PRODUCTIVITY ANALYSIS

OF BOX JACKING

By

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ABSTRACT

PRODUCTIVITY ANALYSIS OF

BOX JACKING

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Trenchless Technology (TT) offers methods to install utilities through the ground without damaging the surface. Box Jacking is a trenchless method for installation of prefabricated box and drainage structures without digging a trench. The concept of box jacking is similar to pipe jacking operations by first excavating an entry shaft, building the thrust block and concrete base, and setting jacking equipment. The process starts with pushing boxes while excavating at face, however, the movement of each box is achieved each time excavation at the shield is completed. Additionally, a pilot tube might be required in advance of box jacking operations. Box jacking projects often face schedule delays or loss of productivity due to inherent uncertainties in identifying unmarked underlying structures, type of soil and subsurface conditions. Although there are uncertainties in each and every construction project, management factors have a key role in reducing loss of productivity due to lack of prior investigations and/or improper planning and preparations including means and methods. The main objective of this study is to analyze productivity of box jacking operations, and make recommendations for improvements. To achieve goals of this thesis, a box jacking project was observed. Productivity data was collected and analyzed by MicroCYCLONE simulation and Method Productivity Delay Model (MPDM). While conclusions of this study showed it is possible to improve box jacking productivity, the cost may become major a factor when additional crews and equipment are selected. It should be noted that contractors and field personnel make resource decisions based on their past experiences which allow considerations for safety, productivity and costs. These issues are considered in this thesis while describing features of the case study project.

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CHAPTER 1

INTRODUCTION

1.1 Overall Review

Pipe/box jacking technology is emerging in highway and transportation systems due to needs to add more drainage structures and culverts under existing structures. Also many new pipelines including gas, oil, sewer, and water are placed or crossing under existing embankments, and the traditional method, the open-cut digging, might be impractical and may have increased costs in addition to environmental issues. Trenchless technology, as an alternative or method of choice to the open-cut method may reduce costs and may enhance sustainability by going under existing structures without digging. The trenchless pipe or box jacking technology significantly minimizes the impacts on the footprint on the construction sites.

Open-cut includes digging a trench, placing the pipe on suitable bedding materials and embedment and backfilling. Due to the nature of the open-cut method, it involves various social costs including costs to the general public, safety issues for workers and the general public, environmental impacts, and so on. Advancements in technology and development of new equipment have led to development of new methods to facilitate utility-pipe work and decrease social costs and surface disruptions. These new methods are called trenchless technology (TT) (Najafi & Gokhale, 2005). Trenchless technology includes all the methods, materials and equipment that can be used to install, repair or replace underground facilities with little or no excavation of the surface (Piehl, 2005).

The term pipe jacking can be used to describe either a TT method process or a specific method. When it refers to a TT method process, it can apply to several methods including the auger boring method in which a casing pipe is jacked through the ground as the spoil is transported through the casing by the auger (Iseley & Gokhale, 1997). In this research, pipe and box jacking refer to a specific method that is used for installation of a new pipe or box.

The pipe jacking method was used at the end of 19^{th} century for the first time and new capabilities were added in the 1950s and 1960s by the Europeans and Japanese. These capabilities included extended drive lengths, upgraded line and grade accuracy, enhanced joint mechanism, new pipe materials and improved excavation efficiency (Najafi & Gokhale, 2005). Box jacking process is very similar to pipe jacking while in box jacking instead of a circular pipe, a rectangular prefabricated concrete is used. Excavation method is another difference between box jacking and pipe jacking. In pipe jacking the most common excavation method is use of a tunnel boring machine (TBM), but it in box jacking, hand mining (most common) or special excavator may be used... Despite the method of excavation and shape of pipe and box, the operation in both pipe jacking and box jacking is similar. Productivity of pipe jacking is normally higher than box jacking because mainly the arching effects of supporting soils above pipe while it is being jacked.

This research analyzed box jacking installation for Texas Department of Transportation (TxDOT) in Vernon, Texas. The project scope focused on the problems, solutions and advantages derived from jacking 240 feet of a new 6 ft x 4 ft x 7 ft concrete box through the ground. The main purpose of the project is to investigate the productivity of box jacking as evidenced by the installment of the new box close to an existing box. This project provided a good opportunity for a thorough study on the productivity of box jacking operation using a concrete box.

1.2 Need Statement

The use of box jacking method to install a new box underground is increasing since it minimizes social costs and environmental impacts. Although there are many research projects conducted on productivity of pipe jacking, there is not any previous research on box jacking productivity. Considering many differences in pipe jacking and box jacking operation, such as excavation method, box handling, jacking operations, need for pilot tube, and so on, the need to better understand box jacking operation is important. This understanding will lead to increase in productivity and decrease costs and duration. Luo

(2005) analyzed productivity of microtunneling pipe installation by using simulation. While in microtunneling method, excavation is done by machine; in box jacking hand mining is used to excavate the tunnel. Therefore, to analyze the productivity of box jacking, labors as one of the main resources should be considered.

1.3 Scope

The scope of this study is limited to the productivity analysis of a box jacking project, through a case study and development of a prototype model, analysis of duration for each task, model development and validation.

A simulation process was performed for the cyclic part of the project which is jacking the box through the ground. Other activities including mobilization, demobilization, shaft excavation, tunneling and hauling operation were not considered in the simulated model. Additionally, a Method Productivity Delay Model (MPDM) along with Work Sampling Model was applied to evaluate loss of productivity and analyze efficiency of crews. Cost analysis was not part of this research.

1.4 Goals and Objectives

The main goal of this thesis was to evaluate productivity of box jacking operations by observing an actual project and using MicroCYCLONE as a simulation tool. Additionally, the following factors affecting productivity of box jacking projects were identified:

1) Identifying resources,
2) Describing the procedure of box jacking operation,
3) Developing the simulation model,
4) Analyzing the cyclic production, and
5) Comparing the simulated productivity results with MPDM results and actual observations at the project, and modifying the model if necessary.

1.5 Methodology

The thesis started with the literature research and review for studies on different trenchless methods, especially pipe jacking and microtunneling using various research databases such as Engineering Village, Science Direct, and American Society of Civil Engineers (ASCE) Database.

To obtain data, an actual box jacking project was observed. The case study included a Texas Department of Transportation (TxDOT) box jacking operation in City of Vernon near Wichita Falls, along Highway 287. Work included the installation of a 6 ft × 4 ft reinforced concrete box culvert (RCB) by jacking and tunneling. Jacking occurred from a "launch shaft," with labors tunneling the embankment with pneumatic hand tools and removed spoil by carts to the launch shaft. Then, spoil was hoisted to the surface and temporarily stockpiled. Hydraulic jacks in the launch shaft were used to advance the RCB into the excavated area under the shield. Figure 1.1 illustrates a new and old culvert and Figure 1.2 shows the layout of the project. Red line shows the direction of jacking. The length of jacking was 240 feet. Collected data from this project were used as input for the simulation. To analyze data obtained, MicroCYCLONE (Purdue, 2012) and Method Productivity Delay Model (MPDM) (Adrian, 2004) were used. Also to determine the effectiveness of crews as a main resource in box jacking, work sampling was used. Figure 1.3 shows a flowchart for methodology used in this research. Outputs from the simulated model were compared with actual productivity in the project.

