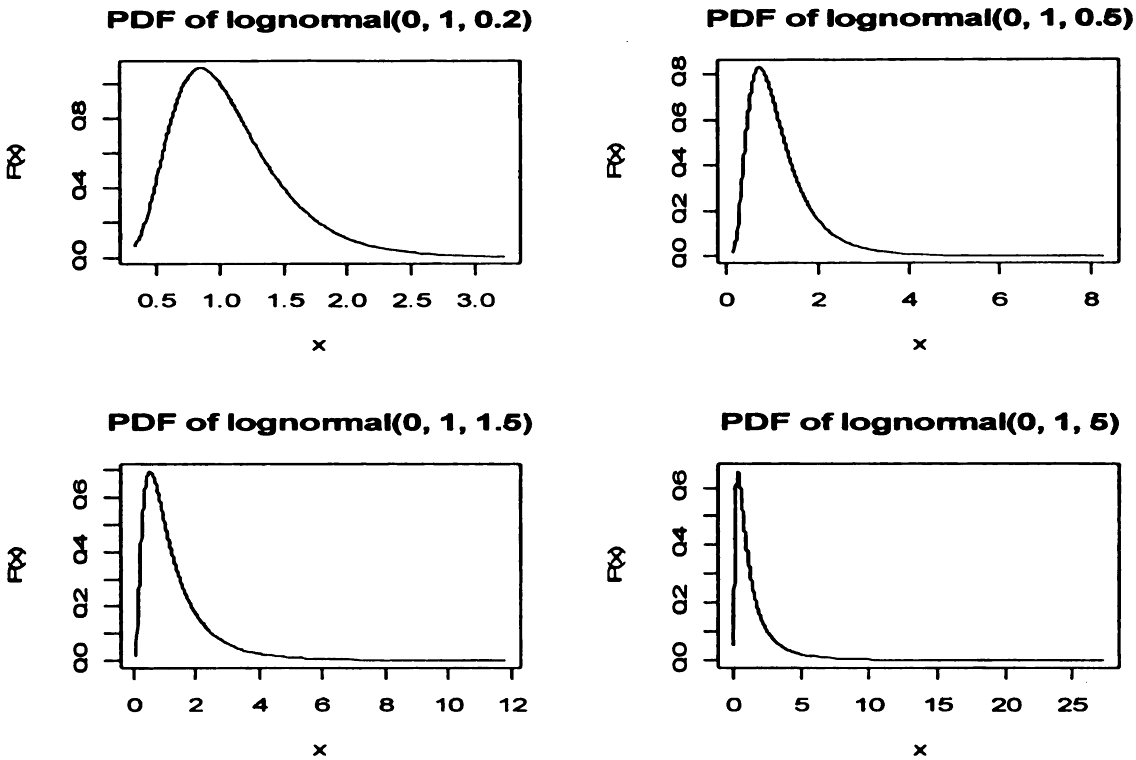


Figure 4.5 –PDFs of Lognormal Distributions

5. Beta distribution: $\beta(a, b, c, d)$

The probability density function (pdf) of the beta distribution $\beta(a, b, c, d)$ is

$$f(x) = \frac{1}{b-a} \cdot \frac{\Gamma(c+d)}{\Gamma(c)\Gamma(d)} (1 - \frac{x-a}{b-a})^{d-1} (\frac{x-a}{b-a})^{c-1},$$

$a \le x \le b$; $a > 0$, b > 0, c > 0, d > 0,

where c and d are the shape parameters, a and b are the lower and upper bounds, respectively of the distribution. Here $\Gamma(x)$ is the gamma function, which is defined as

$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt$. If x is an integer $n = 1, 2, 3, \ldots$, then

$\Gamma(n) = (n-1)(n-2)(n-3)\cdots 1 = (n-1)!$.

The case where a = 0 and b = 1 is called the standard beta distribution. The uniform distribution $U(a,b)$ is a special case of beta distribution when $c = d = 1$.

The mean of $\beta(a,b,c,d)$ equals to $a + (b-a)\frac{c}{c+d}$, and its standard deviation equals to $(b-a)\sqrt{\frac{cd}{(c+d)^2(c+d+1)}}$.

The shape of the beta distribution is quite variable depending on the values of the parameters. As illustrated by the plot below, when $c < 1$ and $d < 1$, the distribution is U-shaped; when the two parameters are equal, the distribution is symmetrical, and a special case is uniform distribution when; if $c < d$, then the distribution is skewed to the left; if $c > d$, then the distribution is skewed to the right. The beta distribution is often used to estimate the proportion of defective items in a shipment or model time to complete a task. Figure 4.6 shows the plot of the beta probability density function for different values.

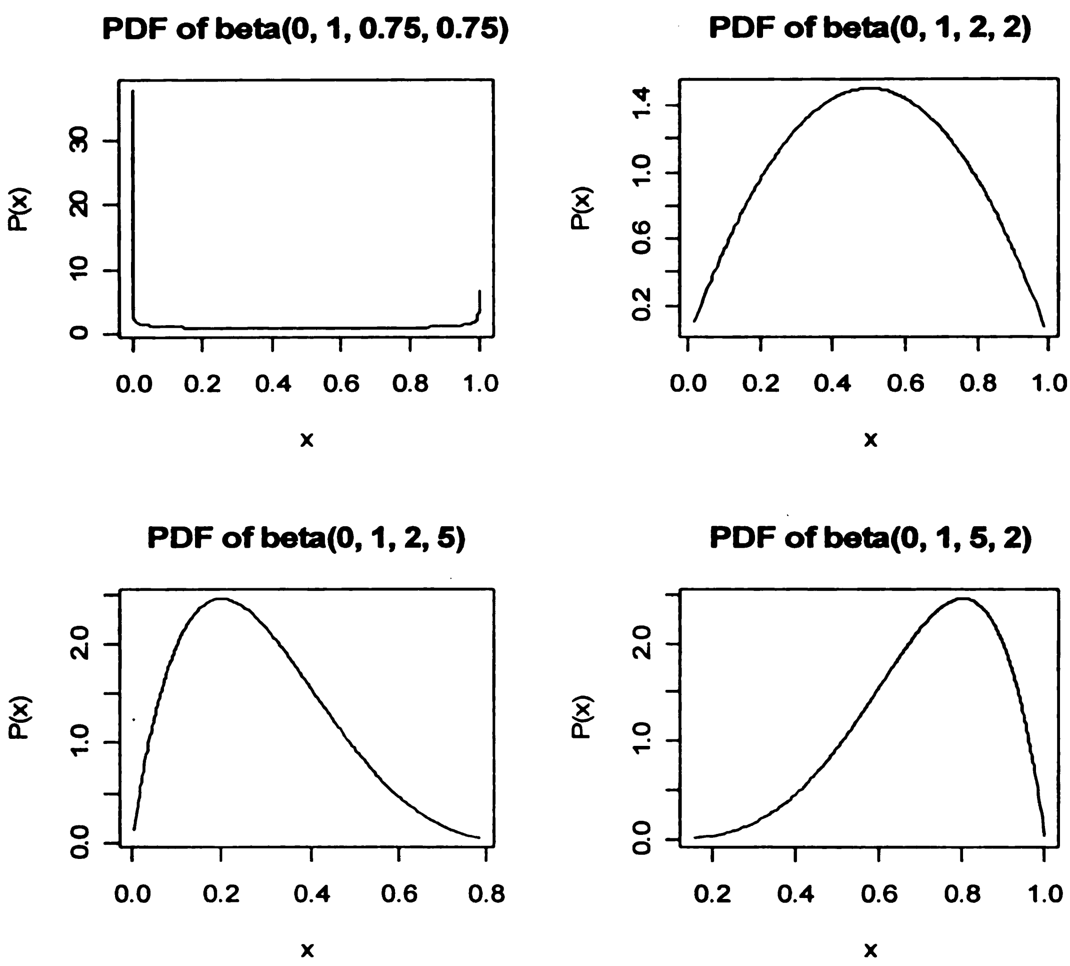


Figure 4.6 – PDFs of Beta Distributions

4.3 Kolmogorov-Smirnov Goodness-of-Fit Test

To decide the distributions for the duration time random variables, we follow the below steps. First we assume a pre-specified distribution based on the statistical properties, for instance the histogram plot, of the duration data. Then we estimate the distribution parameters from the data using the Maximum Likelihood Estimation (MLE) method. Next we test the assumed distribution using Kolmogorov-Simirnov test. If the assumed distribution is rejected, we will choose another distribution, and repeat the above steps until we find an appropriate distribution.

The Kolmogorov-Smirnov test was developed by Kolmogorov and Smirnov in the 1930s to to determine if a sample comes from a given hypothesized distribution. The Kolmogorov-Smirnov test is based on the empirical cumulative distribution function (ECDF). Given n ordered data points $x_{(1)} \le x_{(2)} \le \cdots \le x_{(n)}$, the ECDF is defined as

$$F_n(x) = \begin{cases} 0, & x < x_{(1)} \\ \frac{1}{n}, & x_{(1)} \le x < x_{(2)} \\ \cdots & \\ \frac{i}{n}, & x_{(i)} \le x < x_{(i+1)} \\ \cdots & \\ 1, & x_{(n)} \le x \end{cases}$$

The Kolmogorov-Smirnov test statistic D is defined as the maximum difference between the empirical distribution function and the theoretical cumulative distribution function (cdf) of the hypothesized distribution. The hypothesized distribution is rejected when D is large enough, or equivalently when the p-value is smaller than the significance level α, which is commonly chosen as 0.05.

4.4 Distributions Suggested for the Duration Time Random Variables

Table 4.1 summarizes the distributions determined, the correspondent estimations of parameter, the test statistics D and the p-values of the Kolmogorov-Smirnov test.

Table 4.1–Distributions, Parameters, Test Statistics, and P-values

Variables	Distribution Determined	Parameters	D-statistic of Kolmogorov-Smirnov test	P-value of Kolmogorov-Smirnov test	Comment
NOR 42	$\log normal(\theta,\lambda,\sigma^2)$	Lognormal (8, 30.177, 0.756)	0.0917	0.988	GOOD
NOR 42	BETA (Par1) (Par2) (Par3) (Par4)	Beta(12, 102, 0.854, 1.403)	0.159	0.579	OK (suggest)
NOR 42	Triangular(a, θ, b)	Triangular(12, 31, 92)	0.168	0.507	OK (suggest)
COMBI 5	BETA (Par1) (Par2) (Par3) (Par4)	BETA (28, 80, 0.761, 1.841)	0.1129	0.920	Good (suggest)
COMBI 5	$\log normal(\theta,\lambda,\sigma^2)$	Lognormal (25, 14.062, 0.783)	0.1021	0.964	Good
COMBI 10	$\log normal(\theta,\lambda,\sigma^2)$	Lognormal (0, 6.838, 0.377)	0.1615	0.559	Good
COMBI 10	BETA (Par1) (Par2) (Par3) (Par4)	Beta (3, 23, 1.481, 5.353)	0.2059	0.261	Worse than Triangular
COMBI 10	Triangular(a, θ, b)	Triangular (2, 5, 15)	0.1891	0.357	OK (suggest)
COMBI 3	$\log normal(\theta,\lambda,\sigma^2)$	Lognormal (5, 5.537, 0.650)	0.1226	0.880	Good
COMBI 3	BETA (Par1) (Par2) (Par3) (Par4)	BETA (7, 33, 0.643, 3.020)	0.1304	0.8288	Good (suggest)
COMBI 3	Triangular(a, θ, b)	Triangular (3, 7, 27)	0.1696	0.5228	OK (worse than beta)

Figures 4.7 to 4.10 show the CDFs of the determined distributions for NORMAL 42, COMBI 5, COMBI 10, COMBI 3 respectively.

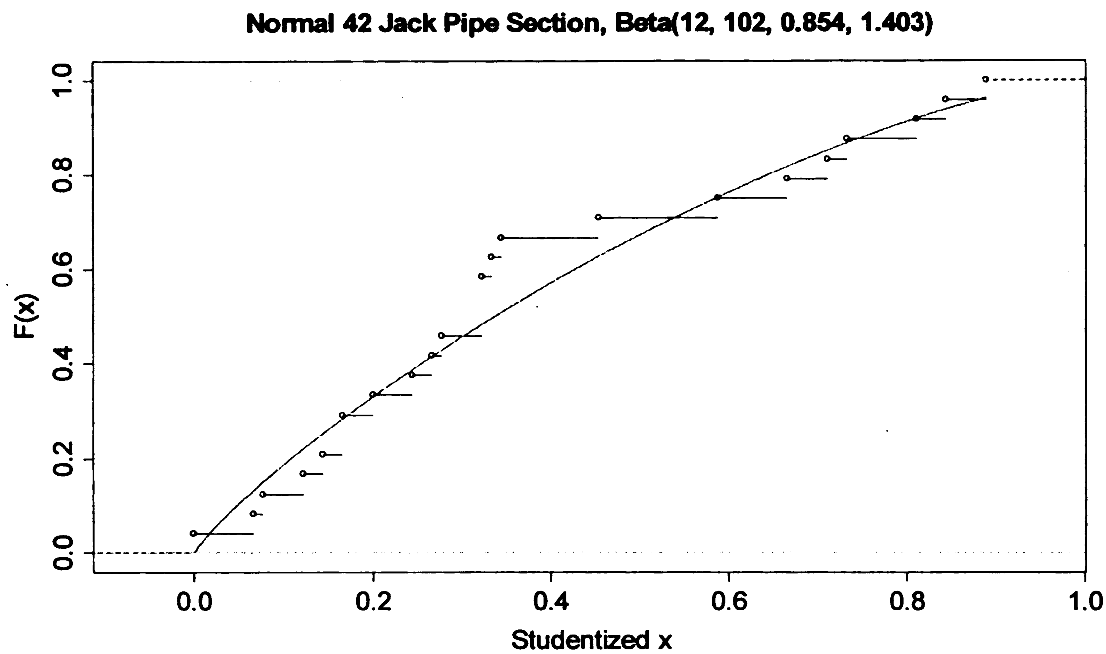


Figure 4.7 –CDF of NORMAL 42 Jack Pipe Section

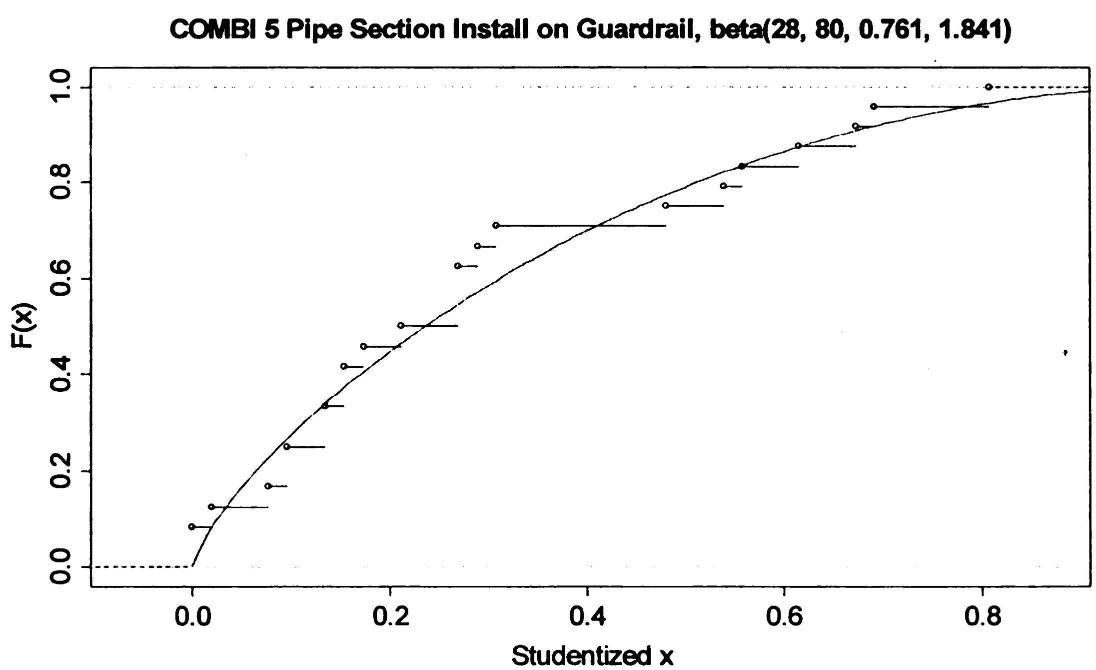


Figure 4.8 –CDF of COMBI 5 Install Pipe Section on Guardrail

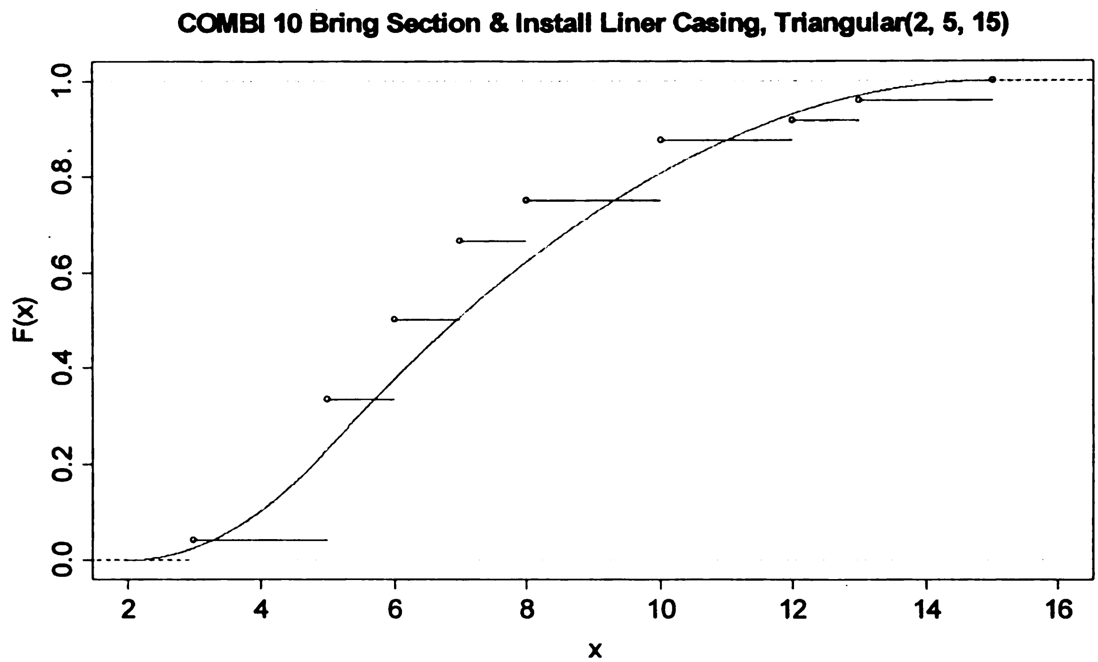


Figure 4.9 – CDF of COMBI 10 Bring Section and Install Liner Casing

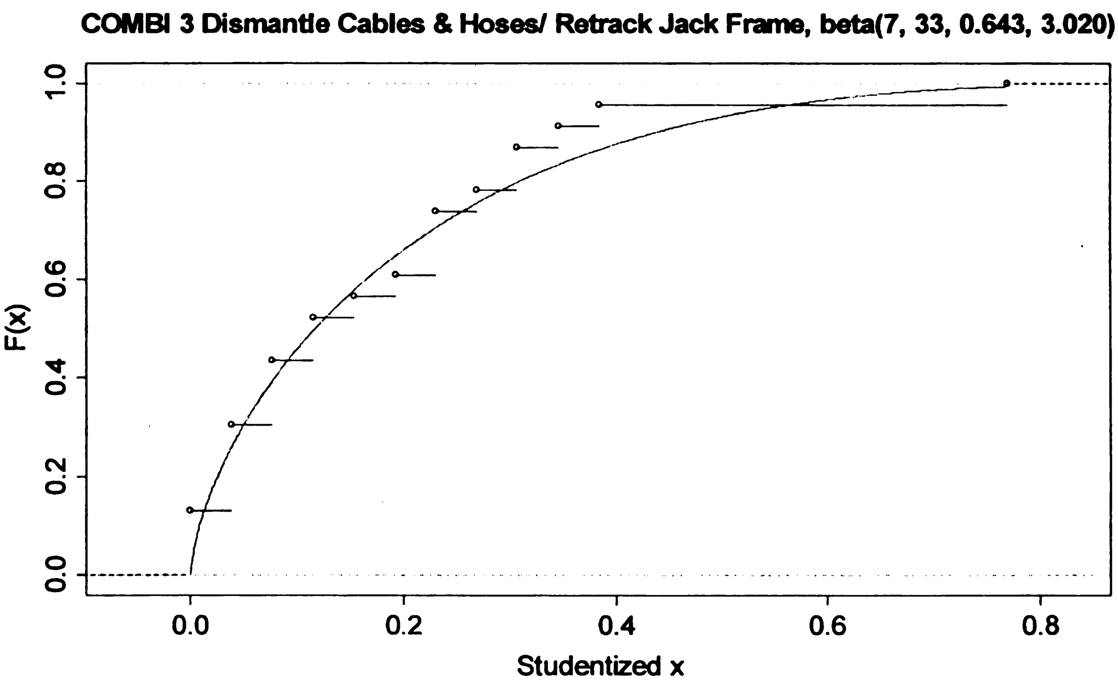


Figure 4.10 –CDF of COMBI 3 Dismantle Cables & Hoses/ Retrack Jack Frame

Activity duration distributions used in the simulation are shown in Table 4.2. It was discovered that lognormal distribution was not implemented in WebCYCLONE. Thus, any statistically suggested lognormal distribution was replaced by the second good distribution in the simulation as shown in Table 4.1.