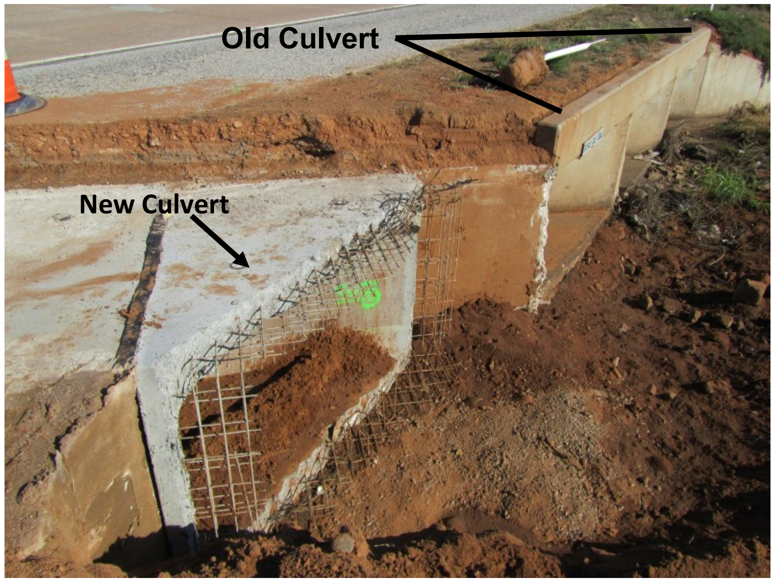


Figure 1.1 Old and New Culverts

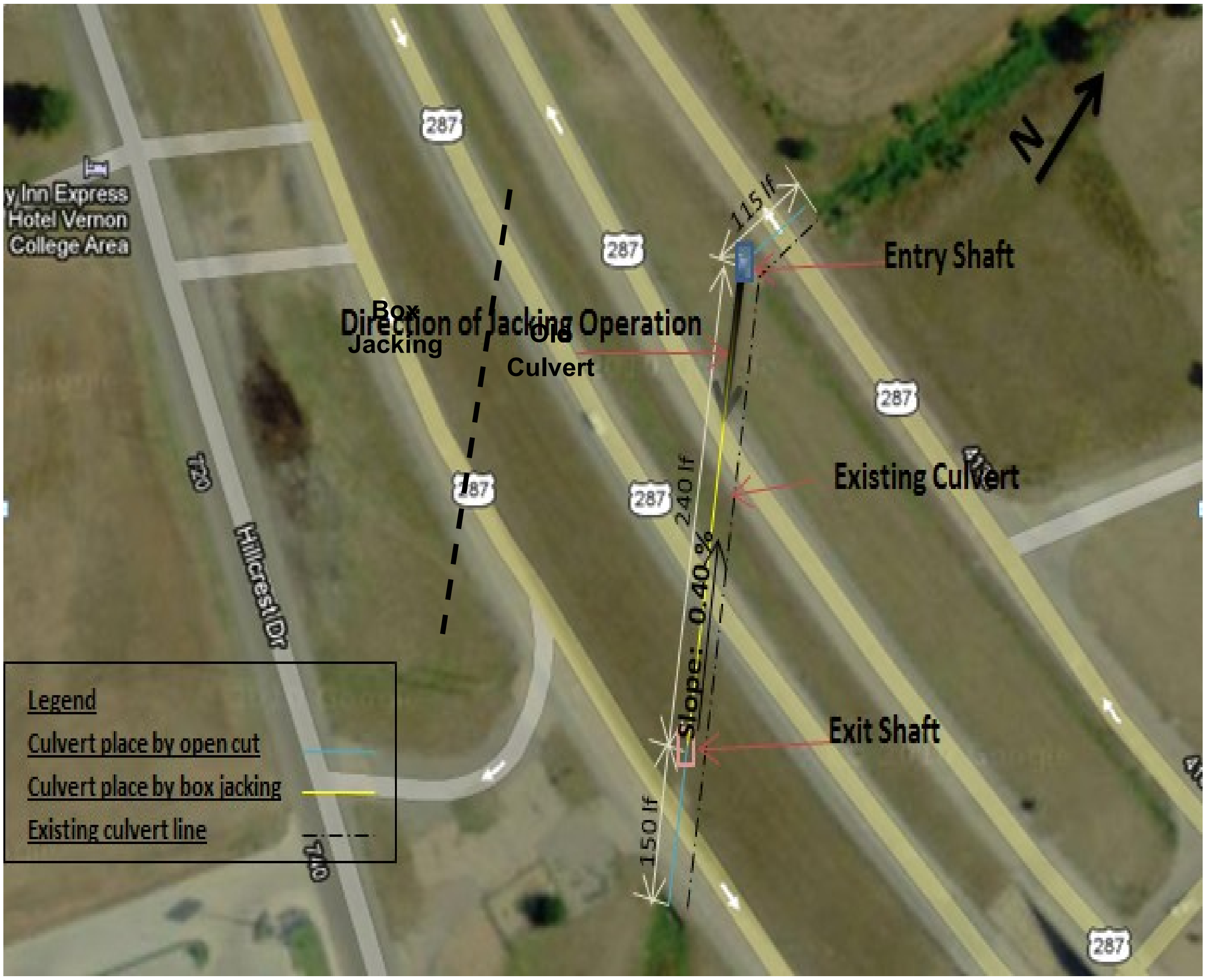


Figure 1.2 Project Layouts

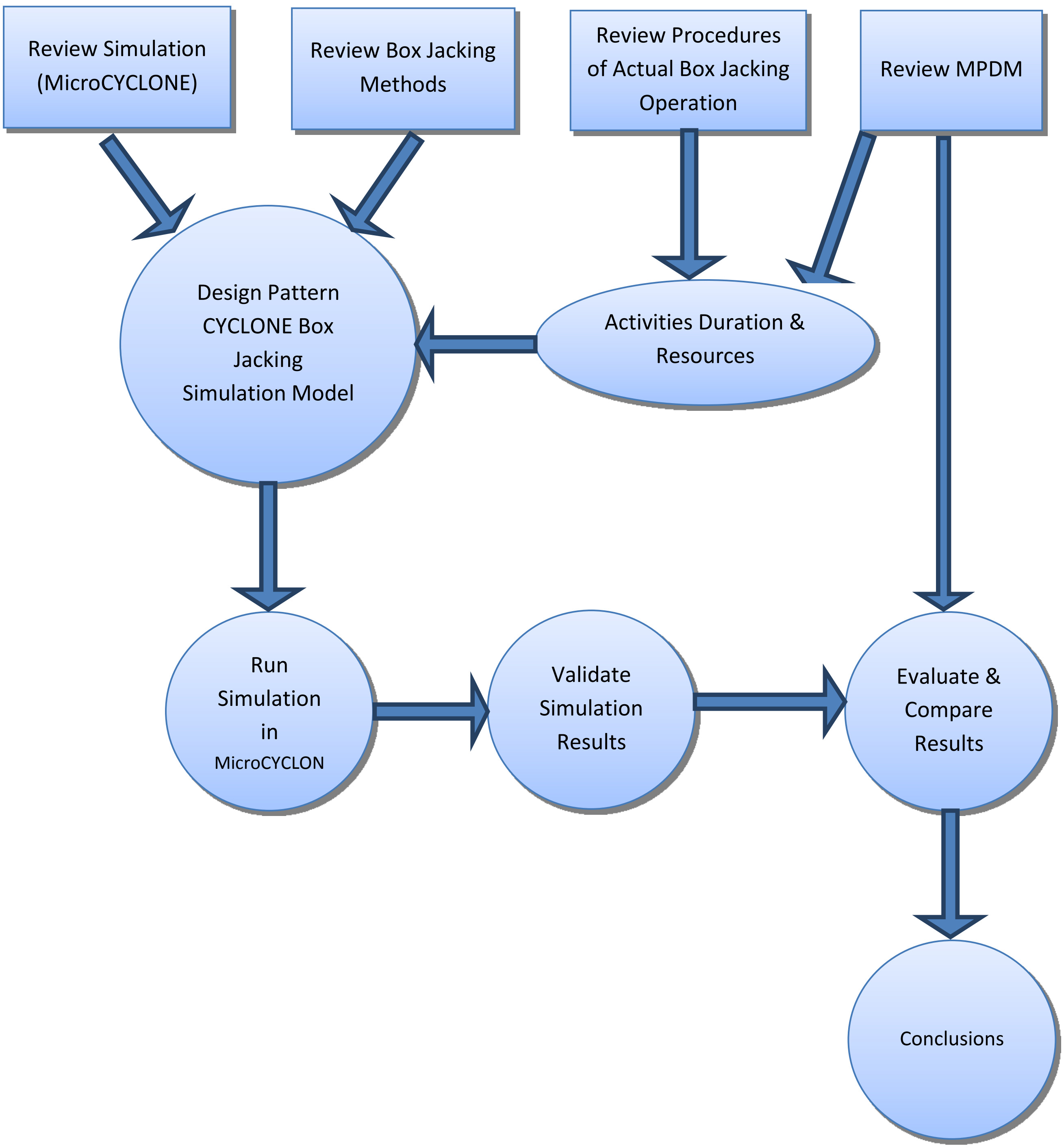


Figure 1.3 Research Methodology

1.6 Expected Outcome

The expected outcome of this research is development of a productivity model for box jacking using simulation. Using MicroCYCLONE, a model was developed to identify productivity rate for similar box jacking projects. The expected outcome for this research is to improve production and allow for shorter box jacking durations. By developing MPDM, loss of productivity and factors impacting productivity can be identified.

1.7 Thesis Organization

Chapter 1 presented an introduction to this thesis and included research objectives and methodology. Chapter 2 presents a literature review about trenchless technology and pipe jacking method in. Chapter 3 provides a review of MicroCYCLONE and Method Productivity Delay Model (MPDM). Chapter 4 includes results and discussion of results of this study. . In Chapter 5, a summary of findings is presented along with recommendations for future research.

1.8 Chapter Summary

Simulation of construction process helps contractors and consultants to identify potential challenges and optimize production and cost of the project. This research is focused on box jacking projects. A production model using a case study and simulation was developed to optimize production of box jacking projects.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

One of the most conventional methods for construction, replacement, and repair of underground utilities has been the open-cut method which includes digging a trench, placing the pipe in the trench, and embedment and backfilling. However, the open-cut method places various social costs on the general public and