Table 4.2 –Duration Information

Activity number	Description	Probabilistic distribution
1	Discharge and refill desandman	TRI (10,12,15)
2	Mix lubrication	TRI (25,30,35)
3	Dismantle cables and hoses	BETA (7,33,0.643,3.020)
4	Empty spoil tank	TRI (20,30,35)
5	Setup pipe section on guard rail	BETA (28,80,0.761,1.841)
6	Lower section into shaft	UNI (1,2)
7	Adjust air gripper	UNI (10,15)
8	Install and check air gripper	UNI (10, 15)
9	Attach section to crane	DET (2)
10	Bring section from storage and install liner casing	TRI (2,5,15)
40	Lift section to position	DET (1)
41	Crane returns	DET (2)
42	Jack pipe section	BETA (12, 102, 0.854, 1.403)
43	Dummy	DET (0)

4.5 Compare the Duration Time of Jacking Pipe Section in Different Soil Conditions

In this section, the differences between the jacking pipe activity durations in four types of soils are compared. When microtunneling in different types of soils, the major productivity difference comes from the activity COMBI 42 *Jack Pipe Section*, which is the direct interaction between soil composition and microtunneling productivity. If the differences of durations are significant, then building model with different soils enhancement is a valid approach. In addition, distributions of jacking pipe sections in different soils need to be found.

Table 4.3 shows the sample means and sample standard deviations for each soil. From Table 4.3, we see that the mean jacking time in clay is the largest, which is mainly due to the incompatibility of slurry system and clay soil; the next largest is clayey gravel; silt and sand takes the shortest times.

Table 4.3 – Sample Means and Standard Deviations of Jacking Durations in Different Soils

Soils	Sample Mean	Sample Standard Deviation
Clay	70.67	22.89
Silt	29.167	8.40
Sand	26.83	10.87
Clayey Gravel	57.5	17.56

To test further whether the differences are significant, we perform the pairwise comparisons between the pushing times on four different soils using Welch's two sample t-test where equal variances are not assumed, and Wilcoxon rank sum test. The t-test is a popular test used to compare the means of two populations, and it assumes that the two populations are both normal distributed. The Wilxocon rank sum test is a nonparametric version of the two sample t-test, and it tests the equality of the medians of two populations. The Wilxocon rank sum test is very commonly used when the sample size is very small or when the normality assumption is violated, which is the case of this study.

Table 4.4 and 4.5 summarize the pairwise comparison results from t-test and Wilcoxon rank tests, respectively. Both t-test and Wilcoxon rank tests give the similar results.

There is no statistical significant difference between clay and clayey gravel, neither between silt and sand. The mean jacking durations between the rest 4 pairs: clay and silt, clay and sand, clayey gravel and silt, clayey gravel and sand are significantly different. More specifically, the jacking time in clay and clayey gravel are significantly longer than those on silt and sand.

Table 4.4 – Pairwise comparison results from two sample t-test

Pair	Test statistic	p-value	Significant
Clay vs Silt	4.1694	0.005243	Yes
Clay vs Sand	4.2374	0.003676	Yes
Clay vs Clayey gravel	1.118	0.2914	No
Silt vs Sand	0.416	0.6867	No
Silt vs Clayey gravel	-3.5656	0.008783	Yes
Sand vs Clayey gravel	-3.6375	0.00616	Yes

Table 4.5 – Pairwise comparison results from Wilcoxon rank test

Pair	Test statistic	p-value	Significant
Clay vs Silt	34	0.01291	Yes
Clay vs Sand	34	0.008658	Yes
Clay vs Clayey gravel	25	0.3095	No
Silt vs Sand	20.5	0.7479	No
Silt vs Clayey gravel	0.5	0.0063	Yes
Sand vs Clayey gravel	0.5	0.006392	Yes

Using the Kolmogorov-Smirnov test, jacking duration distributions in different soils are found as shown in Table 4.6.

Table 4.6 –Jacking Pipe Duration Distributions in Different Soils

Activity	**Soil Condition**	**Probabilistic distribution**
Jack Pipe Section	Clay	BETA (19, 92, 0.781, 0.323)
Jack Pipe Section	Silt	BETA (17, 51, 0.989, 1.775)
Jack Pipe Section	Sand	BETA (12, 46, 0.613, 0.793)
Jack Pipe Section	Clayey Gravel	BETA (26, 88, 1.075, 1.041)

5 SIMULATION RESULTS AND DISCUSSION

In chapter 3, the prototype model and soil impacts enhanced model of microtunneling have been developed. In addition, chapter 4 studied the activity duration data in both models. Combining previous work, this chapter presents simulation results from two models subsequently. Firstly, simulations with the prototype model are conducted and the validation of the prototype model is discussed with simulation results. After the validation, considerations of different soil compositions are added into the model, which was presented in chapter 3 (section 3.7). Simulations have been conducted again with enhanced model. Simulation results from enhanced model are validated and conducted sensitivity analysis to optimize the productivity. Finally in this chapter, different soil composition impacts on microtunneling productivity are studied.

5.1 Simulation Results with Prototype CYCLONE Model

A total of 30 simulation runs were performed with the prototype CYCLONE microtunneling model. Appendix C has the coding for prototype model with duration data distribution discussed in chapter 4. Appendix E presents the full set of data from simulation results, which includes productivity information for each cycle, duration statistics for CYCLONE active elements, idling percentage and waiting time statistics for CYCLONE passive elements, and elements trace information.

For validation purpose, the productivities generated from the simulations are studied thoroughly. Other results as resource idling and limitations will be analyzed with soil enhanced model. Table 5.1 and 5.2 show the productivities obtained from the simulation.

Table 5.1 –Simulated Microtunneling Process Productivity Information by Cycle

Sim. Time (Accumulative)	Cycle No.	Duration Per Pipe Section (min.)	Productivity Per Time Unit
160.4	1	160.4	0.006234
280.9	2	140.45	0.007120
337.1	3	112.3666667	0.008899
396.8	4	99.2	0.010080
629.7	5	125.94	0.007940
751.5	6	125.25	0.007984
898.1	7	128.3	0.007794
967.9	8	120.9875	0.008265
1066.1	9	118.4555556	0.008442
1195.2	10	119.52	0.008367
1271.2	11	115.5636364	0.008653
1343.9	12	111.9916667	0.008929
1425.2	13	109.6307692	0.009121
1496.9	14	106.9214286	0.009353
1550.4	15	103.36	0.009675
1607.3	16	100.45625	0.009955
1706.7	17	100.3941176	0.009961
1802.5	18	100.1388889	0.009986
1936.0	19	101.8947368	0.009814
2031.1	20	101.555	0.009847
2199.3	21	104.7285714	0.009549
2374.4	22	107.9272727	0.009265
2501.4	23	108.7565217	0.009195
2629.1	24	109.5458333	0.009129
2715.5	25	108.62	0.009206
2818.7	26	108.4115385	0.009224
2908.8	27	107.7333333	0.009282
3013.0	28	107.6071429	0.009293
3170.4	29	109.3241379	0.009147
3235.4	30	107.8466667	0.009272

Table 5.2 –Overall Simulated Microtunneling Process Productivity Information

Total Sim. Time Unit (in minute)	Cycle No.	Productivity (per pipe section)	Productivity (per time unit)
3235.4	30	107.867	0.009272409316360385

Figure 5.1 shows the change of productivities in thirty cycles. A pattern can be easily observed on the plot. The duration time decreasing steeply on the initial four pipe sections reflects the preparation work has to be done at the beginning stage of the project. Moreover, it can be explained as following productivity learning curve (Abdelhamid 2004), which predicts productivity will increase as units being constructed, and the increase rate is slowing down to zero eventually. There always is a limit of productivity increase through learning. Abnormal pattern appears after pipe section number four that cycle duration climbs suddenly. This abrupt change can only be explained as resource limitation. Rearranging resource might release this bottleneck. With the soil-enhanced model, resources will be studied to find the sensitive ones (bottlenecks) and different alternative resource allocations will be simulated to optimize the operation.

The rest parts of the plot in Figure 5.1 show the same pattern, after a short platform of pipe section 6, productivities increase from pipe 7 to 16, following exactly the learning curve. Then another platform starts from section 16 to 20, which could reflect the bottom of productivity improving. Duration jumps from section 20 to 24, not as sharp as the previous but still indicates some resource arrangements need to be adjusted. A platform from section 25 to 30 finishes the curve.

Overall, the productivity simulation results are in reasonable patterns. The validation of the prototype model with these results will be discussed in next section.

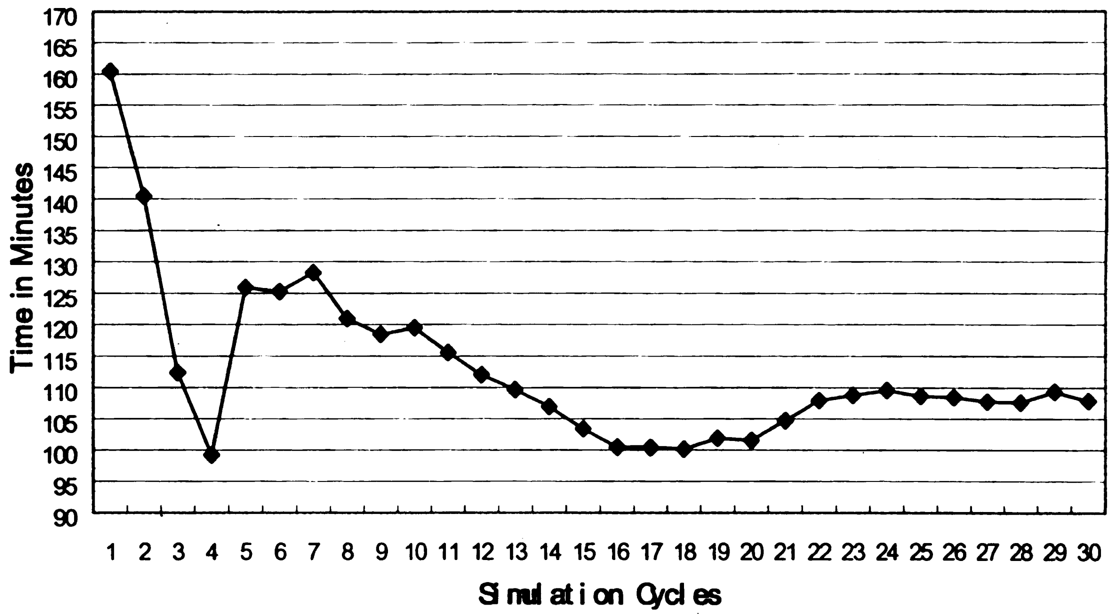


Figure 5.1 –Simulation Cycle Durations with Prototype Model

5.2 Validation of the Prototype Simulation Model

In Appendix B, the actual production measured in the field was recorded as follows:

Table 5.3 –Actual Cycle Time Measured in the Field

Average cycle time for installation of an 8-ft section of PVC pipe in:	
Clay	169 min.
Silt	97 min.
Sand	91 min.
Clayey Gravel	130 min.

For a soil composition of 25% clay, 25% silt, 25% sand, and 25% clayey gravel, the average duration for installing one 8 feet pipe section is 121.75 minutes. Consulting with expert, it was found that the production rates of the project for jacking pipe were within acceptable range of a microtunneling project for the specified type of soil (Najafi 1993). However, the average rate of production for the candidate project was 8.5 meter (28 feet) per day, while the reported rates for typical microtunneling projects are about 12 to 15 meters (36 to 45 feet) per day (Kramer et al. 1992). The main reason for overall production being lower than a standard microtunneling project is due to the experimental nature of the candidate project (Najafi 1993). The averaged simulated productivity from 30 cycles is 13% higher than the productivity observed in the field, which is clearly in a reasonable range of typical microtunneling project. Therefore, the logic and structure of the prototype model and accuracy of input data have been validated.

After verifying the simulation results with actual data the model can be enhanced with soil compositions and used for experimentation. Using a soil composition of equal portions of clay, silt, sand, and clayey gravel, the simulations are conducted to identify the resource bottlenecks. Alternative resource arrangements are simulated to find the optimized productivity of the operation. The enhanced model is also modified for testing the impacts of different soil compositions on productivity, which is discussed in Section 5.5.

5.3 Simulation Results with Enhanced Model Considering Soil Composition Changes

A total of 30 simulation runs were performed with the soil enhanced CYCLONE microtunneling model. Appendix D has the coding for soil enhanced model with duration data distribution discussed in chapter 4. Appendix F presents the full set of data from simulation results, which includes productivity information for each cycle, duration statistics for CYCLONE active elements, idling percentage and waiting time statistics for

CYCLONE passive elements, and elements trace information. Table 5.4 and 5.5 show the productivities obtained from the simulation.

Table 5.4 –Simulated Microtunneling Process Productivity Information by Cycle

Sim. Time (Accumulative)	Cycle No.	Duration Per Pipe Section (min.)	Productivity Per Time Unit
155.7	1	155.739	0.006421
303.5	2	151.7681	0.006589
441.6	3	147.2104	0.006793
550.5	4	137.6084	0.007267
702.9	5	140.5877	0.007113
831.6	6	138.6001	0.007215
934.6	7	133.5113	0.007490
1042.2	8	130.2762	0.007676
1146.2	9	127.3561	0.007852
1246.1	10	124.6106	0.008025
1345.6	11	122.3242	0.008175
1403.1	12	116.918	0.008553
1482.3	13	114.0251	0.008770
1616.2	14	115.4468	0.008662
1691.3	15	112.7523	0.008869
1762.8	16	110.1686	0.009077
1887.1	17	111.0001	0.009009
1980.0	18	109.9989	0.009091
2129.9	19	112.0951	0.008921
2230.7	20	111.5325	0.008966
2372.3	21	112.9688	0.008852
2546.8	22	115.7675	0.008638
2679.9	23	116.5094	0.008583
2822.2	24	117.5917	0.008504
2926.7	25	117.0686	0.008542
3063.1	26	117.8134	0.008488
3175.8	27	117.6194	0.008502
3304.1	28	118.008	0.008474
3456.5	29	119.1895	0.008390
3541.3	30	118.0498	0.008471

Table 5.5 –Overall Simulated Microtunneling Process Productivity Information

Total Sim. Time Unit (in minute)	Cycle No.	Productivity (per pipe section)	Productivity (per time unit)
3541.3	30	118.043	0.00847140496726565 5

The averaged duration time of 118.043 minutes is longer than simulation result from the prototype model of 107.867 minutes by 9.4% due to the modified model structure and input jacking duration data. However, it is closer to the average of actual measured durations in the field, 121.45 minutes. Only 3% difference exists between the soil enhanced simulation results and actual measured data, which indicates an improved accuracy of modeling.

Figures 5.2 to 5.16 show the trace information for QUEUE elements, where resource units wait until the successive activity starts. The trace information for all QUEUE elements is recorded in Appendix F.

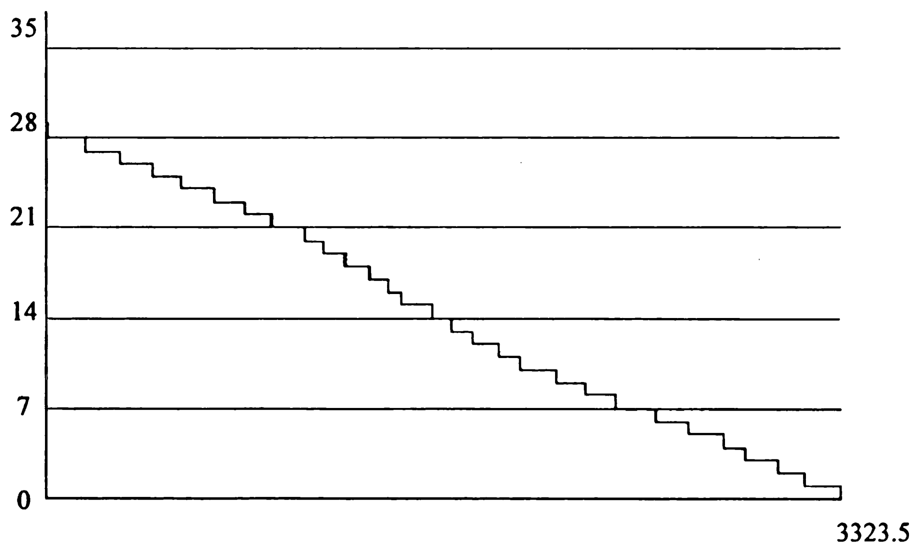


Figure 5.2 –Trace Chart for QUEUE-11 Section on Storage

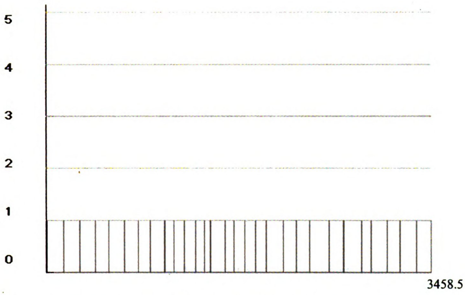


Figure 5.3 –Trace Chart for QUEUE-12 Position Available

Figure 5.4 –Trace Chart for QUEUE-13 Labor A Idle

Figure 5.5 –Trace Chart for QUEUE-14 Supervisor Idle

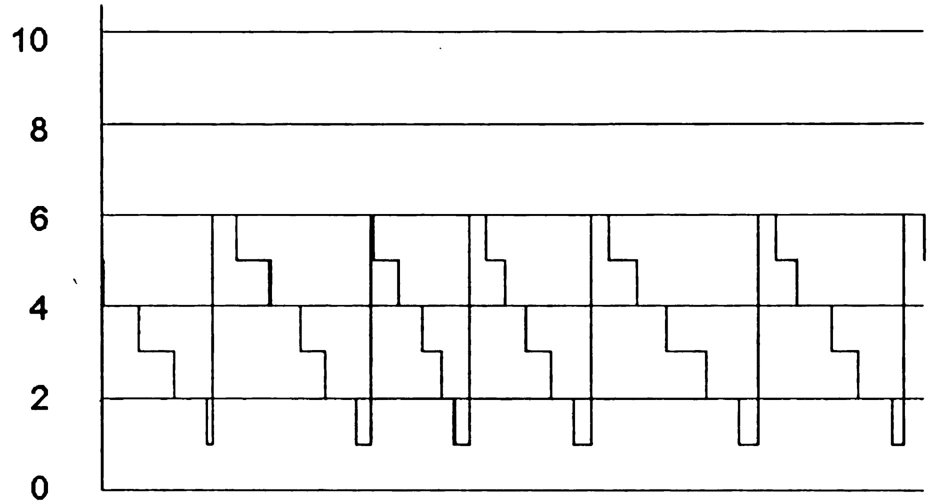


Figure 5.6 –Trace Chart for QUEUE-15 Air Gripper Ready

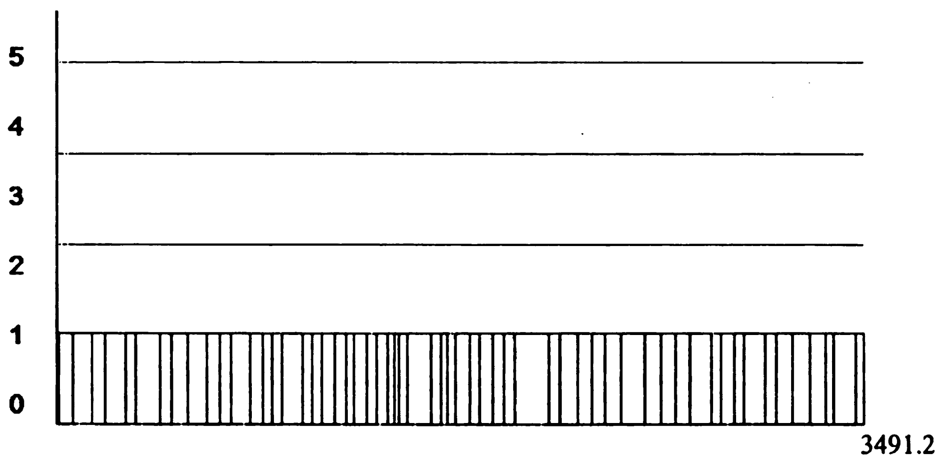


Figure 5.7 –Trace Chart for QUEUE-16 Crane Idle

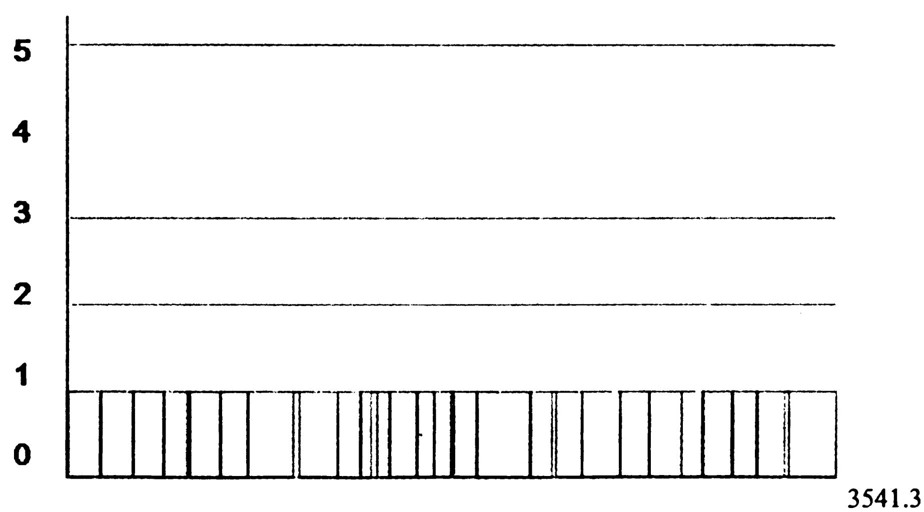


Figure 5.8 –Trace Chart for QUEUE-17 Control Crane

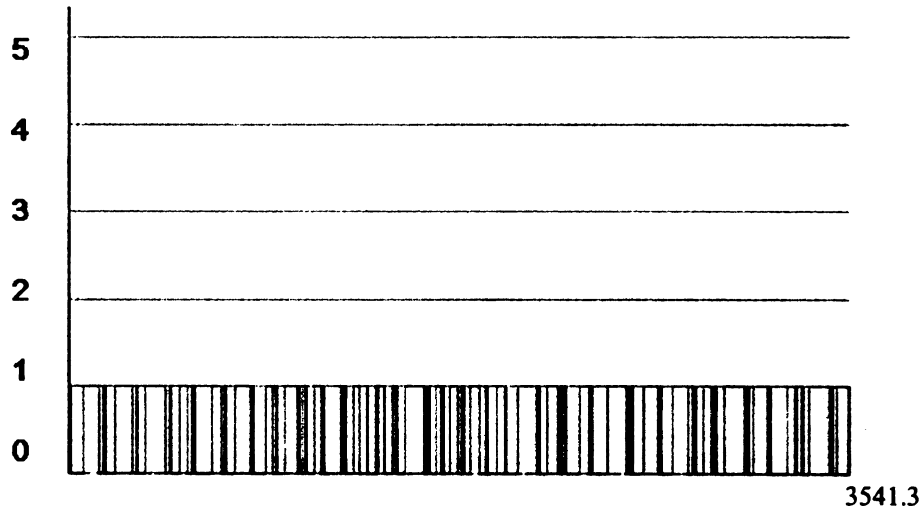


Figure 5.9 –Trace Chart for QUEUE-18 Labor B Idle

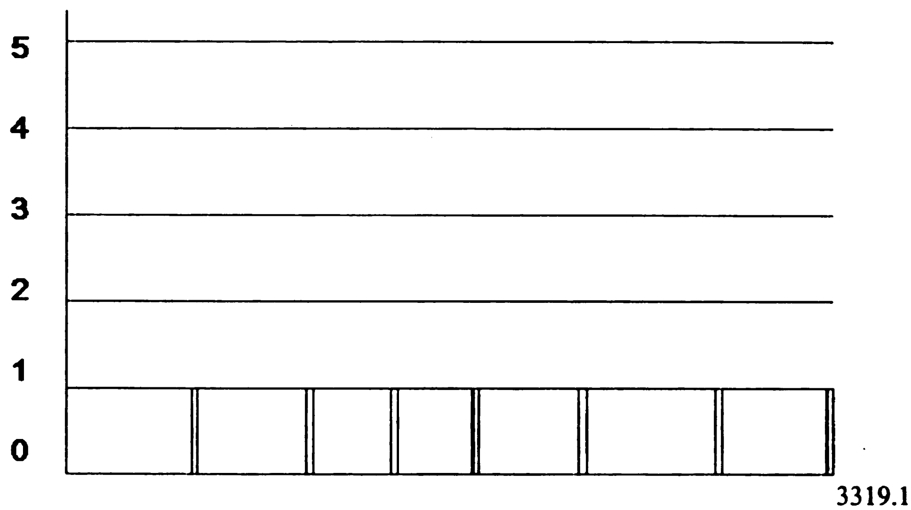


Figure 5.10 –Trace Chart for QUEUE-19 Truck Idle

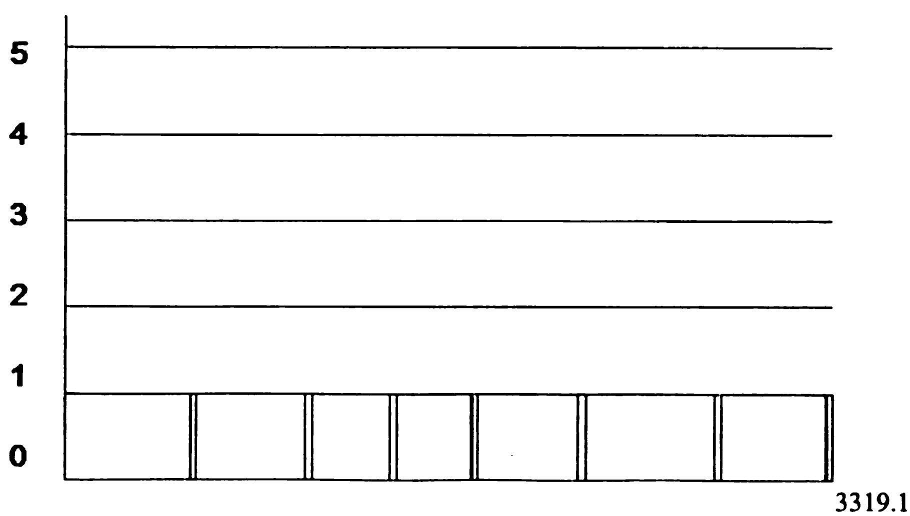


Figure 5.11 –Trace Chart for QUEUE-20 Backhoe Idle

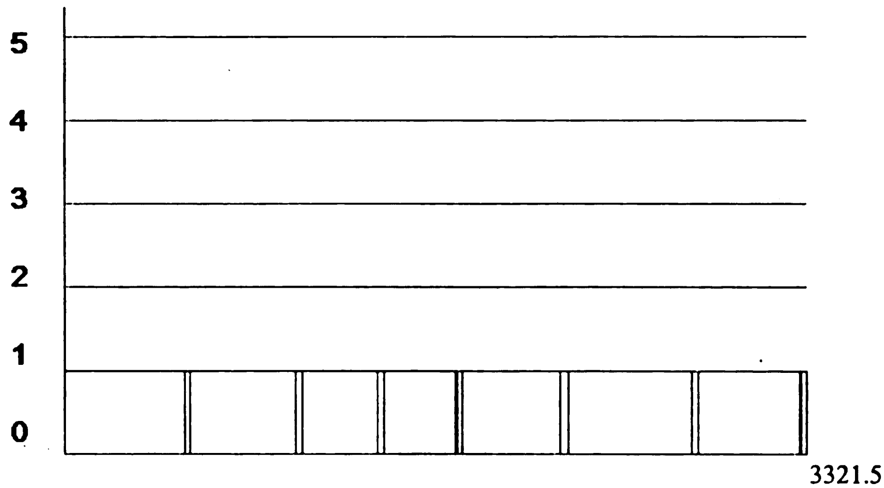


Figure 5.12 –Trace Chart for QUEUE-22 Bentonite Ready

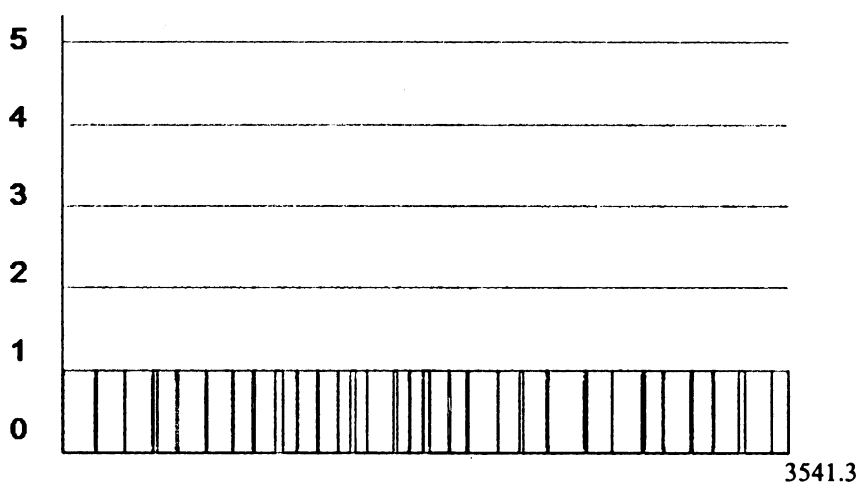


Figure 5.13 –Trace Chart for QUEUE-23 Jacking System Idle

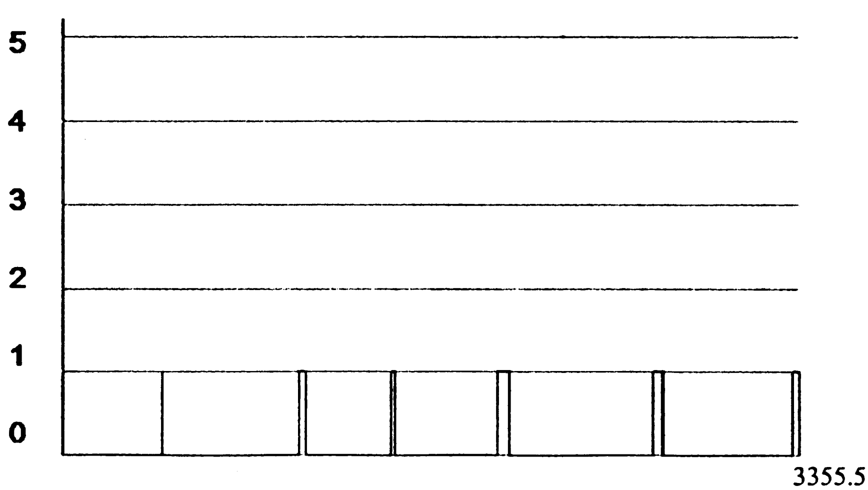


Figure 5.14 –Trace Chart for QUEUE-25 Need Air Gripper

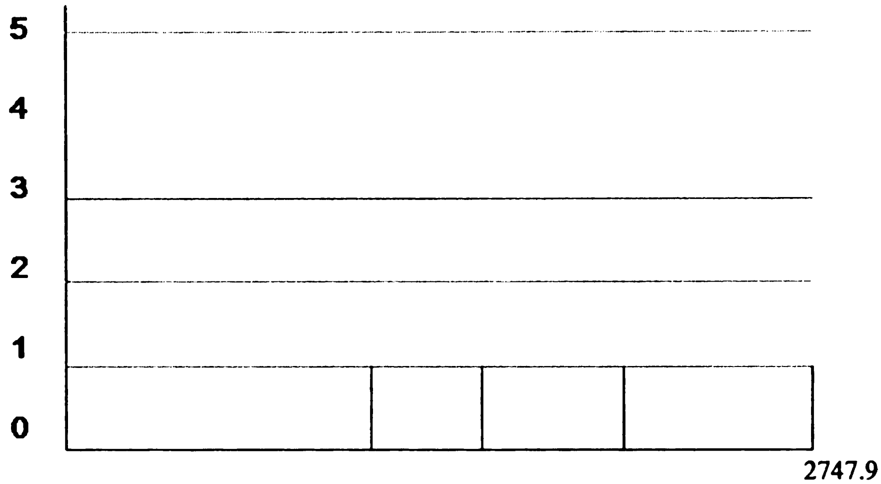


Figure 5.15 –Trace Chart for QUEUE-26 Air Gripper Need Adjust

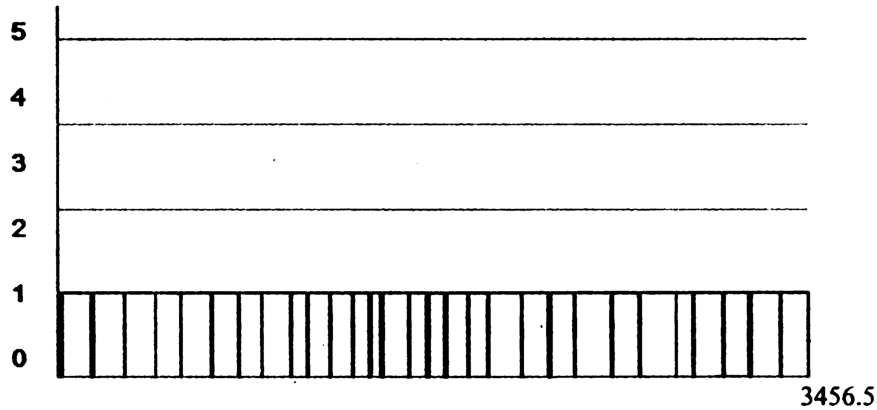


Figure 5.16 –Trace Chart for QUEUE-28 Position Occupied

As shown in Figure 5.2, thirty pipe sections were brought from storage and prepared with different durations. The overall pattern is linear with reasonable variations. From Figure 5.3 and 5.16, we can see there is less waiting time in QUEUE 12 than QUEUE 28, which could be explained as attaching section to crane takes long time to put next pipe section on wait. While on the contrary, the only position on the crane is filled immediately when it is emptied. The limitation resources of attaching section to crane activity are cranes and Labor A, which need sensitivity analysis. From Figure 5.4, 5.5 and 5.9, we found Labor A, Supervisor and Labor B are idling very frequently, which is proved in Appendix F, where Labor A has 80.87% idling time, Labor B and supervisor has 50.43% and 47.81% idling time, respectively. Apparently, they are not bottleneck resources compared with crane in Figure 5.8 with 3.93% idle time. However, in sensitivity analysis of next section, when crane number is added, it may trigger labor shortage.

For air gripper installation, in Figure 5.14, when the pipe section need air gripper, only in 5.1% of the time it need to wait; in Figure 5.15, when air gripper need adjust, 100% of the time adjustment is in time; in Figure 5.6, air gripper is in 97.6% of the time ready when pipe section need to be attached to crane. Conclusion can be drawn that air gripper installation is efficient and create no delays for the operation.

Truck, backhoe, and bentonite are three resources that follow the same pattern, because of the assumption made in model development. Every four times of jacking pipe sections activate the truck, backhoe, and bentonite preparation once. These three resources are idling for 88.17% of the time in microtunneling operation, which have no effect on delaying the productivity.

In Figure 5.13, the jacking system is regarded busy. Only in 8.93% of the time, it is idling. This may indicate that jacking system is one of the limiting factors. Jacking system is the resource with one of the highest utilization rate. By changing the Microtunnel Boring Machine cutting head design to more appropriate, production can be increased. This change can be reflected in the model by changing the jacking pipe section activity duration. The optimization of MTBM with the soil conditions will increase the productivity.

5.4 Sensitivity Analysis

In this section, the numbers of crane and labor crews will be analyzed as discussed in the previous section. Different combinations are simulated to find the optimization plan. As Shown in Table 5.6 and 5.7, all combinations of one to two Cranes, one to three Labor A crews, one to three Labor B crews, and one to three Supervisors have been simulated. Due to the space limitation on the site, no more than two cranes have been simulated. The highest productivity appears with one Labor A crew, three Labor B crews, two Supervisors, and two cranes. The second highest plan is to have three Labor A crews and three Labor B crews, one Supervisor, and two cranes. The third highest plan is to have three Labor A crews, two Supervisors, one crane and one Labor B crew. The productivity of the second and third plans are both very close to the first plan. The fourth highest plan is to add two Supervisors to the original. This indicates the supervisor is one of the bottleneck resources, who is responsible for too many activities. The maximum productivity plans do not consider cost factor. Therefore, it can not be concluded that which one is the optimized.

By adding one Labor A crew, one Labor B crew, one Supervisor, or one Crane to the system, production improves. Coincidently, the productivity improvements due to adding one Labor A crew or one Labor B crew are the same. When adding both to two or three, the productivity slightly decreases. Labor A and B crews reach the limitation of improving productivity when used without adding other resources. When jointly used with one new crane, the Labor A and B crews contribute more to productivity improvement.

The productivity improvements due to adding one supervisor or one crane are the same, which are higher than adding one labor crew. Both of them are bottlenecks of the original operation. Consideration of cost factor should be taken to judge which plan is more feasible.

Figure 5.17 –Sensitivity Analysis Results

Resource Information					Productivity Information	
# of LABOR' at LABOR A IDLE	**# of SUPERVISOR' at SUPERVISOR IDLE**	**# of CRANE' at CRANE IDLE**	**# of CRANE CONTROL SIGNAL at CONTROL CRANE**	**# of LABOR' at LABOR B IDLE**	**Productivity Per Unit Time (Section/ min)**	**Time Duration Per Pipe Section Installation (min)**
1	1	1	1	1	0.0086	116.2791
1	1	1	1	2	0.0091	109.8901
1	1	1	1	3	0.0093	107.5269
1	1	2	2	1	0.0090	111.1111
1	1	2	2	2	0.0092	108.6957
1	1	2	2	3	0.0092	108.6957
1	2	1	1	1	0.0090	111.1111
1	2	1	1	2	0.0093	107.5269
1	2	1	1	3	0.0091	109.8901
1	2	2	2	1	0.0090	111.1111
1	2	2	2	2	0.0087	114.9425
1	2	2	2	3	0.0101	99.0099
1	3	1	1	1	0.0097	103.0928
1	3	1	1	2	0.0092	108.6957
1	3	1	1	3	0.0092	108.6957
1	3	2	2	1	0.0090	111.1111
1	3	2	2	2	0.0091	109.8901
1	3	2	2	3	0.0090	111.1111
2	1	1	1	1	0.0091	109.8901
2	1	1	1	2	0.0090	111.1111
2	1	1	1	3	0.0085	117.6471

Figure 5.187 (cont'd)

Resource Information					Productivity Information	
# of LABOR' at LABOR A IDLE	**# of SUPERVISOR' at SUPERVISOR IDLE**	**# of CRANE' at CRANE IDLE**	**# of CRANE CONTROL SIGNAL at CONTROL CRANE**	**# of LABOR' at LABOR B IDLE**	**Productivity Per Unit Time (Section/ min)**	**Time Duration Per Pipe Section Installation (min)**
2	1	2	2	1	0.0095	105.2632
2	1	2	2	2	0.0096	104.1667
2	1	2	2	3	0.0086	116.2791
2	2	1	1	1	0.0086	116.2791
2	2	1	1	2	0.0090	111.1111
2	2	1	1	3	0.0090	111.1111
2	2	2	2	1	0.0093	107.5269
2	2	2	2	2	0.0091	109.8901
2	2	2	2	3	0.0086	116.2791
2	3	1	1	1	0.0094	106.383
2	3	1	1	2	0.0095	105.2632
2	3	1	1	3	0.0093	107.5269
2	3	2	2	1	0.0096	104.1667
2	3	2	2	2	0.0086	116.2791
2	3	2	2	3	0.0091	109.8901
3	1	1	1	1	0.0094	106.383
3	1	1	1	2	0.0089	112.3596
3	1	1	1	3	0.0086	116.2791
3	1	2	2	1	0.0092	108.6957
3	1	2	2	2	0.0093	107.5269
3	1	2	2	3	0.0100	100
3	2	1	1	1	0.0099	101.0101
3	2	1	1	2	0.0092	108.6957
3	2	1	1	3	0.0091	109.8901
3	2	2	2	1	0.0087	114.9425
3	2	2	2	2	0.0092	108.6957
3	2	2	2	3	0.0091	109.8901
3	3	1	1	1	0.0095	105.2632
3	3	1	1	2	0.0093	107.5269
3	3	1	1	3	0.0095	105.2632
3	3	2	2	1	0.0093	107.5269
3	3	2	2	2	0.0097	103.0928
3	3	2	2	3	0.0092	108.6957

5.5 Impacts of Different Soil Conditions

After analyzing the resource limitations, productivity changes in the operation due to different soil composition are introduced as shown in Figure 5.19. The soil compositions have been modified from 25% of each soil type to variety of combinations. Simulation runs with the soil enhanced model generate corresponding productivities. A linear regression is conducted to find the correlations between microtunneling productivity in the candidate project and soil compositions. All the analyses are done with R1.9.0. R is a free version of S-plus and can be downloaded from http://www.r-project.org/.

Figure 5.19 –Productivity in Different Soil Compositions

Percentage of Clayey Gravel in the Operation (X1)	Percentage of Sand in the Operation (X2)	Percentage of Silt in the Operation (X3)	Percentage of Clay in the Operation (X4 = 100-X1-X2-X3)	Productivity Per Unit Time (1/Y) (Section/ min)	Time Duration Per Pipe Section Installation (Y) (min)
10	10	10	70	0.00819	122.1
10	10	20	60	0.008266	120.98
10	10	30	50	0.008554	116.9
10	10	40	40	0.008586	116.4733
10	10	50	30	0.008849	113.0033
10	10	60	20	0.009123	109.6133
10	20	10	60	0.008242	121.3333
10	30	10	50	0.008595	116.3533
10	40	10	40	0.0086	116.28
10	50	10	30	0.008809	113.5233
10	60	10	20	0.009028	110.7633
10	20	10	60	0.008242	121.3333
10	20	20	50	0.008531	117.22
10	20	30	40	0.008505	117.58
10	20	40	30	0.00873	114.5533
10	20	50	20	0.008969	111.5
10	20	60	10	0.009766	102.3933

Figure 5.19 (cont'd)

10	30	20	40	0.008615	116.08
10	40	20	30	0.008858	112.8933
10	50	20	20	0.009066	110.3
10	30	30	30	0.008767	114.06
10	30	40	20	0.00896	111.6067
10	30	50	10	0.009692	103.18
10	40	30	20	0.009139	109.4167
20	10	10	60	0.00817	122.4
30	10	10	50	0.007969	125.4933
40	10	10	40	0.007856	127.29
50	10	10	30	0.007793	128.3267
60	10	10	20	0.007888	126.78
20	10	10	60	0.00817	122.4
20	10	20	50	0.008454	118.2867
20	10	30	40	0.008428	118.65
20	10	40	30	0.008628	115.8967
20	10	50	20	0.008884	112.5667
20	10	60	10	0.009637	103.77
30	10	20	40	0.007986	125.22
40	10	20	30	0.008055	124.15
50	10	20	20	0.007993	125.1033
30	10	30	30	0.008117	123.2
30	10	40	20	0.008282	120.7467
30	10	50	10	0.008903	112.32
40	10	30	20	0.008287	120.6733
20	20	10	50	0.008457	118.24
20	30	10	40	0.008399	119.0667
20	40	10	30	0.008629	115.8933
20	50	10	20	0.008865	112.8067
20	60	10	10	0.009349	106.96
30	20	10	40	0.008051	124.2033
40	20	10	30	0.008098	123.4933
50	20	10	20	0.007951	125.77
60	20	10	10	0.008342	119.8767

Figure 5.19 (cont'd)

30	30	10	30	0.008182	122.2133
30	40	10	20	0.008349	119.77
30	50	10	10	0.008826	113.3033
40	30	10	20	0.008262	121.0433
50	30	10	10	0.008484	117.8733
25	25	25	25	0.008475	118

- **Linear regression of Y vs X1, X2, X3 and X4**

The estimated coefficients are shown in Figure 5.20, where the estimated value are the coefficients, and Pr(>|t|) is the p-value. All the p-values are significant small, which means the data plots follow linear patterns on different dimensions. Such patterns are also shown in Figure 5. 21.