environment. Therefore, new methods have been introduced to improve the process of utility-pipe work and reduce open-cut's social costs. Trenchless technology (Najafi & Gokhale, 2005) uses specific methods, materials, and equipment to construct, repairs, or replace utilities without disrupting the surface (Piehl, 2005). Trenchless technology has become one of the fastest growing technologies in underground utility installation, and has also become more complicated over the years. Trenchless technology methods are divided into three main categories: 1) New Installation Methods, which includes all the methods for installing a new pipeline or utility, 2) Renewal Methods, which includes all the methods used to renew or renovate an existing utility, and 3) Replacement Methods, which includes all the inline methods used to remove an old pipeline and install a new one in its place (Najafi, 2010).

2.2 Methods of New Pipe Installation Using Trenchless Technology

As shown in Figure 2.1 new installation methods are also divided into three main categories:

1. Horizontal Earth Boring
2. Conventional Pipe Jacking
3. Utility Tunneling

Horizontal earth boring methods do not require any workers inside the tunnel during pipe installation, and the process is accomplished through mechanical means; whereas, conventional pipe jacking and utility tunneling require workers in the tunnel during the installation process. Pipe jacking and utility tunneling utilize the same equipment; the difference between the two is the structure of tunnel soil support. Pipe jacking method uses a one-phase installation, in which pipe installation is made at the same time as soil excavation, whereas in the utility tunneling method, first the tunnel is excavated and then the pipe sections are transported and installed inside the completed tunnel one by one.