Figure 5.20 –Confinements Estimation

	Estimate	Std. Error	t value	Pr(>|t|)	Significance
(Intercept)	129.32946	1.30947	98.765	< 2e-16	***
X1	0.06841	0.02386	2.867	0.00593	**
X2	-0.28765	0.02386	-12.054	< 2e-16	***
X3	-0.30163	0.02238	-13.480	< 2e-16	***

The residual standard error is 2.202 on 53 degrees of freedom. Multiple R-Squared is 0.8774; adjusted R-squared is 0.8704. F-statistic is 126.4 on 3 and 53 degree of freedom, where p-value < 2.2e-16.

In Figure 5.17, X1, X2, X3, and X4 are plotted with Y separately. Clear linear patterns can be found on the plots. The application of linear regression on the data is appropriate.

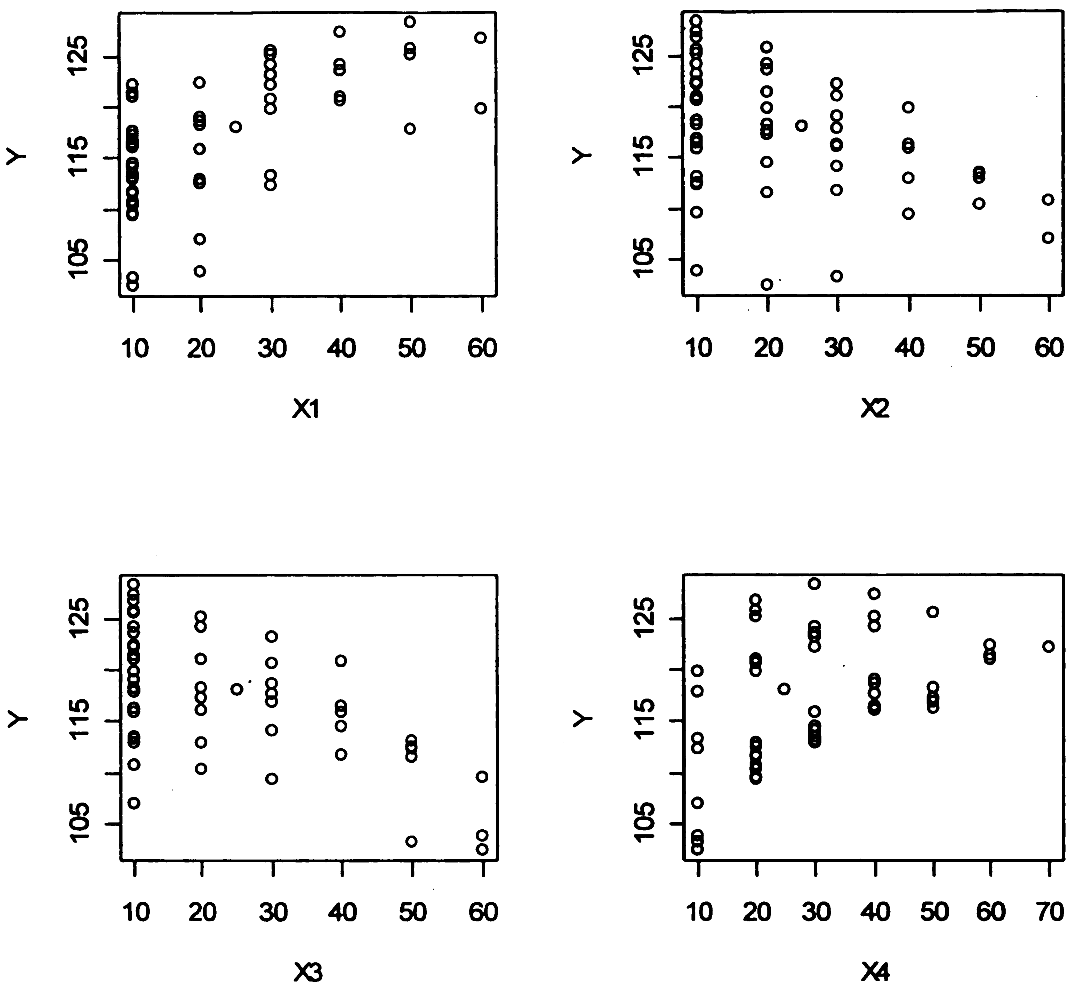


Figure 5.21 –Data Plots on X and Y

The regression results are as following:

Y=a0+ a1X1+ a2X2+ a3X3+ a4X4

=a0+ a1X1+ a2X2+ a3X3+ a4(1-X1-X2-X3)

=a0+a4 + (a1-a4)X1 + (a2-a4)X2 + (a3-a4) X3, where the estimated coefficients:

a0 + a4 = 129.32946

a1 – a4 = 0.06841

a2 – a4 = -0.28765

a3 – a4 = -0.30163

All three are significant, and this means that a1, a2, and a3 are all different from a4. More specifically, a1 is significantly larger than a4, and a2, a3 are significantly smaller than a4. Because X4 can be expressed as 100-X1-X2-X3, a1, a2, a3, and a4 do not have unique values. However, the differences between them do have unique values.

6 SUMMARY AND CONCLUSIONS

6.1 Overall Summary

In previous chapters, in order to analyze microtunneling technology an actual project was reviewed with other background information. The data collected at the Louisiana Tech University LLB Microtunneling Field Test Project in Ruston, Louisiana has been analyzed for modeling inputs. CYCLONE models have been built to reflect the microtunneling operation with soil impacts. Through WebCYCLONE simulations, the productivity of microtunneling operation has been analyzed and the limiting factors have been evaluated. Recommendations are given to optimize the productivity. In addition, the correlations between different soil compositions and microtunneling productivity have been studied. The following research objectives have been completed:

1. Portrayed the process of microtunneling operation in Chapter 2,
2. Identified resources and develop the model for simulation in Chapter 3,
3. Analyzed the production cycle data and find statistical distributions in Chapter 4,
4. Input the distribution data in the model and run simulation with WebCYCLONE, and presented the results in Appendix C and D.
5. Validated the simulated productivity results with actual observations at the project in Section 5.1 and 5.2
6. Performed sensitivity analysis and discussed the optimization of productivity in Section 5.3 and 5.4,

7. Enhanced CYCLONE model with consideration of soil compositions in Section 3.7,
8. Ran simulation with variety of soil compositions to obtain corresponding productivity and presented the results in Appendix E and F,
9. Researched the correlation between soil composition and microtunneling productivity in Section 5.5.

6.2 Conclusions based on the Simulation

1. CYCLONE models accurately represent the microtunneling process

From the validation of simulation results, It is clear that the averaged simulated productivity is in a reasonable range of the productivity observed from the field. This indicates that the model developments are successful. Such models can be used as a base for future microtunneling productivity research.

2. Kolmogorov-Smirnov Goodness-of-Fit Test

The Kolmogorov-Smirnov Goodness-of-Fit Test generates valid distributions based on a relatively small set of duration data, which supported the success of the simulation. In construction simulation, data collected from the field is normally fewer than data collected from labs. Facing shortage of data, researchers have to perform well statistical analysis to obtain modeling input as accurate as possible. The accuracy of input duration data is critical to the validation of simulation results.

3. Soil Compositions Affecting Microtunneling Productivity

Based on the successfulness of CYCLONE model building and the Kolmogorov-Smirnov Goodness-of-Fit Test, the goal of studying correlations between soil compositions and microtunneling productivity become achievable. The proportions of four types of soil show strong linear correlations with productivity. Stemmed from such result, the coefficients of proportion of each type of soil and microtunneling productivity has been estimated. Through multi-linear regression, an experimental formula was developed to reflect the soil composition effects on microtunneling productivity: $Y = 129.32946 + 0.06841*X1 - 0.28765*X2 - 0.30163*X3$, where Y is time duration in minutes of each 8-foot pipe section installation with microtunneling; X1 is percentage of clayey gravel in the soil composition; X2 is percentage of sand in the soil composition; X3 is percentage of silt in the soil composition. In the full-scale test in Louisiana Tech University, the proportion of clay (X4) can be expressed as 100% minus other three proportions, therefore only three coefficients have certain values, thus X4 does not exist in the expression. The result is for general knowledge of microtunneling productivity. Since it is highly associated with the candidate project's conditions, it can not be used directly to predict another microtunneling project without considering operations and soil composition. Modifications have to be made to reflect any project condition variations.

The durations of jacking pipe sections in four different soils have been studied. The conclusion is that clay and clayey gravel tend to have similar property, while the sand and silt don't have significant difference. The clay and gravel differ mainly on soil property and friction. Possible explanation of close productivities in clay and gravel is that jacking pipe speed in clay soil was impacted by other factors than soil property, for example, the slurry pump incompatible with clay as recorded in Appendix B. Changing of slurry pump could reflect shorter jacking time in clay in the model.

The limited times of simulation inevitably brought in skewness to the research. In the simulations with the soil enhanced model, the portion of four different types of soil was set to 25% each. Due to the random nature of the modeling structure, only two pipe section went though silt, and eleven went through gravel, which skewed the simulation results. However, if large number of simulations performed, the pipe sections in each type of soil will be approximately 25%. The skewness is from the limit number of simulations, instead of model structures.

4. Resource Limitations

Resource limitations have been studied through sensitivity analysis in WebCYCLONE. The Jacking System is the resource with the highest utilization rate, in 92.17% of the construction duration, it is kept busy. By changing the MTBM cutting head design more appropriate to the soil conditions, productivity can be increased. This change will be reflected in the model by decreasing Jacking Pipe Section activity durations, instead of adding more resource.

The supervisor was found another bottleneck of the operation. That might come from the candidate project's scientific experimental nature. The supervisor in the project takes a serious of responsibilities, which should be shared by peers. Introducing of another supervisor will increase the productivity. In equipment, crane is the most significant resource limitation. However, from a practical perspective, adding one crane would be infeasible due to site limitation. In labor crews, crew B's activities are mostly related to jacking system, which keeps crew B occupied. If the MTBM cutting head design can be improved to decrease Jacking Pipe Section activity durations, adding Crew B will become unnecessary. Crew A works with supervisor on most activities. Productivity can be improved by adding Labor A with supervisor. The idling time of above bottle neck resources are about 50% except Jacking System, conclusion can be drawn that the microtunneling project in Louisiana Tech University was planned properly. There is no need to adjust resource usage but improve the MTBM cutting head design.

6.3 Limitations of this Research

Major limitation of this study was introduced by the data collected. The data amount of the scientific experimental project in Louisiana Tech University was relatively limited, which is due to the high cost of microtunneling operation. Twenty-four pipe sections were installed in the project within four different types of soil. Consequently, twenty-four sets of data were collected, which are merely enough for distribution studies. Furthermore, the data set was divided by four; only six sets of data are available for installing pipe in each type of soil. Although the simulation results met the research objective, the chance of confidentiality can not be eliminated. The limitation of data could undermine the significance of this research.

Although cost factor is not considered in this research due to data limitation, cost must be analyzed when adding any resources to microtunneling operations to achieve optimization.

6.4 Recommendations and Areas of Future Research

Every project manger strives to achieve three goals on any project – to complete the project on time with the highest possible quality at the lowest possible cost. Simulation is a powerful tool for microtunneling project managers. It provides an appealing approach to analyze and improve repetitive processes in microtunneling. The repetitive nature and the complexity of microtunneling operations make it an ideal candidate for simulation analysis. Simulation allows experimentation with costly microtunneling operations before they are actually performed in the field. By experimenting with multiple scenarios, equipment, labor force and materials, the operation may be streamlined to the project manager's needs. By using simulation the requirements of the operation and the relationships between their resources can be studied in detail, thus enabling managers to make more informed decisions at different stages of the project. Through better planning and scheduling, the overall performance of a microtunneling project can be improved.

Simulation modeling may be done at different levels of detail based on the project manager's needs. This allows the use of the same model for different operations since the basic work tasks are similar. Microtunneling operations share many similarities with respect to the pipe jacking process, the slurry removal process, the cleaning and recycle of slurry, etc. Thus, a “template” model of a “standard” microtunneling operation can be modified with ease to incorporate variations in specific projects.

Since microtunneling operations are highly repetitive, small improvements in one cycle could lead to considerable cost and/or time reductions in the full process. A database containing activity durations and productivities on different soil conditions can be interacted with simulation models to continuously improve model results, hence making it an automated viable decision making tool for cost estimating and project planning purposes.

When data is collected and such a database built, graphic interface can be developed for microtunneling operation simulation. Each piece of key components in microtunneling as labor, equipment, and materials will be graphically represented on screen. A user interactive simulation program with graphical appearance and menu or click-and-drop commands can be developed. When microtunneling project managers choose different operation options from the menu, the coding module in the system is triggered to translate options into codes and integrate data from the database. Such information tells the system what and how resources are altered and the corresponding duration distributions. It is sent to the simulation engine for simulating. The results will be returned to an animation generator to project altered activity duration into animation on the graphic user interface. Any changes made to the simulation model, resources, and duration input will be reflected into animation simultaneously. Such software can be loaded on the computer in microtunneling control unit, thus simplify the simulation use for microtunneling project managers. Simulation tool will be popularized on microtunneling project management. Microtunneling productivity optimization will be achieved widely, furthermore lower the associated cost and improve microtunneling competitiveness.

APPENDICES

APPENDIX A

Microtunneling Glossary[1]

Adapter Ring: In microtunneling, a fabricated ring usually made from steel, that serves to mate the microtunneling machine to the first pipe section. This ring is intended to create a waterproof seal between the machine and the spigot of the first joint.

Auger MTBM: A type of microtunnel-boring machine that uses auger flights to remove the spoil through a separate casing placed through the product pipeline.

Can: A principal module that is part of a shield machine as in microtunneling or tunnel-boring machines (TBMs). Trailing cans may be used, depending on the installation dimensions required and the presence of an articulated joint to facilitate steering. May also be referred to as a trailing tube.

Cased Bore: A bore in which a pipe, usually a steel sleeve, is inserted simultaneously with the boring operation.

Casing: A pipe to support a bore. Usually not a product pipe.

Control Console: An electronic unit inside a container located on the ground surface that controls the operation of the microtunneling machine. The machine operator drives the runnel from the control console. Electronic information is transmitted to the control console from the heading of the machine. This information includes head position, steering angle, jacking force, progression rates, machine face torque, slurry and feed line pressures, and laser position. Some control consoles are equipped with a computer that tracks the data for a real-time analysis of the tunnel drive.

[1] ASCE (2001): Standard Construction Guidelines for Microtunneling

Crossing: Pipeline installation in which the primary purpose is to provide one or more passages beneath a surface obstruction.

Compression Ring: A ring fitted between the end-bearing area of the bell and spigot to help distribute applied loads more uniformly. The compression ring is attached to the trailing end of each pipe and is compressed between the pipe sections during jacking. The compression rings compensate for slight misalignment, pipe ends that are not perfectly square, gradual steering corrections, and other pipe irregularities. Also referred to as packers.

Cutterhead: Any rotating tool or system of tools on a common support that excavates at the face of a bore.

Driveshaft: See Jacking Shaft.

Entrance Seal: See Launch Seal

Entry Ring: See Launch Seal

EPB Machine: Earth pressure balance type of microtunneling or tunneling machine in which mechanical pressure is applied to the material at the face and controlled to provide the correct counter-balance to earth pressures in order to prevent heave or subsidence. The term is usually not applied to systems in which the primary counterbalance of earth pressures is supplied by pressurized slurry.

Exit Seal: Same as launch seal except for retrieval of the machine at the reception shaft. Used in high groundwater to prevent the loss of ground.

Exit Shaft: See Reception Shaft.

Grouting: The process of filling voids or modifying/improving ground conditions. Grouting materials may be cementitious, chemical, or other mixtures. In microtunneling, grouting may be used to fill voids around the pipe or shaft or to improve ground conditions.

Interjack Pipes: Pipes specially designed for use with an intermediate jacking station.

Intermediate Jacking Station: A fabricated steel cylinder fitted with hydraulic jacks that is incorporated into a pipeline between two pipe segments. Its function is to distribute the jacking load over the pipe string on long drives.

Jacking Frame: A structural component that houses the hydraulic cylinders used to propel the microtunneling machine and pipeline. The jacking frame serves to distribute the thrust load to the pipeline and the reaction load to the shaft wall or thrust wall.

Jacking Pipes: Pipes designed to be installed using pipe jacking techniques.

Jacking Shaft: Excavation from which trenchless technology equipment is launched for the installation or renovation of a pipeline, conduit, or cable. May incorporate a thrust wall to spread reaction loads to the ground.

Jacking Shield: A fabricated steel cylinder from within which the excavation is carried out either by hand or by machine. Incorporated within the shield are facilities to allow it to be adjusted to control line and grade.

Launch Seal: A mechanical seal, usually composed of a rubber flange that mounted to the wall of the drive shaft. The flange seal is distened by the MTBM as it passes through, creating a seal to prevent water or lubrication inflow into the shaft during tunneling operation.

Lubrication: A fluid, normally bentonite, used to reduce jacking loads on the jacking pipe.

Muck: Spoil or removal of same.

Obstruction: Any object or feature that lies completely or partially within the cross-section of the microtunnel and prevents continued forward progress.

Overcut: The annular space between the excavated hole and the outside diameter of the jacking pipe.

Packer: See Compression Ring.

Pilot Tube Method: A multistage method of accurately installing a product pipe to line and grade by use of a guided pilot tube followed by upsizing to install the product pipe.

Product Pipe: Pipe used for conveyance of water, gas, sewage, and other products and services.

Push Ring Adapter: Mechanical structure mounted on the thrust ring to prevent the thrust ring from coming in contact with the pipe collar and causing damage to the collar.

Receiving Shaft: See Reception Shaft.

Reception Shaft: Excavation into which the microtunneling equipment is driven and recovered.

Slurry: A fluid, normally water, used in a closed loop system for the removal of spoil and for the balance of groundwater pressure during microtunneling.

Slurry Chamber: Located behind the cutting head of a slurry microtunneling machine, a chamber in which excavated material is mixed with slurry for transport to the surface.

Slurry Line: A series of hoses or pipes that transport tunnel muck and slurry from the face of a slurry microtunneling machine to the ground surface for separation.

Slurry Separation: A process in which excavated material is separated from the circulation slurry.

Spacer: Mechanical structure used to transfer the jacking load from the jacking thrust ring to the pipe and used to accommodate lengths of pipe that are longer than the stroke length of the jacks.

Spoil: Earth, rock, and other materials removed during installation.

Thrust Ring: A fabricated ring that is mounted on the face of the jacking frame. It is intended to transfer the jacking load from the jacking frame to the thrust-bearing area of the pipe section being jacked.

Trenchless Technology: Techniques for utility or other line installation, replacement, renovation, inspection, leak location and detection, with minimum excavation from the ground surface.

Tunneling: A construction method of excavating an opening beneath the ground without continuous disturbance of the ground surface and of large enough diameter to allow individuals access and erection of a ground support system at the location of material excavation.

Uncased Bore: Any bore without a lining or pipe inserted, i.e., self-supporting, whether temporary or permanent.

Water Jets: Internal cleaning mechanism of the cutterhead in which high-pressure water is sprayed from nozzles to help remove cohesive soils.

APPENDIX B

Duration Data Collected from the Louisiana Tech University Microtunneling Project (Najafi, 1993)

Durations for jacking pipe sections					
Pipe No.	**Date**	**Start Time**	**Finish Time**	**Duration (min)**	**Notes**
Boring machine adapters	6/16/1992	11:00 AM	11:30 AM	30	From 1:30 to 3:45 pm reconnect adapters, electric lines and extensions.
Boring machine adapters	6/17/1992	3:45 PM	4:10 PM	25	From 3:45 to 4:10 pm continue boring for the machine
1	6/17/1992	8:50 AM	9:43 AM	53	Boring within clay section
2	6/17/1992	1:35 PM	3:07 PM	92	Boring within clay section
3	6/18/1992	8:18 AM	9:46 AM	88	Boring within clay section
4(with gripper)	6/18/1992	1:07 PM	2:32 PM	85	Boring within clay section
5	6/18/1992	3:40 PM	4:52 PM	72	Boring within clay section (average duration = 74 minutes and average speed = 1.3 inch/minutes)
6	6/19/1992	8:12 AM	8:46 AM	34	Boring machine began entering inside silt.
7	6/19/1992	9:56 AM	10:23 AM	27	
8	6/19/1992	11:20 AM	12:01 AM	41	
9(with gripper)	6/19/1992	2:40 PM	4:34 PM	114	From 2:43 to 2:51 pm machine was stopped because slurry back pressure was high and flow volume was low. From 2:53 to 3:53 pm wood pieces in the silt clogged the slurry pump inside pit. Same problem happened from 3:57 to 4:00 and from 4:17 to 4:21 and from 4:26 to 4:28 pm.
10	6/20/1992	8:14 AM	8:39 AM	25	
11	6/20/1992	9:39 AM	10:06 AM	27	
12	6/20/1992	10:35 AM	10:53 AM	18	Boring within sand section
13	6/22/1992	8:50 AM	9:40 AM	50	9:05 to 9:25 jacking was stopped for crack sealant to dry up.
14(with gripper)	6/22/1992	11:09 AM	11:45 AM	36	
15	6/22/1992	2:08 AM	2:20 AM	12	
16	6/22/1992	3:30 AM	3:53 AM	23	
17	6/22/1992	4:50 PM	5:09 PM	19	Boring machine entered clayey gravel section

18	6/23/1992	8:20 AM	9:57 AM	97	8:26 to 8:35 jacking pressure obstruction. 8:40 to 9:08 slurry line obstruction. 9:11 to 9:30 slurry line obstruction. Note: 28 liters of lubricant (bentonite) used to push this section
19	6/23/1992	11:12 AM	11:54 AM	42	85 liters of lubricant was used.
20	6/23/1992	1:53 PM	2:34 PM	41	93 liters of lubricant was used.
21	6/23/1992	3:33 PM	5:29 PM	116	4:05 to 4:43 pm the slurry pump inside the pit clogged.
22	6/24/1992	8:09 AM	9:25 AM	76	Slurry pump inside the pit clogged
23	6/24/1992	10:15 AM	11:15	60	10:24 to 10:41 am the slurry pump inside the pit clogged
24	6/24/1992	1:16 PM	2:21 PM	65	At 1:53 pm boring machine entered the clay zone. Total jacking force 39 ton. Jacking force on the plastic pipe 2 tons. Maximum jacking load on plastic pipe occurred at pipe No.12 and at a load of 3.5 tons.

Durations for installation of the pipe section on the guard rail (including installation of cables and hoses and setting up the laser)					
Pipe No.	**Date**	**Start Time**	**Finish Time**	**Duration (min)**	**Notes**
1	6/17/1992	8:50 AM	9:43 AM	53	
2	6/17/1992	10:00 AM	12:15 AM	135	From 10:45 to 11:50 am waiting to grind the pipe joint.
3	6/18/1992	3:25 PM	4:25 PM	60	At 3:25 pm the desandman was discharged. Grinding the joint from 3:28 to 3:31 pm
4(with gripper)	6/18/1992	10:22 AM	11:47 AM	85	Fitting the pipe joints together from 11:10 to 11:38 am. Gripper installation inside plastic pipe from 9:00 to 9:15 am, checking gripper from 9:16 to 9:30 am.
5	6/18/1992	2:49 PM	3:38 PM	49	Laser installation from 3:32 to 3:38 pm. Desandman was discharged at 3:30 pm.
6	6/18/1992	5:05 PM	5:47 PM	42	Laser was not installed. Desandman was discharged.
7	6/19/1992	9:04 AM	9:55 AM	51	Laser installation from 9:46 to 9:55 am
8	6/19/1992	10:36 AM	11:20 AM	44	
9	6/19/1992	1:37 PM	2:40 PM	63	
10	6/19/1992	4:52 AM	5:27 AM	35	
11	6/20/1992	9:00 AM	9:37 AM	37	
12	6/20/1992	10:25 AM	11:30 AM	65	5 minutes for pipe measurements.
13	6/20/1992	12:06 PM	12:42 PM	36	A small crack was noticed when the pipe joints were fitted together.
14(with gripper)	6/22/1992	10:05 AM	11:09 AM	64	
15	6/22/1992	12:04 PM	12:32 PM	28	
16	6/22/1992	2:54 PM	3:30 PM	36	
17	6/22/1992	4:08 PM	4:50 PM	42	
18	6/22/1992	5:22 PM	5:55 PM	33	Laser to be set up in the morning.
19	6/23/1992	10:16 AM	10:55 AM	39	Slurry pump was disassembled and checked for obstructions
20	6/23/1992	12:10 PM	12:42 PM	32	
21	6/23/1992	2:46 PM	3:32 PM	56	
22	6/23/1992	5:38 PM	6:07 PM	29	Laser to be set up in the morning.
23	6/24/1992	9:40 AM	10:15 AM	35	
24	6/24/1992	11:27 AM	12:00 AM	33	

Durations for installation of the casings and grippers inside the plastic pipe (including time necessary to install two slurry pipes, two pullback rods and check the air grippers)					
Pipe No.	**Date**	**Start Time**	**Finish Time**	**Duration (min)**	**Notes**
1	6/16/1992	4:47 PM	4:57 PM	10	
2	6/17/1992	9:44 AM	9:57 AM	13	
3	6/17/1992	2:02 PM	2:12 PM	10	
4(with gripper)	6/18/1992	9:00 AM	9:30 AM	30	Gripper installation inside plastic pipe from 9:00 to 9:15 am, checking gripper from 9:16 to 9:30 am.
5	6/18/1992	2:15 PM	2:25 PM	10	
6	6/18/1992	4:47 PM	4:52 PM	5	
7	6/19/1992	8:52 AM	8:58 AM	6	
8	6/19/1992	10:07 AM	10:14 AM	7	
9(with gripper)	6/19/1992	11:50 AM	12:05 PM	15	From 11:55 to 12:05 checking gripper
10	6/19/1992	4:00 PM	4:08 PM	8	
11	6/20/1992	8:35 AM	8:40 AM	5	
12	6/20/1992	9:42 AM	9:50 AM	8	
13	6/20/1992	10:40 AM	10:47 AM	7	
14(with gripper)	6/22/1992	9:35 AM	9:50 AM	15	10 minutes for checking the gripper
15	6/22/1992	11:40 AM	11:45 AM	5	
16	6/22/1992	2:31 PM	2:38 PM	7	
17	6/22/1992	3:48 PM	3:55 PM	7	
18	6/22/1992	5:07 PM	5:19 PM	12	
19	6/23/1992	9:20 AM	9:26 AM	6	
20	6/23/1992	11:52 AM	11:58 AM	6	
21	6/23/1992	5:00 PM	5:06 PM	6	Wrong pipe loaded with casing
22	6/23/1992	3:53 PM	3:56 PM	3	
23	6/24/1992	8:03 AM	8:08 AM	5	
24	6/24/1992	10:52 AM	10:57 AM	5	

Durations for retraction of Jacks (including dismantling of cables and hoses)					
Pipe No.	**Date**	**Start Time**	**Finish Time**	**Duration (min)**	**Notes**
1	6/17/1992	9:44 AM	9:55 AM	11	
2	6/17/1992	3:10 PM	3:25 PM	15	
3	6/18/1992	9:47 AM	10:14 AM	27	
4(with gripper)	6/18/1992	2:35 PM	2:47 PM	12	
5	6/18/1992	4:56 PM	5:04 PM	8	
6	6/19/1992	8:47 AM	9:00 AM	13	
7	6/19/1992	10:24 AM	10:33 AM	9	
8	6/19/1992	1:18 PM	1:35 PM	17	
9(with gripper)	6/19/1992	4:37 PM	4:51 PM	14	
10	6/20/1992	8:44 AM	8:57 AM	13	
11	6/20/1992	10:15 AM	10:22 AM	7	
12	6/20/1992	11:53 AM	12:04 PM	11	Taking off laser from 10:53 to 10:55 am.
13	6/22/1992	9:40 AM	9:55 AM	15	
14(with gripper)	6/22/1992	11:50 AM	12:03 AM	13	
15	6/22/1992	2:29 PM	2:45 PM	16	
16	6/22/1992	3:58 PM	4:06 PM	8	
17	6/22/1992	5:09 PM	5:17 PM	8	
18	6/23/1992	10:02 AM	10:12 AM	10	
19	6/23/1992	12:00 PM	12:10 PM	10	
20	6/23/1992	2:35 PM	2:42 PM	7	
21	6/23/1992	5:30 PM	5:37 PM	7	
22	6/24/1992	9:27 AM	9:35 AM	8	
23	6/24/1992	11:17 AM	11:25 AM	9	
24	N/A	N/A	N/A	N/A	

Summary of Production Rates	
Type of Work	**Time Required**
Opening the crates and installation of all microtunneling equipment	3 days
Checking the microtunneling equipment	1 day
Average hoisting time	2 min.
Average time for installation of casing inside PVC pipe	8.8 min.
Average time for installation of PVC pipe (with casing) on the guide rails (including connection of slurry pipes, hoses and cables)	43 min.
Average time for setting up of laser transit	10 min.
Average time for pushing the pipe	
Clay	33 mm/min. (1.3 in./min.)
Silt	101.6 mm/min. (4.0 in./min.)
Sand	134.6 mm/min. (5.3 in./min.)
Clayey Gravel	43.2 mm/min. (1.7 in./min.)
Average time for retraction of jacks (including dismantling of cables and hoses)	11.6 min.
Average cycle time for installation of an 8-ft section of PVC pipe in:	
Clay	169 min.
Silt	97 min.
Sand	91 min.
Clayey Gravel	130 min.
Average time for pulling back of one liner casing and dismantling of all slurry pipes, hoses and cables for each PVC pipe section	20 min. (10 min. to retract the jacks)
Dismantling, washing and crating of equipment	2 days
Loading equipment	1 day

APPENDIX C

Coding of the Prototype CYCLONE Microtunneling Simulation Model:

Input Model

Line 1: NAME MICROTUNNELING PROCESS LENGTH 10000 CYCLES 30

Line 2: NETWORK INPUT

Line 3: 1 COM 'DISCHARGE & REFILL DESANDMAN' SET 1 PRE 33 18 14 FOL 18 14 24

Line 4: 2 COM 'MIX LUBRICATION' SET 2 PRE 13 22 32 FOL 13 21 22

Line 5: 3 COM 'DISMANTLE CABLES & HOSES' SET 3 PRE 34 14 18 FOL 17 23 14 18 39 99

Line 6: 4 COM 'EMPTY SPOIL TANK' SET 4 PRE 31 19 20 FOL 27 19 20

Line 7: 5 COM 'PIPE SECTION INSTALL ON GUARD RAIL' SET 5 PRE 30 18 14 35 24 23 21 27 FOL 41 18 14 42

Line 8: 6 COM 'LOWER SECTION INTO SHAFT' SET 6 PRE 29 18 FOL 30 18

Line 9: 7 COM 'ADJUST AIR GRIPPER' SET 7 PRE 13 26 14 FOL 13 14 15

Line 10: 8 COM 'INSTALL & CHECK AIR GRIPPER' SET 8 PRE 13 25 14 FOL 13 14 43

Line 11: 9 COM 'ATTACH SECTION TO CRANE' SET 9 PRE 28 13 17 16 15 FOL 40 13 12

Line 12: 10 COM 'BRING SECTION & INSTALL CASING' SET 10 PRE 11 13 12 FOL 36 13 28

Line 13: 11 QUE 'SECTION ON STORAGE'

Line 14: 12 QUE 'POSITION AVAILABLE'

Line 15: 13 QUE 'LABOR A IDLE'

Line 16: 14 QUE 'SUPERVISOR IDLE'

Line 17: 15 QUE 'AIR GRIPPER READY' GEN 5

Line 18: 16 QUE 'CRANE IDLE'

Line 19: 17 QUE 'CONTROL CRANE'

Line 20: 18 QUE 'LABOR B IDLE'

Line 21: 19 QUE 'TRUCK IDLE'

Line 22: 20 QUE 'BACKHOE IDLE'

Line 23: 21 QUE 'LUBRICATION READY' GEN 4

Line 24: 22 QUE 'BENTONITE READY'

Line 25: 23 QUE 'JACKING SYSTEM IDLE'

Line 26: 24 QUE 'WATER READY' GEN 4

Line 27: 25 QUE 'NEED AIR GRIPPER'

Line 28: 26 QUE 'GRIPPER NEED ADJUST'

Line 29: 27 QUE 'SPOIL TANK NOT FULL' GEN 4

Line 30: 28 QUE 'POSITION OCCUPIED'

Line 31: 29 QUE 'SECTION READY'

Line 32: 30 QUE 'SECTION READY'

Line 33: 31 QUE 'SPOIL TANK FULL'

Line 34: 32 QUE 'NEED LUBRICATION'

Line 35: 33 QUE 'DESANDMAN READY TO DISCHARGE'

Line 36: 34 QUE 'SECTION IN PLACE'

Line 37: 35 QUE 'CABLE HOSE LASER READY'

Line 38: 36 FUN CON 5 FOL 25

Line 39: 37 FUN CON 4 FOL 32

Line 40: 38 FUN CON 4 FOL 31

Line 41: 39 FUN CON 4 FOL 33

Line 42: 40 NOR 'LIFT SECTION TO POSITION' SET 40 FOL 29

Line 43: 41 NOR 'CRANE RETURNS' SET 41 FOL 16

Line 44: 42 NOR 'JACK PIPE SECTION' SET 42 FOL 34 37 38

Line 45: 43 NOR 'DUMMY' SET 43 FOL 26 15 PROBABILITY .33 .67

Line 46: 99 FUN COU FOL 35 QUA 1

Line 47: DURATION INPUT

Line 48: SET 1 TRI 10 12 15

Line 49: SET 2 TRI 25 30 35

Line 50: SET 3 BET 7 33 0.643 3.02

Line 51: SET 4 TRI 20 30 35

Line 52: SET 5 BETA 28 80 0.761 1.841

Line 53: SET 6 UNI 1 2

Line 54: SET 7 UNI 10 15

Line 55: SET 8 UNI 10 15

Line 56: SET 9 DET 2

Line 57: SET 10 TRI 2 5 15

Line 58: SET 40 DET 1

Line 59: SET 41 DET 2

Line 60: SET 42 BETA 12 102 0.854 1.403

Line 61: SET 43 DET 0

Line 62: RESOURCE INPUT

Line 63: 30 'PIPE SECTION' AT 11

Line 64: 1 'POSITION' AT 12

Line 65: 1 'LABOR' AT 13

Line 66: 1 'SUPERVISOR' AT 14

Line 67: 1 'GRIPPER READY SIGNAL' AT 15

Line 68: 1 'CRANE' AT 16

Line 69: 1 'CRANE CONTROL SIGNAL' AT 17

Line 70: 1 'LABOR' AT 18

Line 71: 1 'TRUCK' AT 19

Line 72: 1 'BACKHOE' AT 20

Line 73: 1 'LUBRICATION READY SIGNAL' AT 21

Line 74: 1 'BENTONITE READY SIGNAL' AT 22

Line 75: 1 'JACKING SYSTEM' AT 23

Line 76: 1 'WATER READY SIGNAL' AT 24

Line 77: 1 'SPOIL TANK NOT FULL SIGNAL' AT 27

Line 78: 1 'CABLE HOSE LASER READY SIGNAL' AT 35

APPENDIX D

Coding of the CYCLONE Microtunneling Simulation Model with Soil Condition Enhancement:

Input Model

Line 1: NAME MICROTUNNELING PROCESS IN DIFFERENT SOILS LENGTH 10000 CYCLES 30

Line 2: NETWORK INPUT

Line 3: 1 COM 'DISCHARGE & REFILL DESANDMAN' SET 1 PRE 33 18 14 24 FOL 18 14 24

Line 4: 2 COM 'MIX LUBRICATION' SET 2 PRE 13 22 32 FOL 13 21 22

Line 5: 3 COM 'DISMANTLE CABLES & HOSES 1' SET 3 PRE 34 14 18 FOL 17 23 14 18 51 24 99

Line 6: 44 COM 'DISMANTLE CABLES & HOSES 2' SET 13 PRE 47 14 18 FOL 17 23 14 18 51 24 99

Line 7: 45 COM 'DISMANTLE CABLES & HOSES 3' SET 23 PRE 48 14 18 FOL 17 23 14 18 51 24 99

Line 8: 46 COM 'DISMANTLE CABLES & HOSES 4' SET 33 PRE 49 14 18 FOL 17 23 14 18 50 24 99

Line 9: 4 COM 'EMPTY SPOIL TANK' SET 4 PRE 31 19 20 FOL 27 19 20

Line 10: 5 COM 'PIPE SECTION INSTALL ON GUARD RAIL' SET 5 PRE 30 18 14 35 24 23 21 27 FOL 41 18 14 52

Line 11: 6 COM 'LOWER SECTION INTO SHAFT' SET 6 PRE 29 18 FOL 30 18

Line 12: 7 COM 'ADJUST AIR GRIPPER' SET 7 PRE 13 26 14 FOL 13 14 15

Line 13: 8 COM 'INSTALL & CHECK AIR GRIPPER' SET 8 PRE 13 25 14 FOL 13 14 43

Line 14: 9 COM 'ATTACH SECTION TO CRANE' SET 9 PRE 28 13 17 16 15 FOL 40 13 12

Line 15: 10 COM 'BRING SECTION & INSTALL CASING' SET 10 PRE 11 13 12 FOL 36 13 28

Line 16: 11 QUE 'SECTION ON STORAGE'

Line 17: 12 QUE 'POSITION AVAILABLE'

Line 18: 13 QUE 'LABOR A IDLE'

Line 19: 14 QUE 'SUPERVISOR IDLE'

Line 20: 15 QUE 'AIR GRIPPER READY' GEN 5

Line 21: 16 QUE 'CRANE IDLE'

Line 22: 17 QUE 'CONTROL CRANE'

Line 23: 18 QUE 'LABOR B IDLE'

Line 24: 19 QUE 'TRUCK IDLE'

Line 25: 20 QUE 'BACKHOE IDLE'

Line 26: 21 QUE 'LUBRICATION READY' GEN 4

Line 27: 22 QUE 'BENTONITE READY'

Line 28: 23 QUE 'JACKING SYSTEM IDLE'

Line 29: 24 QUE 'WATER READY'

Line 30: 25 QUE 'NEED AIR GRIPPER'

Line 31: 26 QUE 'GRIPPER NEED ADJUST'

Line 32: 27 QUE 'SPOIL TANK NOT FULL' GEN 4

Line 33: 28 QUE 'POSITION OCCUPIED'

Line 34: 29 QUE 'SECTION READY'

Line 35: 30 QUE 'SECTION READY'

Line 36: 31 QUE 'SPOIL TANK FULL'

Line 37: 32 QUE 'NEED LUBRICATION'

Line 38: 33 QUE 'DESANDMAN READY TO DISCHARGE'

Line 39: 34 QUE 'SECTION IN PLACE 1'

Line 40: 47 QUE 'SECTION IN PLACE 2'

Line 41: 48 QUE 'SECTION IN PLACE 3'

Line 42: 49 QUE 'SECTION IN PLACE 4'

Line 43: 35 QUE 'CABLE HOSE LASER READY'

Line 44: 36 FUN CON 5 FOL 25

Line 45: 37 FUN CON 4 FOL 32

Line 46: 38 FUN CON 4 FOL 31

Line 47: 50 FUN CON 2 FOL 33

Line 48: 51 FUN CON 3 FOL 50

Line 49: 40 NOR 'LIFT SECTION TO POSITION' SET 40 FOL 29

Line 50: 41 NOR 'CRANE RETURNS' SET 41 FOL 16

Line 51: 42 NOR 'JACK PIPE SECTION 1' SET 42 FOL 34 37 38

Line 52: 57 NOR 'JACK PIPE SECTION 2' SET 57 FOL 47 37 38

Line 53: 58 NOR 'JACK PIPE SECTION 3' SET 58 FOL 48 37 38

Line 54: 59 NOR 'JACK PIPE SECTION 4' SET 59 FOL 49 37 38

Line 55: 43 NOR 'DUMMY' SET 43 FOL 26 15 PROBABILITY .33 .67

Line 56: 52 NOR 'DUMMY 1' SET 44 FOL 53 54 55 56 PROBABILITY .25 .25 .25 .25

Line 57: 53 NOR 'DUMMY SOIL TYPE CLAYEY GRAVEL' SET 45 FOL 42

Line 58: 54 NOR 'DUMMY SOIL TYPE SAND' SET 46 FOL 57

Line 59: 55 NOR 'DUMMY SOIL TYPE SILT' SET 47 FOL 58

Line 60: 56 NOR 'DUMMY SOIL TYPE CLAY' SET 48 FOL 59

Line 61: 99 FUN COU FOL 35 QUA 1

Line 62: DURATION INPUT

Line 63: SET 1 TRI 10 12 15

Line 64: SET 2 TRI 25 30 35

Line 65: SET 3 BET 7 33 0.643 3.02

Line 66: SET 4 TRI 20 30 35

Line 67: SET 5 BETA 28 80 0.761 1.841

Line 68: SET 6 UNI 1 2

Line 69: SET 7 UNI 10 15

Line 70: SET 8 UNI 10 15

Line 71: SET 9 DET 2

Line 72: SET 10 TRI 2 5 15

Line 73: SET 13 BET 7 33 0.643 3.02

Line 74: SET 23 BET 7 33 0.643 3.02

Line 75: SET 33 BET 7 33 0.643 3.02

Line 76: SET 40 DET 1

Line 77: SET 41 DET 2

Line 78: SET 42 BETA 26 88 1.075 1.041

Line 79: SET 43 DET 0

Line 80: SET 44 DET 0

Line 81: SET 45 DET 0

Line 82: SET 46 DET 0

Line 83: SET 47 DET 0

Line 84: SET 48 DET 0

Line 85: SET 57 BETA 12 46 0.613 0.793

Line 86: SET 58 BETA 17 51 0.989 1.775

Line 87: SET 59 BETA 19 92 0.781 0.323

Line 88: RESOURCE INPUT

Line 89: 30 'PIPE SECTION' AT 11

Line 90: 1 'POSITION' AT 12

Line 91: 1 'LABOR' AT 13

Line 92: 1 'SUPERVISOR' AT 14

Line 93: 1 'GRIPPER READY SIGNAL' AT 15

Line 94: 1 'CRANE' AT 16

Line 95: 1 'CRANE CONTROL SIGNAL' AT 17

Line 96: 1 'LABOR' AT 18

Line 97: 1 'TRUCK' AT 19

Line 98: 1 'BACKHOE' AT 20

Line 99: 1 'LUBRICATION READY SIGNAL' AT 21

Line 100: 1 'BENTONITE READY SIGNAL' AT 22

Line 101: 1 'JACKING SYSTEM' AT 23

Line 102: 1 'WATER READY SIGNAL' AT 24

Line 103: 1 'SPOIL TANK NOT FULL SIGNAL' AT 27

Line 104: 1 'CABLE HOSE LASER READY SIGNAL' AT 35

APPENDIX E

Simulation Results with Prototype CYCLONE Microtunneling model:

Simulation Run Times: 30

MICROTUNNELING PROCESS		
PRODUCTIVITY INFORMATION		
Sim. Time	Cycle No.	Productivity Per Time Unit
160.4	1	0.006234
280.9	2	0.007120
337.1	3	0.008899
396.8	4	0.010080
629.7	5	0.007940
751.5	6	0.007984
898.1	7	0.007794
967.9	8	0.008265
1066.1	9	0.008442
1195.2	10	0.008367
1271.2	11	0.008653
1343.9	12	0.008929
1425.2	13	0.009121
1496.9	14	0.009353
1550.4	15	0.009675
1607.3	16	0.009955
1706.7	17	0.009961
1802.5	18	0.009986
1936.0	19	0.009814
2031.1	20	0.009847
2199.3	21	0.009549
2374.4	22	0.009265
2501.4	23	0.009195
2629.1	24	0.009129
2715.5	25	0.009206
2818.7	26	0.009224
2908.8	27	0.009282
3013.0	28	0.009293
3170.4	29	0.009147
3235.4	30	0.009272