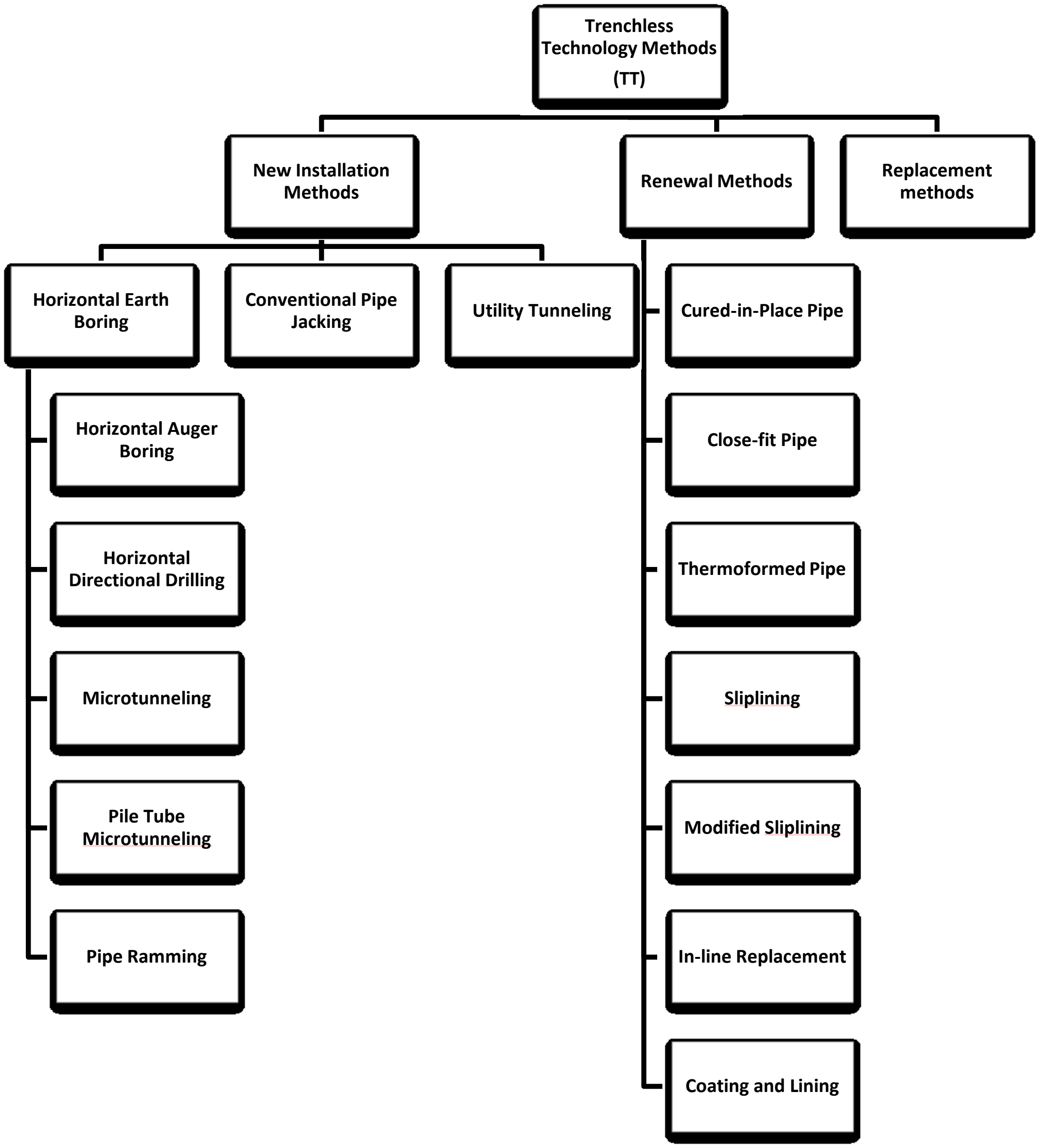


Figure 2.1 Classifications of Trenchless Technology Methods (Najafi & Gokhale, 2005)

2.2.1 Horizontal Earth Boring

Since workers are not required to enter the bore/tunnel or the installed pipe in horizontal earth boring methods, small-diameter pipes can be installed using these methods. As shown in Figure 2.1, horizontal earth boring consists of a number of methods: 1) Horizontal Auger Boring, 2) Horizontal Directional Drilling, 3) Microtunneling, 4) Pilot-tube Microtunneling, and 5) Pipe Ramming.

Horizontal auger boring (HAB) is a cost-effective trenchless technology method used to install pipes crossing a road/highway. This method is used to install up to a 60-inch diameter pipeline that extend out to 600 feet in length (Najafi & Gokhale, 2005). The borehole is made by a rotating cutting head while HAB is in operation. As the machine pushes the casing ahead, the cutting head rotating in the steel casing and spoil is hauled to launch shaft (Piehl, 2005). Auger boring machines can be arranged on loose soil when the diameter of pipe is small; however, for large-diameter pipes, a concrete block is required to provide thrust force.

Horizontal Directional Drilling (HDD) is “a steerable system for the installation of pipes, conduits, and cables along a desired profile using a surface-launched drilling rig” (Najafi, 2010). HDD is used to install pipes up to 48 inches in diameter. In this method, a fluid-lubricated pilot bore is drilled and enlarged to achieve the required pipe size (Piehl, 2005).

Microtunneling used to install new gravity underground facilities such as sanitary or storm sewers. This precise method uses a remote-controlled tunneling boring machine (TBM) for the purpose of jacking pipes behind the TBM. Initially, the microtunneling method was used for 36-inch pipes or smaller; however, remote-controlled technology has made it possible to use microtunneling for installation of larger pipes as well.

Pilot-tube microtunneling (PTMT) can be used as an alternative to microtunneling. PTMT combines the accuracy of microtunneling, the steering mechanism of a directional drill, and the spoil-removal system of an auger-boring machine. When the soil is soft, drive distance is less than 300 ft, and pipe diameter is less than 30 inches, this method is a cost-effective way to install gravity pipes. There are many reasons for the popularity of PTMT including low initial cost, adaptability to shallow installations, and small required workspace.

Pipe ramming is similar to horizontal auger boring which is mainly used for road and railroad crossings pipelines. This method uses a percussive hammer to push the steel casing pipe into the bore from a drive pit. In this method, a borehole is not created; rather, the pipe is pushed through the soil using the ramming equipment. With a length of up to 285 feet, the pipe ramming method may succeed with up to 144-inch pipes (Piehl, 2005).

2.2.2 Pipe Jacking Method

The term pipe jacking can describe either a specific trenchless technology technique or the process under which all trenchless technology methods operate. Pipe jacking, as a process, has been adopted by many trenchless technology methods such as auger boring and microtunneling. Pipe jacking can also refer to "a tunneling operation with the use of thrust boring and pushing pipes with hydraulic jacking force" (Najafi, et al, 2005). However, for the purpose of this thesis, pipe jacking is considered as a specific trenchless technology method.

2.2.2.1 Components of Pipe Jacking Process

As illustrated in Figure 2.2, the main components of pipe jacking process include (Iseley & Gokhale, 1997):

- Entry and exit shafts
- Tunnel-boring machine (TBM), earth-pressure balance machine (EPBM), open shield excavator
- Spoil removal system (such as a conveyer belt and haul units/moving carts over tracks)
- Jacking frame
- Hydraulic jacks

- Thrust block
- Intermediate jacking stations (if needed)
- Lubrication and pumping equipment
- Ventilation system (for the operator who works at the tunnel face)
- Laser guidance system
- Pipe sections
- Ancillary equipment (crane, backhoe, loader, dump trucks, and so on

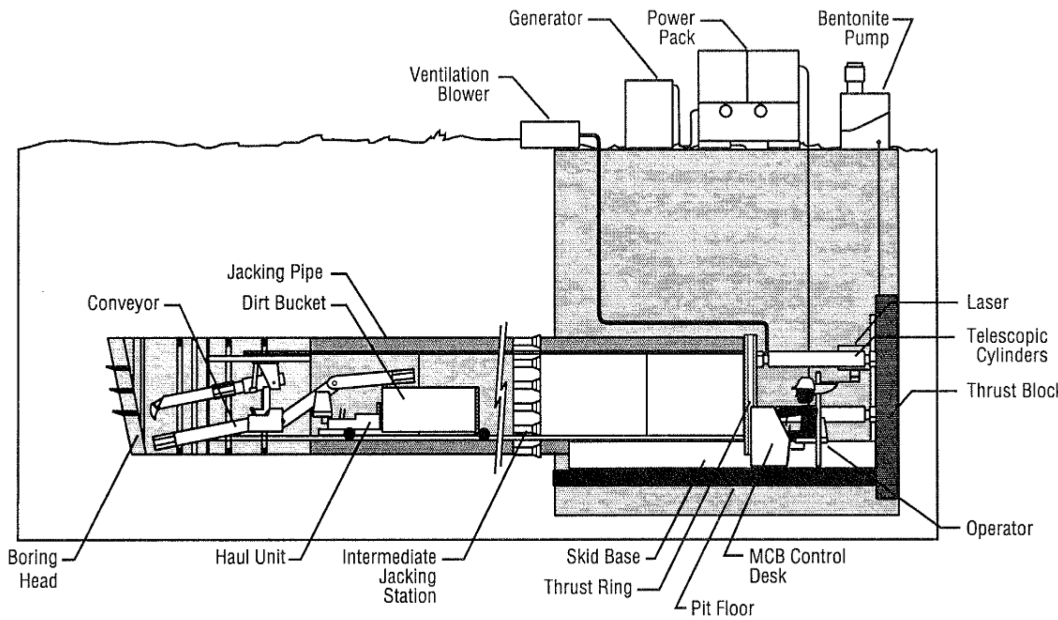


Figure 2.2 Typical Components of Pipe Jacking Process (Iseley & Gokhale, 1997)

2.2.2.2 Pipe Jacking Process

Pipe jacking method is considered as a cyclic method; with activities which repeat in each cycle. The construction sequence of pipe jacking process is shown in Figure 2.3.