MICROTUNNELING PROCESS		
PRODUCTIVITY INFORMATION		
Total Sim. Time Unit	Cycle No.	Productivity (per time unit)
3235.4	30	0.00927240931636038 5

CYCLONE ACTIVE ELEMENTS STATISTICS INFORMATION						
Activity Type	No.	Name	Access Counts	Average Duration	Maximum Duration	Minimum Duration
COMBI	1	DISCHARGE & REFILL DESANDMAN	7	12.3	14.2	10.8
COMBI	2	MIX LUBRICATION	7	29.9	33.5	26.8
COMBI	3	DISMANTLE CABLES & HOSES	30	11.6	29.1	7.1
COMBI	4	EMPTY SPOIL TANK	7	28.1	33.2	23.1
COMBI	5	PIPE SECTION INSTALL ON GUARD RAIL	30	41.9	77.8	28.4
COMBI	6	LOWER SECTION INTO SHAFT	30	1.4	2.0	1.0
COMBI	7	ADJUST AIR GRIPPER	4	13.2	14.8	11.1
COMBI	8	INSTALL & CHECK AIR GRIPPER	6	12.5	14.8	10.3
COMBI	9	ATTACH SECTION TO CRANE	30	2.0	2.0	2.0
COMBI	10	BRING SECTION & INSTALL CASING	30	6.6	12.6	2.3
NORMAL	40	LIFT SECTION TO POSITION	30	1.0	1.0	1.0
NORMAL	41	CRANE RETURNS	30	2.0	2.0	2.0
NORMAL	42	JACK PIPE SECTION	30	44.3	100.7	13.3
NORMAL	43	DUMMY	6	0.0	0.0	0.0

CYCLONE PASSIVE ELEMENTS STATISTICS INFORMATION									
Type	No.	Name	Average Units Idle	Max. Idle Units	Times not empty	% Idle	Total Sim Time	Average Wt Time	Units at end
QUEUE	11	SECTION ON STORAGE	14.6	30	3036.3	93.85	3235.4	737.2	0
QUEUE	12	POSITION AVAILABLE	0.0	1	0.0	0.00	3235.4	0.0	1
QUEUE	13	LABOR A IDLE	0.8	1	2577.7	79.67	3235.4	33.0	1
QUEUE	14	SUPERVISOR IDLE	0.4	1	1416.8	43.79	3235.4	18.2	1
GEN	15	AIR GRIPPER READY	3.4	6	3170.4	97.99	3235.4	334.2	5
QUEUE	16	CRANE IDLE	0.5	1	1755.5	54.26	3235.4	56.6	1
QUEUE	17	CONTROL CRANE	0.0	1	157.0	4.85	3235.4	5.1	1
QUEUE	18	LABOR B IDLE	0.5	1	1502.3	46.43	3235.4	15.3	1
QUEUE	19	TRUCK IDLE	0.9	1	2835.2	87.63	3235.4	354.4	1
QUEUE	20	BACKHOE IDLE	0.9	1	2835.2	87.63	3235.4	354.4	1
GEN	21	LUBRICATION READY	1.6	4	2466.1	76.22	3235.4	160.6	2
QUEUE	22	BENTONITE READY	0.9	1	2825.1	87.32	3235.4	353.1	1
QUEUE	23	JACKING SYSTEM IDLE	0.1	1	289.5	8.95	3235.4	9.3	1
GEN	24	WATER READY	1.7	4	2532.2	78.27	3235.4	168.5	2
QUEUE	25	NEED AIR GRIPPER	0.1	1	203.6	6.29	3235.4	33.9	0
QUEUE	26	GRIPPER NEED ADJUST	0.0	1	0.0	0.00	3235.4	0.0	0
GEN	27	SPOIL TANK NOT FULL	1.7	4	2478.5	76.61	3235.4	162.1	2
QUEUE	28	POSITION OCCUPIED	0.9	1	2914.9	90.09	3235.4	97.2	0
QUEUE	29	SECTION READY	0.0	1	0.0	0.00	3235.4	0.0	0
QUEUE	30	SECTION READY	0.0	1	0.0	0.00	3235.4	0.0	0
QUEUE	31	SPOIL TANK FULL	0.0	1	0.0	0.00	3235.4	0.0	0
QUEUE	32	NEED LUBRICATION	0.0	1	0.0	0.00	3235.4	0.0	0

QUEUE	33	DESANDMAN READY TO DISCHARGE	0.0	1	0.0	0.00	3235.4	0.0	0
QUEUE	34	SECTION IN PLACE	0.0	1	11.7	0.36	3235.4	0.4	0
QUEUE	35	CABLE HOSE LASER READY	0.1	1	289.5	8.95	3235.4	9.3	1

TRACE INFORMATION			
Sim Time	Activity No.	Type	Name
4.9	10	COMBI	BRING SECTION & INSTALL CASING
6.9	9	COMBI	ATTACH SECTION TO CRANE
7.9	40	NORMAL	LIFT SECTION TO POSITION
9.1	6	COMBI	LOWER SECTION INTO SHAFT
19.5	10	COMBI	BRING SECTION & INSTALL CASING
67.3	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
69.3	41	NORMAL	CRANE RETURNS
143.4	42	NORMAL	JACK PIPE SECTION
160.4	3	COMBI	DISMANTLE CABLES & HOSES
160.4	99	COUNTER	-
162.4	9	COMBI	ATTACH SECTION TO CRANE
163.4	40	NORMAL	LIFT SECTION TO POSITION
165.4	6	COMBI	LOWER SECTION INTO SHAFT
172.7	10	COMBI	BRING

			SECTION & INSTALL CASING
212.0	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
214.0	41	NORMAL	CRANE RETURNS
268.7	42	NORMAL	JACK PIPE SECTION
280.9	3	COMBI	DISMANTLE CABLES & HOSES
280.9	99	COUNTER	-
282.9	9	COMBI	ATTACH SECTION TO CRANE
283.9	40	NORMAL	LIFT SECTION TO POSITION
285.7	6	COMBI	LOWER SECTION INTO SHAFT
290.3	10	COMBI	BRING SECTION & INSTALL CASING
314.8	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
316.8	41	NORMAL	CRANE RETURNS
329.9	42	NORMAL	JACK PIPE SECTION
337.1	3	COMBI	DISMANTLE CABLES & HOSES
337.1	99	COUNTER	-
339.1	9	COMBI	ATTACH SECTION TO CRANE
340.1	40	NORMAL	LIFT SECTION TO POSITION
341.7	6	COMBI	LOWER SECTION INTO SHAFT
345.4	10	COMBI	BRING SECTION & INSTALL

			CASING
345.4	36	CONSOLIDATE	-
371.7	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
373.7	41	NORMAL	CRANE RETURNS
382.7	8	COMBI	INSTALL & CHECK AIR GRIPPER
382.7	43	NORMAL	DUMMY
389.4	42	NORMAL	JACK PIPE SECTION
389.4	37	CONSOLIDATE	-
389.4	38	CONSOLIDATE	-
396.8	3	COMBI	DISMANTLE CABLES & HOSES
396.8	39	CONSOLIDATE	-
396.8	99	COUNTER	-
408.3	1	COMBI	DISCHARGE & REFILL DESANDMAN
415.1	4	COMBI	EMPTY SPOIL TANK
417.7	2	COMBI	MIX LUBRICATION
419.7	9	COMBI	ATTACH SECTION TO CRANE
420.7	40	NORMAL	LIFT SECTION TO POSITION
422.1	6	COMBI	LOWER SECTION INTO SHAFT
423.3	10	COMBI	BRING SECTION & INSTALL CASING
499.9	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
501.9	41	NORMAL	CRANE RETURNS
600.6	42	NORMAL	JACK PIPE SECTION
629.7	3	COMBI	DISMANTLE

			CABLES & HOSES
629.7	99	COUNTER	-
631.7	9	COMBI	ATTACH SECTION TO CRANE
632.7	40	NORMAL	LIFT SECTION TO POSITION
633.8	6	COMBI	LOWER SECTION INTO SHAFT
636.9	10	COMBI	BRING SECTION & INSTALL CASING
678.3	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
680.3	41	NORMAL	CRANE RETURNS
742.0	42	NORMAL	JACK PIPE SECTION
751.5	3	COMBI	DISMANTLE CABLES & HOSES
751.5	99	COUNTER	-
753.5	9	COMBI	ATTACH SECTION TO CRANE
754.5	40	NORMAL	LIFT SECTION TO POSITION
755.7	6	COMBI	LOWER SECTION INTO SHAFT
757.5	10	COMBI	BRING SECTION & INSTALL CASING
808.5	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
810.5	41	NORMAL	CRANE RETURNS
886.9	42	NORMAL	JACK PIPE SECTION
898.1	3	COMBI	DISMANTLE CABLES & HOSES

898.1	99	COUNTER	-
900.1	9	COMBI	ATTACH SECTION TO CRANE
901.1	40	NORMAL	LIFT SECTION TO POSITION
902.2	6	COMBI	LOWER SECTION INTO SHAFT
903.4	10	COMBI	BRING SECTION & INSTALL CASING
935.0	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
937.0	41	NORMAL	CRANE RETURNS
959.7	42	NORMAL	JACK PIPE SECTION
959.7	37	CONSOLIDATE	-
959.7	38	CONSOLIDATE	-
967.9	3	COMBI	DISMANTLE CABLES & HOSES
967.9	39	CONSOLIDATE	-
967.9	99	COUNTER	-
982.1	1	COMBI	DISCHARGE & REFILL DESANDMAN
992.9	4	COMBI	EMPTY SPOIL TANK
993.3	2	COMBI	MIX LUBRICATION
995.3	9	COMBI	ATTACH SECTION TO CRANE
996.3	40	NORMAL	LIFT SECTION TO POSITION
997.3	6	COMBI	LOWER SECTION INTO SHAFT
1003.4	10	COMBI	BRING SECTION & INSTALL CASING
1003.4	36	CONSOLIDATE	-

1031.3	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1033.3	41	NORMAL	CRANE RETURNS
1046.1	8	COMBI	INSTALL & CHECK AIR GRIPPER
1046.1	43	NORMAL	DUMMY
1056.5	42	NORMAL	JACK PIPE SECTION
1057.2	7	COMBI	ADJUST AIR GRIPPER
1066.1	3	COMBI	DISMANTLE CABLES & HOSES
1066.1	99	COUNTER	-
1068.1	9	COMBI	ATTACH SECTION TO CRANE
1069.1	40	NORMAL	LIFT SECTION TO POSITION
1070.8	6	COMBI	LOWER SECTION INTO SHAFT
1071.7	10	COMBI	BRING SECTION & INSTALL CASING
1120.9	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1122.9	41	NORMAL	CRANE RETURNS
1180.6	42	NORMAL	JACK PIPE SECTION
1195.2	3	COMBI	DISMANTLE CABLES & HOSES
1195.2	99	COUNTER	-
1197.2	9	COMBI	ATTACH SECTION TO CRANE
1198.2	40	NORMAL	LIFT SECTION TO POSITION
1199.3	6	COMBI	LOWER SECTION INTO SHAFT

1203.8	10	COMBI	BRING SECTION & INSTALL CASING
1234.4	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1236.4	41	NORMAL	CRANE RETURNS
1261.8	42	NORMAL	JACK PIPE SECTION
1271.2	3	COMBI	DISMANTLE CABLES & HOSES
1271.2	99	COUNTER	-
1273.2	9	COMBI	ATTACH SECTION TO CRANE
1274.2	40	NORMAL	LIFT SECTION TO POSITION
1275.7	6	COMBI	LOWER SECTION INTO SHAFT
1279.4	10	COMBI	BRING SECTION & INSTALL CASING
1309.1	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1311.1	41	NORMAL	CRANE RETURNS
1335.6	42	NORMAL	JACK PIPE SECTION
1335.6	37	CONSOLIDATE	-
1335.6	38	CONSOLIDATE	-
1343.9	3	COMBI	DISMANTLE CABLES & HOSES
1343.9	39	CONSOLIDATE	-
1343.9	99	COUNTER	-
1357.3	1	COMBI	DISCHARGE & REFILL DESANDMAN
1367.0	4	COMBI	EMPTY SPOIL TANK
1367.7	2	COMBI	MIX LUBRICATION

1369.7	9	COMBI	ATTACH SECTION TO CRANE
1370.7	40	NORMAL	LIFT SECTION TO POSITION
1372.1	6	COMBI	LOWER SECTION INTO SHAFT
1379.0	10	COMBI	BRING SECTION & INSTALL CASING
1401.7	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1403.7	41	NORMAL	CRANE RETURNS
1417.9	42	NORMAL	JACK PIPE SECTION
1425.2	3	COMBI	DISMANTLE CABLES & HOSES
1425.2	99	COUNTER	-
1427.2	9	COMBI	ATTACH SECTION TO CRANE
1428.2	40	NORMAL	LIFT SECTION TO POSITION
1430.0	6	COMBI	LOWER SECTION INTO SHAFT
1437.1	10	COMBI	BRING SECTION & INSTALL CASING
1437.1	36	CONSOLIDATE	-
1460.3	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1462.3	41	NORMAL	CRANE RETURNS
1474.5	8	COMBI	INSTALL & CHECK AIR GRIPPER
1474.5	43	NORMAL	DUMMY
1478.2	42	NORMAL	JACK PIPE SECTION
1489.3	7	COMBI	ADJUST AIR

			GRIPPER
1496.9	3	COMBI	DISMANTLE CABLES & HOSES
1496.9	99	COUNTER	-
1498.9	9	COMBI	ATTACH SECTION TO CRANE
1499.9	40	NORMAL	LIFT SECTION TO POSITION
1501.2	10	COMBI	BRING SECTION & INSTALL CASING
1501.7	6	COMBI	LOWER SECTION INTO SHAFT
1530.1	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1532.1	41	NORMAL	CRANE RETURNS
1543.4	42	NORMAL	JACK PIPE SECTION
1550.4	3	COMBI	DISMANTLE CABLES & HOSES
1550.4	99	COUNTER	-
1552.4	9	COMBI	ATTACH SECTION TO CRANE
1553.4	40	NORMAL	LIFT SECTION TO POSITION
1554.4	6	COMBI	LOWER SECTION INTO SHAFT
1563.8	10	COMBI	BRING SECTION & INSTALL CASING
1583.8	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1585.8	41	NORMAL	CRANE RETURNS
1600.0	42	NORMAL	JACK PIPE SECTION
1600.0	37	CONSOLIDATE	-

1600.0	38	CONSOLIDATE	-
1607.3	3	COMBI	DISMANTLE CABLES & HOSES
1607.3	39	CONSOLIDATE	-
1607.3	99	COUNTER	-
1619.7	1	COMBI	DISCHARGE & REFILL DESANDMAN
1629.2	4	COMBI	EMPTY SPOIL TANK
1630.4	2	COMBI	MIX LUBRICATION
1632.4	9	COMBI	ATTACH SECTION TO CRANE
1633.4	40	NORMAL	LIFT SECTION TO POSITION
1635.3	6	COMBI	LOWER SECTION INTO SHAFT
1638.2	10	COMBI	BRING SECTION & INSTALL CASING
1667.4	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1669.4	41	NORMAL	CRANE RETURNS
1699.3	42	NORMAL	JACK PIPE SECTION
1706.7	3	COMBI	DISMANTLE CABLES & HOSES
1706.7	99	COUNTER	-
1708.7	9	COMBI	ATTACH SECTION TO CRANE
1709.7	40	NORMAL	LIFT SECTION TO POSITION
1711.0	6	COMBI	LOWER SECTION INTO SHAFT
1712.6	10	COMBI	BRING SECTION & INSTALL CASING

1750.2	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1752.2	41	NORMAL	CRANE RETURNS
1793.0	42	NORMAL	JACK PIPE SECTION
1802.5	3	COMBI	DISMANTLE CABLES & HOSES
1802.5	99	COUNTER	-
1804.5	9	COMBI	ATTACH SECTION TO CRANE
1805.5	40	NORMAL	LIFT SECTION TO POSITION
1806.6	6	COMBI	LOWER SECTION INTO SHAFT
1807.3	10	COMBI	BRING SECTION & INSTALL CASING
1807.3	36	CONSOLIDATE	-
1857.9	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1859.9	41	NORMAL	CRANE RETURNS
1870.7	8	COMBI	INSTALL & CHECK AIR GRIPPER
1870.7	43	NORMAL	DUMMY
1884.9	7	COMBI	ADJUST AIR GRIPPER
1921.6	42	NORMAL	JACK PIPE SECTION
1936.0	3	COMBI	DISMANTLE CABLES & HOSES
1936.0	99	COUNTER	-
1938.0	9	COMBI	ATTACH SECTION TO CRANE
1939.0	40	NORMAL	LIFT SECTION TO POSITION
1940.1	6	COMBI	LOWER SECTION INTO

			SHAFT
1948.8	10	COMBI	BRING SECTION & INSTALL CASING
1979.8	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1981.8	41	NORMAL	CRANE RETURNS
2020.8	42	NORMAL	JACK PIPE SECTION
2020.8	37	CONSOLIDATE	-
2020.8	38	CONSOLIDATE	-
2031.1	3	COMBI	DISMANTLE CABLES & HOSES
2031.1	39	CONSOLIDATE	-
2031.1	99	COUNTER	-
2043.1	1	COMBI	DISCHARGE & REFILL DESANDMAN
2048.7	4	COMBI	EMPTY SPOIL TANK
2050.4	2	COMBI	MIX LUBRICATION
2052.4	9	COMBI	ATTACH SECTION TO CRANE
2053.4	40	NORMAL	LIFT SECTION TO POSITION
2055.2	6	COMBI	LOWER SECTION INTO SHAFT
2062.8	10	COMBI	BRING SECTION & INSTALL CASING
2111.0	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2113.0	41	NORMAL	CRANE RETURNS
2178.3	42	NORMAL	JACK PIPE SECTION
2199.3	3	COMBI	DISMANTLE CABLES & HOSES

2199.3	99	COUNTER	-
2201.3	9	COMBI	ATTACH SECTION TO CRANE
2202.3	40	NORMAL	LIFT SECTION TO POSITION
2204.1	6	COMBI	LOWER SECTION INTO SHAFT
2205.4	10	COMBI	BRING SECTION & INSTALL CASING
2270.5	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2272.5	41	NORMAL	CRANE RETURNS
2359.0	42	NORMAL	JACK PIPE SECTION
2374.4	3	COMBI	DISMANTLE CABLES & HOSES
2374.4	99	COUNTER	-
2376.4	9	COMBI	ATTACH SECTION TO CRANE
2377.4	40	NORMAL	LIFT SECTION TO POSITION
2378.5	6	COMBI	LOWER SECTION INTO SHAFT
2379.0	10	COMBI	BRING SECTION & INSTALL CASING
2428.7	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2430.7	41	NORMAL	CRANE RETURNS
2486.2	42	NORMAL	JACK PIPE SECTION
2501.4	3	COMBI	DISMANTLE CABLES & HOSES
2501.4	99	COUNTER	-
2503.4	9	COMBI	ATTACH

			SECTION TO CRANE
2504.4	40	NORMAL	LIFT SECTION TO POSITION
2505.5	6	COMBI	LOWER SECTION INTO SHAFT
2508.6	10	COMBI	BRING SECTION & INSTALL CASING
2508.6	36	CONSOLIDATE	-
2557.4	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2559.4	41	NORMAL	CRANE RETURNS
2569.5	8	COMBI	INSTALL & CHECK AIR GRIPPER
2569.5	43	NORMAL	DUMMY
2582.3	7	COMBI	ADJUST AIR GRIPPER
2620.7	42	NORMAL	JACK PIPE SECTION
2620.7	37	CONSOLIDATE	-
2620.7	38	CONSOLIDATE	-
2629.1	3	COMBI	DISMANTLE CABLES & HOSES
2629.1	39	CONSOLIDATE	-
2629.1	99	COUNTER	-
2639.9	1	COMBI	DISCHARGE & REFILL DESANDMAN
2643.9	4	COMBI	EMPTY SPOIL TANK
2647.5	2	COMBI	MIX LUBRICATION
2649.5	9	COMBI	ATTACH SECTION TO CRANE
2650.5	40	NORMAL	LIFT SECTION TO POSITION
2651.8	6	COMBI	LOWER SECTION INTO SHAFT

2661.2	10	COMBI	BRING SECTION & INSTALL CASING
2684.3	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2686.3	41	NORMAL	CRANE RETURNS
2706.9	42	NORMAL	JACK PIPE SECTION
2715.5	3	COMBI	DISMANTLE CABLES & HOSES
2715.5	99	COUNTER	-
2717.5	9	COMBI	ATTACH SECTION TO CRANE
2718.5	40	NORMAL	LIFT SECTION TO POSITION
2720.4	6	COMBI	LOWER SECTION INTO SHAFT
2721.6	10	COMBI	BRING SECTION & INSTALL CASING
2754.9	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2756.9	41	NORMAL	CRANE RETURNS
2810.7	42	NORMAL	JACK PIPE SECTION
2818.7	3	COMBI	DISMANTLE CABLES & HOSES
2818.7	99	COUNTER	-
2820.7	9	COMBI	ATTACH SECTION TO CRANE
2821.7	40	NORMAL	LIFT SECTION TO POSITION
2822.8	6	COMBI	LOWER SECTION INTO SHAFT
2826.5	10	COMBI	BRING SECTION &