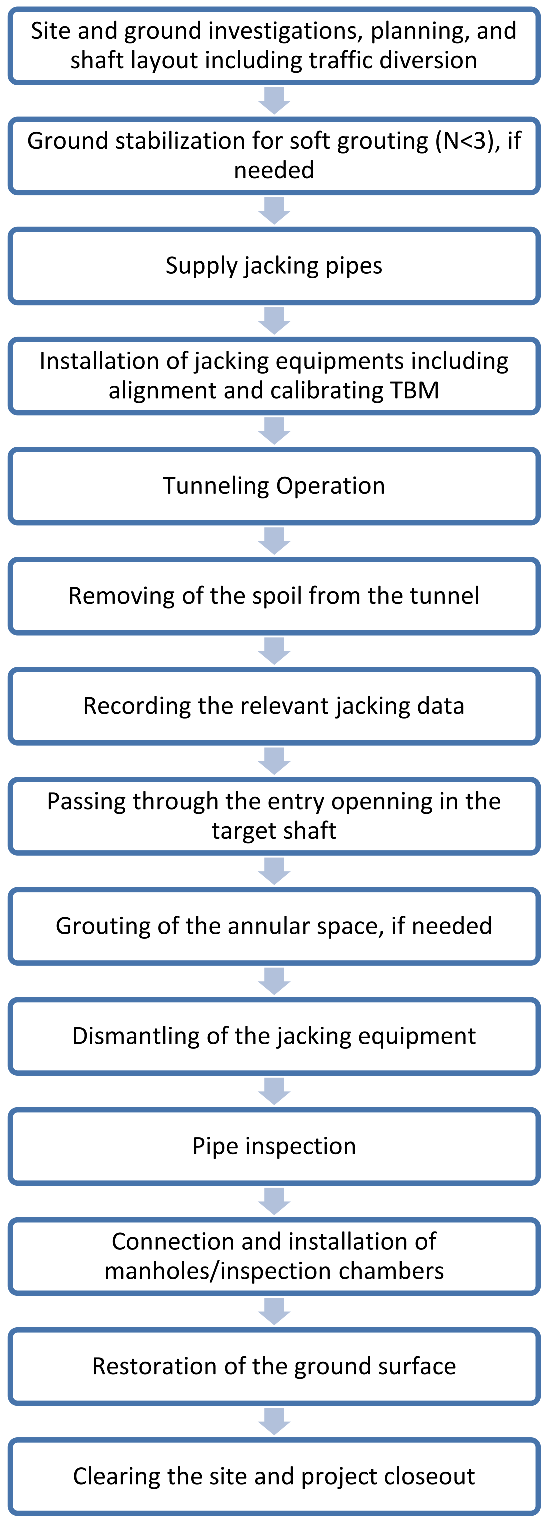


Figure 2.3 Pipe Jacking Construction Sequence (Najafi, 2010)

2.2.2.3 Pipe Jacking Main Features

The pipe size in the pipe jacking method is limited to person-entry size, with the minimum of 42 inches Outside Diameter (OD) or 36 inches Inside Diameter (ID), since the method requires workers to fit inside the jacking pipe. The drive length commonly ranges from 50 ft to 1,000 ft; this length is determined by the amount of available jacking thrust and pipe strength. The most common types of pipe used in pipe jacking are steel pipe, reinforced concrete, centrifugally cast, fiberglass-reinforced and polymer mortar. These pipes should be able to transmit the required jacking force to the tunnel boring machine (TBM). As long as some safety measures are taken, the pipe jacking process can be done in unstable soil conditions; however, the most favorable condition is cohesive soil. Productivity of pipe jacking projects ranges from 33 to 60 ft per day (8-hour shift) using a four- or five-person crew (Najafi & Gokhale, 2005).

2.2.3 Utility Tunneling

Another technique for installing a new pipeline using trenchless technology is utility tunneling (UT) which is similar to pipe jacking. The difference between the two is in the tunnel lining: utility tunneling needs a temporary support structure in the process of excavating the tunnel, whereas, in pipe jacking, the pipe is the lining(Najafi, Trenchless technology: pipeline and utility design, construction, and renewal, 2005). The pipe sections will be placed in the tunnel after the tunneling process is completed.

2.3 Productivity Analysis in Trenchless Technology Techniques

As mentioned earlier, since pipe jacking method decreases the social and environmental costs of installing a new underground pipeline, the use of this method is increasing. Therefore, there is a need to increase its productivity, and decrease the costs associated with it by better understanding the processes involved. Various studies have been implemented to understand the pipe jacking process and its productivity. In this section different productivity models and their results will be discussed.

Luo (2005) developed a model to analyze the productivity of microtunneling by observing the effects of soil type. He developed a MicroCYCLONE model based on different soil type. To identify the factors affecting the productivity of microtunneling projects and to forecast the productivity under different types of soil, another model was developed by Hegab (2003). The overall production of the project was estimated based on three different models: penetration model, preparation model, and delay model. This research has also restricted the types of soil and divided them into two main categories of 1) cohesive soil and 2) granular soil. Hegab states that sand and hard clay soil conditions are the best and the worst conditions for productivity, respectively. Hegab also believes that productivity in microtunneling projects is affected the most by soil type, drive length, machine diameter, and number of pipe sections installed. In another study, Hegab and Salem (2010) surveyed 10 experts using questionnaires designed to determine variables which affect productivity of microtunneling projects. These variables included the type of microtunneling machine, slurry separation equipment, grade and alignment, geotechnical studies, soil type, pipe material, crew experience, lubrication, jacking thrust, torque, type of cutting head, project length, technical support, working hours, slurry rate, shaft design, groundwater, and installation depth.

Luo and Najafi (2007) presented a paper on a simulation model using MicroCYCLONE to study (Luo, 2005) the costs and productivity of microtunneling projects. They developed a model which highlights effects of different soil types in microtunneling productivity.

In another study by Sarireh (2011), the productivity of Horizontal Directional Drilling (HDD) was examined under different soil conditions. However, the model restricted types of soils to clays and sands. An HDD productivity study (Mahmoud, 2009) identified four major HDD activities: 1) site preparation, 2) pilot hole drilling, 3) reaming and 4) pipe pull back and their related duration as keys to productivity. To predict the production rate based on the type of soil, a Neurofuzzy approach was used (Mahmoud, 2009).

An auger boring productivity analysis by Salem et al. (2003) found that productivity and cost is significantly influenced by the length of the borehole. The authors illustrated that due to the cyclic nature of the operation, by increasing the length of borehole, productivity increases and cost decreases. They also claimed that productivity in hard clay soil is better than in gravelly soil (Salem, et al, 2003).