			INSTALL CASING
2854.2	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2856.2	41	NORMAL	CRANE RETURNS
2883.2	42	NORMAL	JACK PIPE SECTION
2908.8	3	COMBI	DISMANTLE CABLES & HOSES
2908.8	99	COUNTER	-
2910.8	9	COMBI	ATTACH SECTION TO CRANE
2911.8	40	NORMAL	LIFT SECTION TO POSITION
2913.1	6	COMBI	LOWER SECTION INTO SHAFT
2921.0	10	COMBI	BRING SECTION & INSTALL CASING
2985.6	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2987.6	41	NORMAL	CRANE RETURNS
3005.7	42	NORMAL	JACK PIPE SECTION
3005.7	37	CONSOLIDATE	-
3005.7	38	CONSOLIDATE	-
3013.0	3	COMBI	DISMANTLE CABLES & HOSES
3013.0	39	CONSOLIDATE	-
3013.0	99	COUNTER	-
3024.6	1	COMBI	DISCHARGE & REFILL DESANDMAN
3031.9	4	COMBI	EMPTY SPOIL TANK
3034.3	2	COMBI	MIX LUBRICATION
3036.3	9	COMBI	ATTACH

			SECTION TO CRANE
3037.3	40	NORMAL	LIFT SECTION TO POSITION
3039.1	6	COMBI	LOWER SECTION INTO SHAFT
3041.5	10	COMBI	BRING SECTION & INSTALL CASING
3041.5	36	CONSOLIDATE	-
3068.3	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
3070.3	41	NORMAL	CRANE RETURNS
3078.7	8	COMBI	INSTALL & CHECK AIR GRIPPER
3078.7	43	NORMAL	DUMMY
3163.3	42	NORMAL	JACK PIPE SECTION
3170.4	3	COMBI	DISMANTLE CABLES & HOSES
3170.4	99	COUNTER	-
3172.4	9	COMBI	ATTACH SECTION TO CRANE
3173.4	40	NORMAL	LIFT SECTION TO POSITION
3174.7	6	COMBI	LOWER SECTION INTO SHAFT
3203.1	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
3205.1	41	NORMAL	CRANE RETURNS
3218.7	42	NORMAL	JACK PIPE SECTION
3235.4	3	COMBI	DISMANTLE CABLES & HOSES
3235.4	99	COUNTER	-

APPENDIX F

Simulation Results with CYCLONE Microtunneling Model with Soil Factor

Enhancement:

Simulation Run Times: 30

MICROTUNNELING PROCESS IN DIFFERENT SOILS		
PRODUCTIVITY INFORMATION		
Sim. Time	Cycle No.	Productivity Per Time Unit
155.7	1	0.006421
303.5	2	0.006589
441.6	3	0.006793
550.5	4	0.007267
702.9	5	0.007113
831.6	6	0.007215
934.6	7	0.007490
1042.2	8	0.007676
1146.2	9	0.007852
1246.1	10	0.008025
1345.6	11	0.008175
1403.1	12	0.008553
1482.3	13	0.008770
1616.2	14	0.008662
1691.3	15	0.008869
1762.8	16	0.009077
1887.1	17	0.009009
1980.0	18	0.009091
2129.9	19	0.008921
2230.7	20	0.008966
2372.3	21	0.008852
2546.8	22	0.008638
2679.9	23	0.008583
2822.2	24	0.008504
2926.7	25	0.008542
3063.1	26	0.008488
3175.8	27	0.008502
3304.1	28	0.008474
3456.5	29	0.008390
3541.3	30	0.008471

MICROTUNNELING PROCESS IN DIFFERENT SOILS		
PRODUCTIVITY INFORMATION		
Total Sim. Time Unit	Cycle No.	Productivity (per time unit)
3541.3	30	0.008471404967265655

MICROTUNNELING PROCESS IN DIFFERENT SOILS						
CYCLONE ACTIVE ELEMENTS STATISTICS INFORMATION						
Activity Type	No.	Name	Access Counts	Average Duration	Maximum Duration	Minimum Duration
COMBI	1	DISCHARGE & REFILL DESANDMAN	7	12.3	14.2	10.8
COMBI	2	MIX LUBRICATION	7	29.9	33.5	26.8
COMBI	3	DISMANTLE CABLES & HOSES 1	11	12.3	29.1	7.2
COMBI	4	EMPTY SPOIL TANK	7	28.1	33.2	23.1
COMBI	5	PIPE SECTION INSTALL ON GUARD RAIL	30	41.9	77.8	28.4
COMBI	6	LOWER SECTION INTO SHAFT	30	1.4	2.0	1.0
COMBI	7	ADJUST AIR GRIPPER	4	13.2	14.8	11.1
COMBI	8	INSTALL & CHECK AIR GRIPPER	6	12.5	14.8	10.3
COMBI	9	ATTACH SECTION TO CRANE	30	2.0	2.0	2.0
COMBI	10	BRING SECTION & INSTALL CASING	30	6.6	12.6	2.3
NORMAL	40	LIFT SECTION TO POSITION	30	1.0	1.0	1.0
NORMAL	41	CRANE RETURNS	30	2.0	2.0	2.0
NORMAL	42	JACK PIPE SECTION 1	11	56.4	83.3	28.6
NORMAL	43	DUMMY	6	0.0	0.0	0.0

COMBI	44	DISMANTLE CABLES & HOSES 2	8	12.7	29.1	7.2
COMBI	45	DISMANTLE CABLES & HOSES 3	2	14.6	17.0	12.2
COMBI	46	DISMANTLE CABLES & HOSES 4	9	12.3	29.1	7.2
NORMAL	52	DUMMY 1	30	0.0	0.0	0.0
NORMAL	53	DUMMY SOIL TYPE CLAYEY GRAVEL	11	0.0	0.0	0.0
NORMAL	54	DUMMY SOIL TYPE SAND	8	0.0	0.0	0.0
NORMAL	55	DUMMY SOIL TYPE SILT	2	0.0	0.0	0.0
NORMAL	56	DUMMY SOIL TYPE CLAY	9	0.0	0.0	0.0
NORMAL	57	JACK PIPE SECTION 2	8	31.4	46.0	12.4
NORMAL	58	JACK PIPE SECTION 3	2	36.1	39.3	32.9
NORMAL	59	JACK PIPE SECTION 4	9	71.9	92.0	24.1

MICROTUNNELING PROCESS IN DIFFERENT SOILS									
CYCLONE PASSIVE ELEMENTS STATISTICS INFORMATION									
Type	No.	Name	Average Units Idle	Max. Idle Units	Times not empty	% Idle	Total Sim Time	Average Wt Time	Units at end
QUEUE	11	SECTION ON STORAGE	14.4	30	3323.5	93.85	3541.3	799.5	0
QUEUE	12	POSITION AVAILABLE	0.0	1	0.0	0.00	3541.3	0.0	1
QUEUE	13	LABOR A IDLE	0.8	1	2863.7	80.87	3541.3	36.7	1
QUEUE	14	SUPERVISOR IDLE	0.5	1	1693.2	47.81	3541.3	21.7	1
GEN	15	AIR GRIPPER READY	3.5	6	3456.5	97.60	3541.3	372.3	5
QUEUE	16	CRANE IDLE	0.6	1	1996.8	56.38	3541.3	64.4	1
QUEUE	17	CONTROL CRANE	0.0	1	139.1	3.93	3541.3	4.5	1

QUEUE	18	LABOR B IDLE	0.5	1	1778.8	50.23	3541.3	18.2	1
QUEUE	19	TRUCK IDLE	0.9	1	3122.3	88.17	3541.3	390.3	1
QUEUE	20	BACKHOE IDLE	0.9	1	3122.3	88.17	3541.3	390.3	1
GEN	21	LUBRICATION READY	1.6	4	2657.2	75.03	3541.3	167.5	2
QUEUE	22	BENTONITE READY	0.9	1	3112.3	87.88	3541.3	389.0	1
QUEUE	23	JACKING SYSTEM IDLE	0.1	1	316.4	8.93	3541.3	10.2	1
QUEUE	24	WATER READY	0.1	1	230.4	6.51	3541.3	6.1	1
QUEUE	25	NEED AIR GRIPPER	0.1	1	180.6	5.10	3541.3	30.1	0
QUEUE	26	GRIPPER NEED ADJUST	0.0	1	0.0	0.00	3541.3	0.0	0
GEN	27	SPOIL TANK NOT FULL	1.6	4	2669.6	75.38	3541.3	168.9	2
QUEUE	28	POSITION OCCUPIED	0.9	1	3201.0	90.39	3541.3	106.7	0
QUEUE	29	SECTION READY	0.0	1	35.3	1.00	3541.3	1.2	0
QUEUE	30	SECTION READY	0.0	1	9.5	0.27	3541.3	0.3	0
QUEUE	31	SPOIL TANK FULL	0.0	1	0.0	0.00	3541.3	0.0	0
QUEUE	32	NEED LUBRICATION	0.0	1	0.0	0.00	3541.3	0.0	0
QUEUE	33	DESANDMAN READY TO DISCHARGE	0.0	1	0.0	0.00	3541.3	0.0	0
QUEUE	34	SECTION IN PLACE 1	0.0	1	0.0	0.00	3541.3	0.0	0
QUEUE	35	CABLE HOSE LASER READY	0.1	1	316.4	8.93	3541.3	10.2	1
QUEUE	47	SECTION IN PLACE 2	0.0	1	0.0	0.00	3541.3	0.0	0
QUEUE	48	SECTION IN PLACE 3	0.0	1	0.0	0.00	3541.3	0.0	0
QUEUE	49	SECTION IN PLACE 4	0.0	1	0.0	0.00	3541.3	0.0	0

MICROTUNNELING PROCESS IN DIFFERENT SOILS			
TRACE INFORMATION			
Sim Time	Activity No.	Type	Name
4.9	10	COMBI	BRING SECTION & INSTALL CASING
6.9	9	COMBI	ATTACH SECTION TO CRANE
7.9	40	NORMAL	LIFT SECTION TO POSITION
9.1	6	COMBI	LOWER SECTION INTO SHAFT
19.5	10	COMBI	BRING SECTION & INSTALL CASING
67.3	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
67.3	52	NORMAL	DUMMY 1
67.3	53	NORMAL	DUMMY SOIL TYPE CLAYEY GRAVEL
69.3	41	NORMAL	CRANE RETURNS
138.7	42	NORMAL	JACK PIPE SECTION 1
155.7	3	COMBI	DISMANTLE CABLES & HOSES 1
155.7	99	COUNTER	-
157.7	9	COMBI	ATTACH SECTION TO CRANE
158.7	40	NORMAL	LIFT SECTION TO POSITION
160.7	6	COMBI	LOWER SECTION INTO SHAFT
168.0	10	COMBI	BRING SECTION & INSTALL CASING

207.3	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
207.3	52	NORMAL	DUMMY 1
207.3	56	NORMAL	DUMMY SOIL TYPE CLAY
209.3	41	NORMAL	CRANE RETURNS
286.5	59	NORMAL	JACK PIPE SECTION 4
303.5	46	COMBI	DISMANTLE CABLES & HOSES 4
303.5	99	COUNTER	-
305.5	9	COMBI	ATTACH SECTION TO CRANE
306.5	40	NORMAL	LIFT SECTION TO POSITION
308.3	6	COMBI	LOWER SECTION INTO SHAFT
313.0	10	COMBI	BRING SECTION & INSTALL CASING
337.4	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
337.4	52	NORMAL	DUMMY 1
337.4	56	NORMAL	DUMMY SOIL TYPE CLAY
339.4	41	NORMAL	CRANE RETURNS
429.4	59	NORMAL	JACK PIPE SECTION 4
441.6	46	COMBI	DISMANTLE CABLES & HOSES 4
441.6	50	CONSOLIDATE	-
441.6	99	COUNTER	-
443.6	9	COMBI	ATTACH SECTION TO CRANE
444.6	40	NORMAL	LIFT SECTION TO POSITION
449.9	10	COMBI	BRING

			SECTION & INSTALL CASING
449.9	36	CONSOLIDATE	-
453.1	1	COMBI	DISCHARGE & REFILL DESANDMAN
454.6	6	COMBI	LOWER SECTION INTO SHAFT
464.2	8	COMBI	INSTALL & CHECK AIR GRIPPER
464.2	43	NORMAL	DUMMY
494.2	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
494.2	52	NORMAL	DUMMY 1
494.2	55	NORMAL	DUMMY SOIL TYPE SILT
496.2	41	NORMAL	CRANE RETURNS
533.4	58	NORMAL	JACK PIPE SECTION 3
533.4	37	CONSOLIDATE	-
533.4	38	CONSOLIDATE	-
550.5	45	COMBI	DISMANTLE CABLES & HOSES 3
550.5	99	COUNTER	-
559.2	4	COMBI	EMPTY SPOIL TANK
561.7	2	COMBI	MIX LUBRICATION
563.7	9	COMBI	ATTACH SECTION TO CRANE
564.7	40	NORMAL	LIFT SECTION TO POSITION
566.2	6	COMBI	LOWER SECTION INTO SHAFT
567.3	10	COMBI	BRING SECTION & INSTALL CASING
644.0	5	COMBI	PIPE SECTION

			INSTALL ON GUARD RAIL
644.0	52	NORMAL	DUMMY 1
644.0	54	NORMAL	DUMMY SOIL TYPE SAND
646.0	41	NORMAL	CRANE RETURNS
685.9	57	NORMAL	JACK PIPE SECTION 2
702.9	44	COMBI	DISMANTLE CABLES & HOSES 2
702.9	51	CONSOLIDATE	-
702.9	99	COUNTER	-
704.9	9	COMBI	ATTACH SECTION TO CRANE
705.9	40	NORMAL	LIFT SECTION TO POSITION
707.0	6	COMBI	LOWER SECTION INTO SHAFT
710.1	10	COMBI	BRING SECTION & INSTALL CASING
751.5	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
751.5	52	NORMAL	DUMMY 1
751.5	53	NORMAL	DUMMY SOIL TYPE CLAYEY GRAVEL
753.5	41	NORMAL	CRANE RETURNS
819.4	42	NORMAL	JACK PIPE SECTION 1
831.6	3	COMBI	DISMANTLE CABLES & HOSES 1
831.6	99	COUNTER	-
833.6	9	COMBI	ATTACH SECTION TO CRANE
834.6	40	NORMAL	LIFT SECTION TO POSITION
835.8	6	COMBI	LOWER

			SECTION INTO SHAFT
837.7	10	COMBI	BRING SECTION & INSTALL CASING
888.6	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
888.6	52	NORMAL	DUMMY 1
888.6	54	NORMAL	DUMMY SOIL TYPE SAND
890.6	41	NORMAL	CRANE RETURNS
922.3	57	NORMAL	JACK PIPE SECTION 2
934.6	44	COMBI	DISMANTLE CABLES & HOSES 2
934.6	99	COUNTER	-
936.6	9	COMBI	ATTACH SECTION TO CRANE
937.6	40	NORMAL	LIFT SECTION TO POSITION
938.7	6	COMBI	LOWER SECTION INTO SHAFT
939.9	10	COMBI	BRING SECTION & INSTALL CASING
971.5	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
971.5	52	NORMAL	DUMMY 1
971.5	53	NORMAL	DUMMY SOIL TYPE CLAYEY GRAVEL
973.5	41	NORMAL	CRANE RETURNS
1035.0	42	NORMAL	JACK PIPE SECTION 1
1035.0	37	CONSOLIDATE	-
1035.0	38	CONSOLIDATE	-
1042.2	3	COMBI	DISMANTLE CABLES & HOSES 1

1042.2	51	CONSOLIDATE	-
1042.2	99	COUNTER	-
1042.2	50	CONSOLIDATE	-
1056.4	1	COMBI	DISCHARGE & REFILL DESANDMAN
1068.2	4	COMBI	EMPTY SPOIL TANK
1068.5	2	COMBI	MIX LUBRICATION
1070.5	9	COMBI	ATTACH SECTION TO CRANE
1071.5	40	NORMAL	LIFT SECTION TO POSITION
1072.6	6	COMBI	LOWER SECTION INTO SHAFT
1078.6	10	COMBI	BRING SECTION & INSTALL CASING
1078.6	36	CONSOLIDATE	-
1106.6	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1106.6	52	NORMAL	DUMMY 1
1106.6	53	NORMAL	DUMMY SOIL TYPE CLAYEY GRAVEL
1108.6	41	NORMAL	CRANE RETURNS
1121.3	8	COMBI	INSTALL & CHECK AIR GRIPPER
1121.3	43	NORMAL	DUMMY
1132.4	7	COMBI	ADJUST AIR GRIPPER
1138.8	42	NORMAL	JACK PIPE SECTION 1
1146.2	3	COMBI	DISMANTLE CABLES & HOSES 1
1146.2	99	COUNTER	-
1148.2	9	COMBI	ATTACH SECTION TO CRANE

1149.2	40	NORMAL	LIFT SECTION TO POSITION
1150.8	6	COMBI	LOWER SECTION INTO SHAFT
1151.8	10	COMBI	BRING SECTION & INSTALL CASING
1201.0	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1201.0	52	NORMAL	DUMMY 1
1201.0	55	NORMAL	DUMMY SOIL TYPE SILT
1203.0	41	NORMAL	CRANE RETURNS
1233.9	58	NORMAL	JACK PIPE SECTION 3
1246.1	45	COMBI	DISMANTLE CABLES & HOSES 3
1246.1	99	COUNTER	-
1248.1	9	COMBI	ATTACH SECTION TO CRANE
1249.1	40	NORMAL	LIFT SECTION TO POSITION
1250.2	6	COMBI	LOWER SECTION INTO SHAFT
1254.7	10	COMBI	BRING SECTION & INSTALL CASING
1285.3	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1285.3	52	NORMAL	DUMMY 1
1285.3	53	NORMAL	DUMMY SOIL TYPE CLAYEY GRAVEL
1287.3	41	NORMAL	CRANE RETURNS
1316.5	42	NORMAL	JACK PIPE SECTION 1
1345.6	3	COMBI	DISMANTLE CABLES &

			HOSES 1
1345.6	51	CONSOLIDATE	-
1345.6	99	COUNTER	-
1347.6	9	COMBI	ATTACH SECTION TO CRANE
1348.6	40	NORMAL	LIFT SECTION TO POSITION
1350.1	6	COMBI	LOWER SECTION INTO SHAFT
1353.8	10	COMBI	BRING SECTION & INSTALL CASING
1383.5	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1383.5	52	NORMAL	DUMMY 1
1383.5	54	NORMAL	DUMMY SOIL TYPE SAND
1385.5	41	NORMAL	CRANE RETURNS
1395.9	57	NORMAL	JACK PIPE SECTION 2
1395.9	37	CONSOLIDATE	-
1395.9	38	CONSOLIDATE	-
1403.1	44	COMBI	DISMANTLE CABLES & HOSES 2
1403.1	99	COUNTER	-
1427.3	4	COMBI	EMPTY SPOIL TANK
1427.9	2	COMBI	MIX LUBRICATION
1429.9	9	COMBI	ATTACH SECTION TO CRANE
1430.9	40	NORMAL	LIFT SECTION TO POSITION
1432.3	6	COMBI	LOWER SECTION INTO SHAFT
1439.3	10	COMBI	BRING SECTION & INSTALL CASING

1461.9	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1461.9	52	NORMAL	DUMMY 1
1461.9	54	NORMAL	DUMMY SOIL TYPE SAND
1463.9	41	NORMAL	CRANE RETURNS
1474.9	57	NORMAL	JACK PIPE SECTION 2
1482.3	44	COMBI	DISMANTLE CABLES & HOSES 2
1482.3	99	COUNTER	-
1484.3	9	COMBI	ATTACH SECTION TO CRANE
1485.3	40	NORMAL	LIFT SECTION TO POSITION
1487.1	6	COMBI	LOWER SECTION INTO SHAFT
1494.2	10	COMBI	BRING SECTION & INSTALL CASING
1494.2	36	CONSOLIDATE	-
1517.4	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1517.4	52	NORMAL	DUMMY 1
1517.4	56	NORMAL	DUMMY SOIL TYPE CLAY
1519.4	41	NORMAL	CRANE RETURNS
1531.5	8	COMBI	INSTALL & CHECK AIR GRIPPER
1531.5	43	NORMAL	DUMMY
1546.3	7	COMBI	ADJUST AIR GRIPPER
1609.0	59	NORMAL	JACK PIPE SECTION 4
1616.2	46	COMBI	DISMANTLE CABLES & HOSES 4
1616.2	50	CONSOLIDATE	-

1616.2	99	COUNTER	-
1618.2	9	COMBI	ATTACH SECTION TO CRANE
1619.2	40	NORMAL	LIFT SECTION TO POSITION
1620.5	10	COMBI	BRING SECTION & INSTALL CASING
1629.6	1	COMBI	DISCHARGE & REFILL DESANDMAN
1631.4	6	COMBI	LOWER SECTION INTO SHAFT
1659.8	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1659.8	52	NORMAL	DUMMY 1
1659.8	56	NORMAL	DUMMY SOIL TYPE CLAY
1661.8	41	NORMAL	CRANE RETURNS
1683.8	59	NORMAL	JACK PIPE SECTION 4
1691.3	46	COMBI	DISMANTLE CABLES & HOSES 4
1691.3	99	COUNTER	-
1693.3	9	COMBI	ATTACH SECTION TO CRANE
1694.3	40	NORMAL	LIFT SECTION TO POSITION
1695.3	6	COMBI	LOWER SECTION INTO SHAFT
1704.6	10	COMBI	BRING SECTION & INSTALL CASING
1724.6	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1724.6	52	NORMAL	DUMMY 1
1724.6	53	NORMAL	DUMMY SOIL TYPE CLAYEY

			GRAVEL
1726.6	41	NORMAL	CRANE RETURNS
1753.3	42	NORMAL	JACK PIPE SECTION 1
1753.3	37	CONSOLIDATE	-
1753.3	38	CONSOLIDATE	-
1762.8	3	COMBI	DISMANTLE CABLES & HOSES 1
1762.8	51	CONSOLIDATE	-
1762.8	99	COUNTER	-
1762.8	50	CONSOLIDATE	-
1775.2	1	COMBI	DISCHARGE & REFILL DESANDMAN
1782.5	4	COMBI	EMPTY SPOIL TANK
1783.6	2	COMBI	MIX LUBRICATION
1785.6	9	COMBI	ATTACH SECTION TO CRANE
1786.6	40	NORMAL	LIFT SECTION TO POSITION
1788.5	6	COMBI	LOWER SECTION INTO SHAFT
1791.4	10	COMBI	BRING SECTION & INSTALL CASING
1820.6	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1820.6	52	NORMAL	DUMMY 1
1820.6	56	NORMAL	DUMMY SOIL TYPE CLAY
1822.6	41	NORMAL	CRANE RETURNS
1858.0	59	NORMAL	JACK PIPE SECTION 4
1887.1	46	COMBI	DISMANTLE CABLES & HOSES 4
1887.1	99	COUNTER	-