Ali et al. (2007) studied effects of subjective factors on the productivity of trenchless technology projects. The authors categorized these factors into three main categories: 1) management factors, which include managerial skills, safety regulations, and operational skills, 2) environmental factors, such as soil and site conditions, groundwater level, and unseen soil complications, and 3) physical factors such as type, length, usage, and depth of the pipe.

In another study by Arachchige (2001), a simulation application using a special purpose simulation (SPS) was developed for utility tunneling to predict soil type during the operation. Since the progress of a tunneling project depends on the progress made in each individual activity in the operation, when idle time is at a minimum, the system is totally optimized. Therefore, to maximize the productivity, it is necessary to evaluate the progress in each activity that impacts the waiting time.

(Najafi & Gokhale, 2005) in the book, *Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal*, states that productivity of pipe jacking is influenced by the presence of groundwater, unanticipated obstructions, and changed conditions. Despite the various productivity analysis models of different trenchless technology techniques, no model has been developed to simulate and estimate the productivity of box jacking projects.

2.4 Chapter Summary

The literature review in this chapter investigated trenchless technology methods and explained the differences between these methods. The literature review also indicated that pipe/box jacking is a cyclic operation; therefore a MicroCYCLONE can be applied to analyze productivity in a candidate project.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter presents the methodology which has been applied to determine productivity of box jacking. In this chapter, the cyclic process of box jacking is explained. MicroCYCLONE as the main methodology will be described. At the end of this chapter the Method Productivity Delay Model (MPDM) and work sampling will be discussed as other methods for determining productivity and efficiency, respectively. Also the tests which were performed in the job site will be described in this chapter.

3.2 MicroCYCLONE[1]

As mentioned earlier, to determine the productivity of box jacking process, the computer simulation program, MicroCYCLONE, was used. This computer simulation program was designed specifically for productivity analysis of those processes which are cyclical. In construction operation modeling, MicroCYCLONE is utilized when the operation involves interaction of several tasks each with specific duration. MicroCYCLONE can help managers to predict the productivity of labor force and design construction operations. In this section, the process of developing a simulation model using MicroCYCLONE is discussed.

3.2.1 What is MicroCYCLONE?

As mentioned above, MicroCYCLONE is utilized when the operation is cyclical and involves interaction of several tasks with specific duration. MicroCYCLONE was developed based on classical

[1] The information in this section has been excerpted from Purdue University Website at https://engineering.purdue.edu/CEM/People/Personal/Halpin/Sim/index_html

networking techniques, and the modeling concepts in CYCLONE (Cyclic Operations Network). Project managers can use MicroCYCLONE as a tool to identify the mixture of resources, activity sequences, and technologies that best fits with the work condition to achieve better productivity. MicroCYCLONE provides the ability to specify initial conditions and resources specifications to predict the results. It also allows the user to experience the result of different construction operation design; this way, the user is able to evaluate and compare the productivity and economic value of those methods and designs.

3.2.2 *Network Input*

The first step in creating a MicroCYCLONE simulation is to create the network model. This step starts with defining the tasks included in the process of interest and defining the logical relationship between them. Then, the time and resources required for each task is stated. To identify this, MicroCYCLONE defined a flow of entities through the network which are delayed by work tasks but which are released to flow through the network again after they have been served or used by other work tasks.

After developing the network model, the construction processes were modeled. The steps required in this phase were:

1. Defining required resources,
2. Identifying the work tasks that are involved with the resources in the process,
3. Determining the processing of resources logic,
4. Building the process model

In order to simulate the process, data from actual projects must be obtained. The data includes start and finish time of each task, the resources, and time required for the processing of each task. The duration for each task was acquired by performing the following steps (Purdue University, 2012):

1. Check if work task can be processed (logical and resource constraints are met). If YES then CONTINUE, else go to step 5
2. Get time required to process this task
3. Calculate the time taken to complete this task
4. Update the resource/entity allocation

5. Advance time
6. Go to step 1

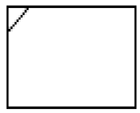
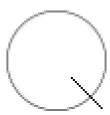
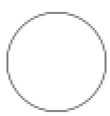
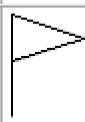
Writing a computer program that can simulate every simulation project using a General Language Purpose (GLP) makes the simulation inefficient and complicated. MicroCYCLONE uses GLP with limited scope to overcome such complications. In MicroCYCLONE, three graphical elements were used to model a specific process. Each of these graphical elements as follows has its particular meaning and models a particular event.

1. ACTIVE STATE which is shown as a square and models a work task.
2. IDLE STATE which is shown as a circle and models an entity waiting for processing.
3. FLOW DIRECTION, which is shown as a directional arc and models the flow of resources after being processed.

Each flow unit flows through the network with specific rules. First, it waits for processing in queue nodes, and then it can initiate another work task. Flow unit can also generate another entity in queue-gen nodes, and consolidate with another unit when they are passing a consolidate function. And finally, when it is passing a counter function, the flow unit can register productions.

Defining the simulation with MicroCYCLONE required the use of modeling elements and flow units in the model. However, since MicroCYCLONE does not distinguish between different entities, it was the modeler’s responsibility to clarify each entity in the model in order to achieve a properly defined model and accurate results. Table 3.1 describes each elements used in a CYCLONE modeling.

Table 3.1 CYCLONE Modeling Elements (Purdue University, 2012)

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

COMBI is used to delay a flow unit by restricting its processing by ingredient constraints. This means that the processing of a flow unit cannot be started unless the required ingredients are available on the preceding queue nodes. The attributes used to define COMBI are:

- Numerical label
- Element type

- Work task title (optional)
- Duration set number
- Preceding QUEUE nodes
- Following nodes

COMBI element can be defined using the following syntax:

(Label.C) COMBI 'description' SET (set number) PRECEDERS (Label.P) FOLLOWERS (Label.F)

NORMAL is also used to delay a flow unit by giving the unit a free access to input property. This means than when the unit arrives at NORMAL, it is given free access to initiate a work task processing for a specific amount of time. Several flow units can flow through NORMAL node and activate processing at the same time. The attributes used to define NORMAL were:

- Numerical label
- Element type
- Work task title (optional)
- Duration set number
- Following nodes

NORMAL element can be defined using the following syntax:

(Label.N) NORMAL 'description' SET (set number) FOLLOWERS (Label.F)

QUEUE is used to define a delay location in a COMBI. This element models the state in which a resource is idle and not utilized. When entities are waiting for the required ingredients, they are held in the QUEUE and released when all ingredients become available. The statistics regarding the performance of the process are collected from this element. The QUEUE element is used to:

- Generate entities in the system
- Track delays of entities
- Generate duplicate entities using GEN syntax

The attributes used to define QUEUE node or a queue node acting as a GENERATE function are:

- Numerical label
- Element type
- QUEUE node title
- Generate function and number

QUEUE element can be defined using the following syntax:

(Label) QUEUE 'description'

GENERATE element can be defined using the following syntax:

(Label) QUEUE 'description' GENERATE (number to be generated)

FUNCTION is used to perform a special function in the model. Each flow unit in the previous nodes can activate the FUNCTION element to perform the assigned function. Activating the function will automatically activate all the following elements. When used as a Consolidate Function (CON), it forces the combination of entities into a specified number. Two different FUNCTION elements have been designed in Micro CYCLONE: 1) COUNTER, and 2) CONSOLIDATE. COUNTER (accumulator) element can be defined using the following syntax:

(Label.C) FUNCTION COUNTER FOLLOWERS (Label.F) QUANTITY (quantity)

ACCUMULATOR is used to count the total completed flow units. This element can be used to terminate the simulation by counting the number of cycles which need to be done before the end of the process. ACCUMULATOR does not delay any flow unit passing through it.