1889.1	9	COMBI	ATTACH SECTION TO CRANE
1890.1	40	NORMAL	LIFT SECTION TO POSITION
1891.4	6	COMBI	LOWER SECTION INTO SHAFT
1893.0	10	COMBI	BRING SECTION & INSTALL CASING
1930.6	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
1930.6	52	NORMAL	DUMMY 1
1930.6	54	NORMAL	DUMMY SOIL TYPE SAND
1932.6	41	NORMAL	CRANE RETURNS
1950.9	57	NORMAL	JACK PIPE SECTION 2
1980.0	44	.COMBI	DISMANTLE CABLES & HOSES 2
1980.0	99	COUNTER	-
1982.0	9	COMBI	ATTACH SECTION TO CRANE
1983.0	40	NORMAL	LIFT SECTION TO POSITION
1984.1	6	COMBI	LOWER SECTION INTO SHAFT
1984.7	10	COMBI	BRING SECTION & INSTALL CASING
1984.7	36	CONSOLIDATE	-
2035.4	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2035.4	52	NORMAL	DUMMY 1
2035.4	53	NORMAL	DUMMY SOIL TYPE CLAYEY GRAVEL
2037.4	41	NORMAL	CRANE RETURNS

2048.2	8	COMBI	INSTALL & CHECK AIR GRIPPER
2048.2	43	NORMAL	DUMMY
2062.3	7	COMBI	ADJUST AIR GRIPPER
2118.7	42	NORMAL	JACK PIPE SECTION 1
2129.9	3	COMBI	DISMANTLE CABLES & HOSES 1
2129.9	99	COUNTER	-
2131.9	9	COMBI	ATTACH SECTION TO CRANE
2132.9	40	NORMAL	LIFT SECTION TO POSITION
2133.9	6	COMBI	LOWER SECTION INTO SHAFT
2142.6	10	COMBI	BRING SECTION & INSTALL CASING
2173.7	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2173.7	52	NORMAL	DUMMY 1
2173.7	53	NORMAL	DUMMY SOIL TYPE CLAYEY GRAVEL
2175.7	41	NORMAL	CRANE RETURNS
2222.5	42	NORMAL	JACK PIPE SECTION 1
2222.5	37	CONSOLIDATE	-
2222.5	38	CONSOLIDATE	-
2230.7	3	COMBI	DISMANTLE CABLES & HOSES 1
2230.7	51	CONSOLIDATE	-
2230.7	99	COUNTER	-
2230.7	50	CONSOLIDATE	-
2242.8	1	COMBI	DISCHARGE & REFILL DESANDMAN
2250.4	4	COMBI	EMPTY SPOIL

			TANK
2252.1	2	COMBI	MIX LUBRICATION
2254.1	9	COMBI	ATTACH SECTION TO CRANE
2255.1	40	NORMAL	LIFT SECTION TO POSITION
2256.9	6	COMBI	LOWER SECTION INTO SHAFT
2264.5	10	COMBI	BRING SECTION & INSTALL CASING
2312.7	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2312.7	52	NORMAL	DUMMY 1
2312.7	56	NORMAL	DUMMY SOIL TYPE CLAY
2314.7	41	NORMAL	CRANE RETURNS
2362.8	59	NORMAL	JACK PIPE SECTION 4
2372.3	46	COMBI	DISMANTLE CABLES & HOSES 4
2372.3	99	COUNTER	-
2374.3	9	COMBI	ATTACH SECTION TO CRANE
2375.3	40	NORMAL	LIFT SECTION TO POSITION
2377.1	6	COMBI	LOWER SECTION INTO SHAFT
2378.5	10	COMBI	BRING SECTION & INSTALL CASING
2443.6	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2443.6	52	NORMAL	DUMMY 1
2443.6	56	NORMAL	DUMMY SOIL TYPE CLAY
2445.6	41	NORMAL	CRANE

			RETURNS
2535.6	59	NORMAL	JACK PIPE SECTION 4
2546.8	46	COMBI	DISMANTLE CABLES & HOSES 4
2546.8	50	CONSOLIDATE	-
2546.8	99	COUNTER	-
2548.8	9	COMBI	ATTACH SECTION TO CRANE
2549.8	40	NORMAL	LIFT SECTION TO POSITION
2551.3	10	COMBI	BRING SECTION & INSTALL CASING
2557.6	1	COMBI	DISCHARGE & REFILL DESANDMAN
2558.7	6	COMBI	LOWER SECTION INTO SHAFT
2608.9	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2608.9	52	NORMAL	DUMMY 1
2608.9	53	NORMAL	DUMMY SOIL TYPE CLAYEY GRAVEL
2610.9	41	NORMAL	CRANE RETURNS
2670.9	42	NORMAL	JACK PIPE SECTION 1
2679.9	3	COMBI	DISMANTLE CABLES & HOSES 1
2679.9	99	COUNTER	-
2681.9	9	COMBI	ATTACH SECTION TO CRANE
2682.9	40	NORMAL	LIFT SECTION TO POSITION
2683.9	6	COMBI	LOWER SECTION INTO SHAFT
2687.1	10	COMBI	BRING SECTION &

			INSTALL CASING
2687.1	36	CONSOLIDATE	-
2735.8	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2735.8	52	NORMAL	DUMMY 1
2735.8	53	NORMAL	DUMMY SOIL TYPE CLAYEY GRAVEL
2737.8	41	NORMAL	CRANE RETURNS
2747.9	8	COMBI	INSTALL & CHECK AIR GRIPPER
2747.9	43	NORMAL	DUMMY
2760.7	7	COMBI	ADJUST AIR GRIPPER
2807.6	42	NORMAL	JACK PIPE SECTION 1
2807.6	37	CONSOLIDATE	-
2807.6	38	CONSOLIDATE	-
2822.2	3	COMBI	DISMANTLE CABLES & HOSES 1
2822.2	99	COUNTER	-
2830.8	4	COMBI	EMPTY SPOIL TANK
2834.4	2	COMBI	MIX LUBRICATION
2836.4	9	COMBI	ATTACH SECTION TO CRANE
2837.4	40	NORMAL	LIFT SECTION TO POSITION
2838.7	6	COMBI	LOWER SECTION INTO SHAFT
2848.1	10	COMBI	BRING SECTION & INSTALL CASING
2871.2	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2871.2	52	NORMAL	DUMMY 1
2871.2	54	NORMAL	DUMMY SOIL

			TYPE SAND
2873.2	41	NORMAL	CRANE RETURNS
2917.2	57	NORMAL	JACK PIPE SECTION 2
2926.7	44	COMBI	DISMANTLE CABLES & HOSES 2
2926.7	51	CONSOLIDATE	-
2926.7	99	COUNTER	-
2928.7	9	COMBI	ATTACH SECTION TO CRANE
2929.7	40	NORMAL	LIFT SECTION TO POSITION
2931.6	6	COMBI	LOWER SECTION INTO SHAFT
2932.8	10	COMBI	BRING SECTION & INSTALL CASING
2966.1	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
2966.1	52	NORMAL	DUMMY 1
2966.1	56	NORMAL	DUMMY SOIL TYPE CLAY
2968.1	41	NORMAL	CRANE RETURNS
3054.9	59	NORMAL	JACK PIPE SECTION 4
3063.1	46	COMBI	DISMANTLE CABLES & HOSES 4
3063.1	50	CONSOLIDATE	-
3063.1	99	COUNTER	-
3065.1	9	COMBI	ATTACH SECTION TO CRANE
3066.1	40	NORMAL	LIFT SECTION TO POSITION
3070.9	10	COMBI	BRING SECTION & INSTALL CASING
3074.7	1	COMBI	DISCHARGE &

			REFILL DESANDMAN
3075.8	6	COMBI	LOWER SECTION INTO SHAFT
3107.2	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
3107.2	52	NORMAL	DUMMY 1
3107.2	53	NORMAL	DUMMY SOIL TYPE CLAYEY GRAVEL
3109.2	41	NORMAL	CRANE RETURNS
3166.5	42	NORMAL	JACK PIPE SECTION 1
3175.8	3	COMBI	DISMANTLE CABLES & HOSES 1
3175.8	99	COUNTER	-
3177.8	9	COMBI	ATTACH SECTION TO CRANE
3178.8	40	NORMAL	LIFT SECTION TO POSITION
3180.2	6	COMBI	LOWER SECTION INTO SHAFT
3188.1	10	COMBI	BRING SECTION & INSTALL CASING
3252.7	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
3252.7	52	NORMAL	DUMMY 1
3252.7	54	NORMAL	DUMMY SOIL TYPE SAND
3254.7	41	NORMAL	CRANE RETURNS
3292.9	57	NORMAL	JACK PIPE SECTION 2
3292.9	37	CONSOLIDATE	-
3292.9	38	CONSOLIDATE	-
3304.1	44	COMBI	DISMANTLE CABLES & HOSES 2

3304.1	99	COUNTER	-
3319.1	4	COMBI	EMPTY SPOIL TANK
3321.5	2	COMBI	MIX LUBRICATION
3323.5	9	COMBI	ATTACH SECTION TO CRANE
3324.5	40	NORMAL	LIFT SECTION TO POSITION
3326.3	6	COMBI	LOWER SECTION INTO SHAFT
3328.7	10	COMBI	BRING SECTION & INSTALL CASING
3328.7	36	CONSOLIDATE	-
3355.5	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL
3355.5	52	NORMAL	DUMMY 1
3355.5	56	NORMAL	DUMMY SOIL TYPE CLAY
3357.5	41	NORMAL	CRANE RETURNS
3365.8	8	COMBI	INSTALL & CHECK AIR GRIPPER
3365.8	43	NORMAL	DUMMY
3447.5	59	NORMAL	JACK PIPE SECTION 4
3456.5	46	COMBI	DISMANTLE CABLES & HOSES 4
3456.5	99	COUNTER	-
3458.5	9	COMBI	ATTACH SECTION TO CRANE
3459.5	40	NORMAL	LIFT SECTION TO POSITION
3460.7	6	COMBI	LOWER SECTION INTO SHAFT
3489.2	5	COMBI	PIPE SECTION INSTALL ON GUARD RAIL

3489.2	52	NORMAL	DUMMY 1
3489.2	54	NORMAL	DUMMY SOIL TYPE SAND
3491.2	41	NORMAL	CRANE RETURNS
3533.1	57	NORMAL	JACK PIPE SECTION 2
3541.3	44	COMBI	DISMANTLE CABLES & HOSES 2
3541.3	51	CONSOLIDATE	-
3541.3	99	COUNTER	-

BIBLIOGRAPHY

Abbott, D. (2005) "UCT Microtunneling Workshops for Municipalities and Engineers" *Underground Construction Technology Conference* Presentation, Houston, TX, Jan 2005.

Abd Al-Jalil, Y. Q. (1998) "Analysis of Performance of Tunnel Boring Machine-Based Systems", Ph.D. Dissertation, The University of Texas at Austin, Austin, TX.

Abdelhamid Tariq. (2004) "Course Material for Lean Construction", Michigan State University, East Lansing, MI.

AbouRizk, S.M. Greenwood, C., Knowles, P., Ruwanpura, J.Y., Van Tol, A., Jancewicz, S., Appleton, B. and Farrar, J. (2000). "Measuring and Improving Construction Productivity – Case Studies of Three Edmonton Projects." *Proceddings of the Seventh Canadian Construction Research Forum*, Edmonton, AB, 53-75.

AbouRizk, S, Ruwanpura, J.Y, Er, K.C. and Fernando, S. (1999). "Special Purpose Simulation Templates for Utility Tunnel Construction." *Proceeding of the Winter Simulation Conference*, Pheonix, AZ, 948-955.

AbouRizk, S. and Hajjar, D. (1998). "A Framework for Applying Simulation in Construction", *Canadian Journal of Civil Engineering*, 25, 604-617

AbouRizk, S., Manavazhi, M. and Dozzi, P. (1997). "Analysis of Productivity on a tunnel operation using computer simulation." *Proceedings of the ASCE Construction Congress* V. Minneapolis, MN, 382-388

AbouRizk, S.M. and Halpin, D.W. (1991). "Probabilistic Simulation Studies for Repetitive Construction Processes." *Journal of Construction Engineering and Management*, ASCE, 116(4), 575-594

Abraham, D., and Gokhale, S. (2002). *Development of a Decision Support System for Selection of Trenchless Technologies to Minimize Impact of Utility Construction on Roadways*. FHWA/IND/JTRP-2002/7, SPR-2453, National Technical Information Service, Springfield, VA.

Allouche, E. N., Ariaratnam, S. T., and Macleod C. W. (2003). "Software for Planning and Cost Control in Directional Drilling Projects". *Journal of Construction Engineering and Management*, Vol. 129, No. 4, July/August 2003, pp. 446-453.

American Society of Civil Engineers (ASCE) (2001). *Standard Construction Guidelines for Microtunneling*. CI/ASCE Standard 36-01, Reston, VA.

Atalah, A. and Hadala, P (1996). "Microtunneling Database For The USA And Canada From 1984 To 1995". *Proceedings of the 1996 Specialty Conference on Pipeline Crossings*, p 332-339, 1996.

Atalah, A. and Hadala, P. (1996). "Microtunneling Database for the USA and Canada from 1984 to 1995". *Proceedings of the Pipeline Crossings*, 1996, Burlington, VT, June 1996, ASCE, Reston, VA.

Banks J. and Carson II, J.S. (1984). *Discrete-Event System Simulation*, Prentice-Hall, Inc. New Jersey.

Baumert, M. E. and Allouche, E. N. (2003). "Real-Time Monitoring for Quality Delivery of Directional Drilling Installations". *Journal of Infrastructure Systems*, Volume 9, Issue 1, pp. 35-43 (March 2003).

Bennett, R.D., Guice, L. K., Khan, S., and Staheli, K. (1995) *Guidelines for Trenchless Technology: CIPP, FFP, Mini-HDD, and Microtunneling.* Construction Productivity Advancement Research (CPAR) Program Technical Report. U.S. Army Corps of Engineers. Washington, D.C.

Bruce, M. H. (2003). "Design and Inspection of Microtunneling". *Underground Construction Technology Conference* Presentation, Houston, TX, Jan 2004.

Construction Technology Centre Atlantic, Inc. (1997). Investigation and Study into Research in Construction. Report submitted to Industrial Research Assistance Program (IRAP), Fredericton, N. B. Canada.

Er K.C., Fernando, S. and Ruwanpura, J.Y. (1999). "Application of Special Purpose Simulation Modeling for Tunnel Construction." *Proceedings of the 6th Canadian Construction Research Forum*, Edmonton, AB, 1-9

Hajjar, D., and AbouRizk, S. (1999). "Simphony: An Environment for Building Special Purpose Construction Simulation Tools." *Proceedings of the 1999 Winter Simulation Conference*, Phoenix, AZ. 998-1006

Hair, D. J. (1996). ''New software helps estimate trenchless job costs. Part 2.'' *Pipeline and Gas Industry*, 41–44, August 1996.

Halpin, D. W. and Woodhead. R (1998) *Construction Management*. 2nd Ed. John Willey & Sons, Inc. New York, NY.

Halpin, D. W. and Riggs, L.S. (1992) *Planning and Analysis of Construction Operations*. John Willey & Sons, Inc. New York, NY.

Halpin, D. W. (1977). "CYCLONE: Method for Modeling of Job Site Processes."

Jounal of the Construction Division, ASCE, 103(3), 489-499
Herrenknecht AG, Schwanau, Germany. (http://www.herrenknecht.com).

Ioannou, P.G. (1989a). *UM-CYCLONE User's Guide*. Department of Civil Engineering, The University of Michigan, Ann Arbor, MI

Iseley, T. and Gokhale, S. (1997). *Trenchless Installation of Conduits Beneath Roadways*. Synthesis of Highway Practice 242, Transportation Research Board, National Academy Press, Washington, D.C.

Iseley, T., Najafi, M. and Tanwani, R. (1999) *Trenchless Construction Methods and Soil Compatibility Manual*. Trenchless Technology Committee, National Utility Contractors Association (NUCA), Arlington, VA.

Iseley, T., Najafi, M., and Tanwani, R. (1999). *Trenchless Construction Methods And Soil Compatibility Manual*, 3rd Ed., National Utility Contractors Association, Arlington, VA.

Kerr Construction Inc., Palmetto, FL. (http://www.kerrconstruction.com).

Kirby, M. J., Kramer, S. R. Pittard, G. T., and Mamoun, M. (1997). "Design guidelines and procedures for guided horizontal drilling, Part II, No-Dig Eng., 3 (4), pp 13-15.

Lawson, G (2003)". Water & Sewer Construction With Horizontal Directional Drilling. The Charles Machine Works, Inc./ Ditch Witch, Perry, OK.

Lee, S. and Chang, L (2004). "Bid-markup determination for microtunneling projects". *Tunnelling and Underground Space Technology* v19, n2, p 151-163, March, 2004.

Martinez, J. and Ioannou P.G. (1994). "General Purpose Simulation with Stroboscope." *Proceedings of the Winter Simulation Conference*, Orlando, FL, 1159-1166

McCabe, B. (1998). "Automated modeling approach for performance improvement." *Proceedings of the 5th Canadian Construction Research Forum*, Edmonton, AB. 43-53

Najafi, M. (2005). *Trenchless Technology - Pipeline and Utiltiy Design, Construction, and Renewal*, McGraw-Hill, New York, NY.

Najafi, M. and Gunnink, B. (2002). "Ground Displacement Monitoring During Horizontal Directional Drilling & Other Trenchless Intallations. Part of: Pipelines 2002" – *Beneath Our Feet: Challengers and Solutions*. By George E, Kurz, (E.).

Najafi, M. (2000) "Current Issues in Horizontal Directional Drilling", *Utility Contractor*, Vol. 24, No. 4, April, 2000.

Najafi, M. (1993). "Evaluation of a New Microtunneling Propulsion System", Ph.D. Dissertation, Louisiana Tech University, Ruston, LA.

Nido, A. (1999). "Productivity Projection Model for Microtunneling Operations based on a Quantitative Analysis of Expert Evaluation." MS Independent Research Study, School of Civil Engineering, Purdue University, West Lafayette, IN.

Nido, A. A., Knies, C. J., and Abraham, D. M. (1999). "Role of operation simulation in the analysis and improvement of microtunneling projects". *Tunnelling and Underground Space Technology*, v14, pp 1-19, 1999.

Ostwald, P. F. (1992). *Engineering cost estimating*, 3rd Ed., Prentice-Hall, Englewood Cliffs, N. J.

Rush, J. W. (2004). "Microtunneling In The U.S.A. 20 Years And Counting". *Trenchless Technology Magazine*, May 2004.

Ruwanpura, J. Y. (2001) "Special Purpose Simulation for Tunnel Construction Operations" Ph.D. Dissertation, University of Alberta, Edmonton, Alberta, Canada.

Salazar, G.F. and Einstein, H.H. (1987). "SIMSUPER5: tunneling construction simulation." *Proceedings of the 4th conference on Computing in Civil Engineering*, ASCE, Boston, MA, 461-467

Salem, O., Galani, N. and Najafi, M. (2003). "Productivity Analysis of Auger Boring Trenchless Pipe Installation Using Simulation. Pipelines 2003". *New Pipeline Technologies, Security, and Safety International Conference on Pipeline Engineering and Construction 2003*, July 13–16, 2003, Baltimore, Maryland.

Sedjo, A (2002). "Microtunneling Poised for Growth in U.S. Market". *Trenchless Technology Magazine*, May 2002.

Shao, Jun (2003), *Mathematical Statistics,* second edition, Springer.

Simicevic, J. and Sterling, R. L. (2003). "Survey of Bid Prices for Trenchless Technology Methods". Trenchless Technology Center, Louisiana Tech Univeristy, Jan 2003.

Simulation Home Page, Division of Construction Engineering and Management, Purdue University, West Lafayette, IN.
(https://engineering.purdue.edu/CEM/People/Personal/Halpin/Sim/index_html, April 22, 2005)

Soltau Microtunneling, Erkelenz, Germany. (2002).
(http://www.microtunneling.com/soltau/index.htm)

Staheli, K. and Hermanson, G. E. (1996). "Microtunneling, When, Where, and How to use it". *Water Environment and Technology* 8(3), 31-36. Alexandria, VA.

Tanaka, Y. (1993). "Cycle Time Simulation of Shield-Tunneling Operation." *Proceedings of the Fifth International Conference on Computing in Civil and Building Engineering*, ASCE, Anaheim, CA, 1386-1389.

Touran, Ali and Asai, T. (1988). Simulation of Tunneling Operations, *Journal of Construction Engineering and Management*, ASCE, 113(4): 554-568.

Ueki, M. (1999). *A Decision Tool for Microtunneling Method Selection.* MS Thesis, University of Texas at Austin, Austin, TX.

Ueki, M., Haas, C. T., and Seo, J. (1999). "Decision Tool for Microtunneling Method Selection". *ASCE Journal of Construction Engineering and Management.* 1252, March/April 123-131.

Ulgen, O.M., Thomasma, T., and Otto. N. (1991). "Reusable Models: Making Your Models More User-Friendly." *Proceeding of the 1991 Winter Simulation Conference*, 554-562

Wilson, J.R. (1984). "Statistical Aspects of Simulation." *Operation Research '84, Proceedings of the 10th Annual International Conference on Operational Research*, J.P. Brans, ed., Elsevier Science Publishes B. V., Amsterdam, The Netherlands, 921-937

Zimmerman, R. and Cusker, M. (2001). "Bringing Information Technology To Infrastructure: A White Paper For A Research Agenda. Background paper for Bringing Information Technology to Infrastructure – A Workshop to Develop a Research Agenda" held by ICIS, June 25-27, 2001 in Arlington, VA.