PROBABILISTIC ARCS can follow any COMBI, NORMAL, or FUNCTION element to specify the probability of the flow unit flowing into the COMBI, NORMAL, and FUNCTION element. For example: 1 NORMAL FOLLOWERS 23 PROBABILITY .3 .7.

Normal Followers 23 Probability .3 .7.means that the 30% of the times, the entity should go through element 2; and 70% of the times, the entity should flow into element 3. Each time a probabilistic element is used, MicroCYCLONE generates a random number between 0 and 1. Figure 3.1 shows the example of probabilistic arc.

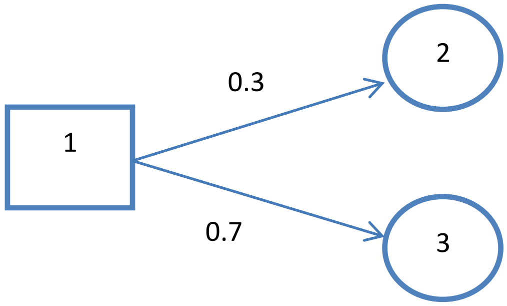
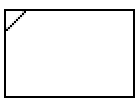
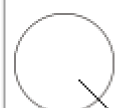
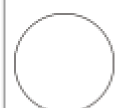
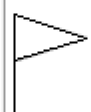
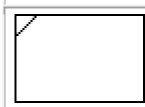
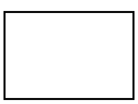
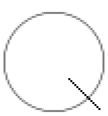
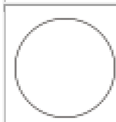
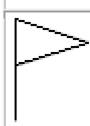


Figure 3.1 Example of Probabilistic Arc

The elements in MicroCYCLONE are preceded by logical rules. Table 3.2 shows the procedures rule for each elements in MicroCYCLONE.

Table 3.2 CYCLONE Elements Precedence Table (Purdue University, 2012)

					
	*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*
Notes: M = required or mandatory, I = immaterial, N = non feasible					

3.2.3 Duration Input

A duration set should be defined for all task elements. The duration number defines the time of the task and the population from which its time will be sampled. The two categories of tasks recognized by MicroCYCLONE are duration-stationary tasks and non stationary tasks; and the recognized statistical distributions include:

- Constant
  - Format: DETERMINISTIC (Par1)
  - Par1: Represents the constant duration describing the duration
- Exponential
  - Format: EXPONENTIAL (Par1)
  - Par1: Represents the mean of the exponential distribution
- Uniform
  - Format: UNIFORM (Par1) (Par2)
  - Par1: Represents the least possible value of the uniform distribution
  - Par2: Represents the highest possible value of the uniform distribution
- Normal
  - Format: NORMAL (Par1) (Par2)
  - Par1: Represents the mean of the normal distribution
  - Par2: Represents the variance of the normal distribution
- Triangular
  - Format: TRIANGULAR (Par1) (Par2) (Par3)
  - Par1: Represents the least possible value of the triangular distribution
  - Par2: Represents the mode value of the triangular distribution
  - Par3: Represents the highest possible value of the triangular distribution
- Log Normal
  - Format: LOGNORMAL (Par1) (Par2) (Par3)

- Par1: Represents the least possible value of the lognormal distribution
- Par2: Represents the scale parameter (μ) of the lognormal distribution
- Par3: Represents the shape parameter (σ^2) of the lognormal distribution

- Beta
  - Format: BETA (Par1) (Par2) (Par3) (Par4)
  - Par1: Represents the least possible value of the beta distribution
  - Par2: Represents the highest possible value of the beta distribution
  - Par3: First shape parameter of the beta distribution (a)
  - Par4: Second shape parameter of the beta distribution (b)

3.2.4 Resource Input

In the resource input section, the number of units required for each resource is defined. Equipment (including cranes, trucks, etc.), labor, and materials (such as pallet of bricks) are three different types of resource. Some information is required to initialize each resource which includes: 1) the number of items in the network, and 2) the starting queue nodes for each item.

This section starts with "RESOURCE INPUT" header in the first line; and the syntax for the input line is:

(# of unit) 'Description' AT (Label.N) VARIABLE (VC) FIXED (FC)

3.2.5 ENDDATA

The last line of data entered in the network is ENDDATA which signals the end of input data in MicroCYCLONE.

3.3 Method Productivity Delay Model (MPDM)

Method Productivity Delay Model (MPDM) is a data gathering technique used to provide "a practical means of measuring, predicting, and improving productivity" (Adrian, 2004). This technique has three components: 1) the compilation of data, 2) processing and analyzing the data, and 3) implementing the model. In this method, the production unit (measurable amount of work) must be established before collecting the data. Once the production unit is chosen, the actual data collection can begin, while the following aspects are observed and documented:

1. Time to complete one production cycle, which is the time between successive occurrences of the production unit.
2. A type of delay that caused productivity to decline. These types include environmental, equipment, labor, material, and management delays. If more than one type of productivity delay takes place in the same cycle, a percentage based on 100 was assigned to each delay.
3. Any out-of-the ordinary incidents that affected the production cycle was observed and documented.

After collecting the data, it was analyzed to determine the probability of occurrence, severity of the delay, the expected percent of delay time for each productivity delay per production cycle, and ultimately the ideal production cycle. Once this information is calculated, it can be demonstrated which productivity delays are causing the most interruptions so solutions to these problems can be implemented. This is one of the main benefits of MPDM which allows the contractor to focus on the specific areas that need improvement to enhance productivity.

3.4 Work Sampling

Work sampling is a method of observing a particular portion or an activity of the work which helps determine the effectiveness of the crew performing the activities. It also assists in determining the necessary crew size to complete the task most efficiently. The methods of work sampling produce data that can measure how the labor force is utilizing their time and, therefore, will produce accurate productivity ratings or worker efficiency percentages. In addition, work sampling helps managers determine where and how often delays occur, and indicate the magnitude of the delay.

Two main forms of work sampling that were applied to determine the effectiveness of the labor force for the box jacking projects is:

Field Rating: this method simply describes how many workers are observed, how many workers are working, and how many are not working (idle).

Productivity Rating: this method describes how many workers are conducting effective work (tasks that directly impact the portion of the work being completed), how many are conducting contributory work (tasks that are not directly impacting the portion of the work being completed, but are assisting in completing the effective work more efficiently), and how many are idle.

3.5 Case Study Project

The case study chosen for this research was a box jacking operation in the City of Vernon, near Wichita Falls, Texas, along Highway 287. The purpose of this project was to alleviate the flood problem on the upstream side of the drainage ditch. There are three existing rows of 6 ft× 4 ft drainage box culverts, which have become out of capacity due to increased flow. Therefore, it was required to install another 6 ft × 4 ft box culvert by jacking adjacent to existing ones to allow of increased flow. The box jacking alignment traversed subgrade of a four-lane highway and two side ramps. The culverts were jacked in accordance with TxDOT 2010 standard specification item 476 (see Appendix D). Prefabricated reinforced concrete box culverts were checked for conformance with approved submittal and relevant standards upon arrival to the jobsite. Table 3.3 presents a chronological list of activities.

Table 3.3 Chronological List of Activities

Day	Date	Activities	Problems
Thursday	30-Aug	Contractor started excavation of launch shaft.	—
Friday	31-Aug	Preparation of launch shaft finished.	—
Wednesday	5-Sep	Contractor started jacking first culvert.	Project stopped due unstable soil condition.
Thursday	6-Sep	Contractor experts came to the job site to evaluate soil condition and find a solution	Project stopped due to preparation of wood boxes.
Friday	7-Sep	No working day	Project has been stopped due to preparation of wood boxes.
Saturday	8-Sep	No working day	Project has been stopped due to preparation of wood boxes.

Table 3.3 – Continued

Sunday	9-Sep	No working day	Project has been stopped due to preparation of wood boxes.
Monday	10-Sep	Contractor started wood boxes to make soil more stable for box jacking.	Today's first shift did not get a full day of tunneling in due to unloading supplies and setting up the wood box operation.
Tuesday	11-Sep	Contractor was working on wood boxes to make soil more stable for box jacking.	—
Wednesday	12-Sep	Contractor has placed 84 feet of wood boxes so far.	—
Thursday	13-Sep	Working on wood box	—
Friday	14-Sep	Working on wood box	—
Saturday	15-Sep	Working on wood box	—
Sunday	16-Sep	Working on wood box	—
Monday	17-Sep	Placing concrete on the bottom of wood box	—
Tuesday	18-Sep	5 Culverts has been jacked today. Each shift jacked about 17 feet	—
Wednesday	19-Sep	5 Culverts has been jacked today. Each shift jacked about 17 feet. An intermediate jack has been placed between culver#7 and culvert#8. Preparation time for installing intermediate jack was about to 2.5 hours.	Air compressor broke down on 11:50 pm and was replaced by another one at 2:00 am and totally caused 2.5 hours delay.
Thursday	20-Sep	5 Culverts has been jacked today. Each shift jacked about 17 feet. Culvert number 11, 12,13,14,15 are placed.	During pressurizing, hose pipe broke down when high pressure bentonite slurry was being pushed, caused 30 minutes delay.
Friday	21-Sep	5 Culverts has been jacked today. Culvert number 16, 17,18,19,20 are placed.	The contractor had to slow down their operation due to visitors at the job site and refueling equipment. The hydraulic unit for slurry pushing kept breaking down.

Table 3.3 – Continued

Saturday	22-Sep	The day shift crew started with culver # 21 in the morning and totally 4 Culverts has been jacked today. The culvert number # 21, 22, 23, 24 were jacked today.	The foreman was not at the jobsite for 3.5 hours in the morning. The superintendent was operating the excavator.
Sunday	23-Sep	The day shift crew started with culver # 25 in the morning and totally 5 Culverts has been jacked today. The culvert number # 25, 26, 27, 28, 29 were jacked today.	—
Monday	24-Sep	The day shift crew started with culver # 30 in the morning and totally 4 Culverts has been jacked today. The culvert number # 30, 31, 32, 33 were jacked today.	—
Tuesday	25-Sep	The day shift crew started with finishing culver 33 and from 12 pm started to jack last culver. Night shift jacked the intermediate jack.	In the afternoon because of heavy rain all activities stopped for 4 hours.
Wednesday	26-Sep	Contractor grouted the boxes using ready grout (concrete) from OK Concrete Company. In the afternoon contractor started to demobilize.	The grout pump stocked many times. Night shift didn't work tonight
Thursday	27-Sep	Contractor removed thrust wall and backfield the trench box. Contractor finished demobilization.	Heavy rain caused many delays in demobilization operation.

3.5.1 Box Jacking Operation Procedures

The first step to start box jacking is to build a thrust wall. Before starting the jacking operation, contractor made two reinforced concrete columns and made a reinforced concrete wall behind the launch shaft to stabilize soil and prevent soil movement during jacking operation. Then the launch shaft was excavated and jacks were placed into it. The size of launch shaft was 17 ft × 13 ft and the 12 ft depth.

The process of launch shaft excavation and box jacking is presented in Appendix A. Box jacking is a cyclic operation which means there are activities need to be done repeatedly. To study productivity of box jacking, all repeated activities should be identified and the production cycle should be recognized. Several steps occurred in the completion of one jacking cycle. It takes approximately 219 -317 minutes to complete one cycle with 7 feet of jacking. The jacking operation process is as follows (for more details, see Appendix A):

1. Lift, placement and line adjustment of next or new Reinforced Concrete Box (RCB): Crane lifts a new concrete box (culvert) from stockpile and places it into the trench box. One labor helps to attach box to crane and guides it in a right direction. Figures 3.2 and 3.3 show the process.

Figure 3.2 Crane Hoists a Culvert from Stockpile

Figure 3.3 One Labor Helps to Place Culvert into the Launch Shaft

2. Lift, placement and line adjustment of Jacking frame: Crane lifts the jacking frame and places it into the trench box. Two labors help to place frame in a right alignment. The process is shown in Figure 3.4 and 3.5.

Figure 3.4 Crane Placing Jacking Frame into Launch Shaft

Figure 3.5 Labors Placing Jacking Frame

3. Lift, placement and line adjustment of mud rail: Crane lifts the two pieces of rail and places it into the trench box. Two labors place the rails on a wood frame and adjust them. These rails will be used to transport spoil from the tunnel. The rail is shown in Figure 3.6.

Figure 3.6 Spoil Cart Rail

4. Installing pipes and hoses for bentonite slurry movement: Two laborers install the pipes for bentonite. These pipes and hoses will be used to pump bentonite. In Figure 3.7, a labor is shown when preparing to pump bentonite.

Figure 3.7 Lubricant Preparation

5. Installing the air supply line: Two laborers install air supply lines in the tunnel. These lines will be used to flow fresh air to the face of the tunnel while workers are excavating. Air supply lines are shown in Figure 3.8.

Figure 3.8 Air Supply Lines

6. Alignment check: Operator checks alignment and extends jacks to push the box culvert forward. A laser, as shown in Figure 3.9, is used to check grade and alignment. Figure 3.10 shows the jacking handle.

Figure 3.9 Laser for Grade and Alignment

Figure 3.10 Jacking Control Handle

7. Excavation cycle: The capacity of each spoil bucket is 0.85 cubic yard (CY). This activity occupies three laborers which will be defined as “Crew C” in future. Figure 3.11 shows how crane unloads

the bucket with the help of a labor. Figure 3.12 shows the spoil cart going into the tunnel to be loaded again.

Figure 3.11 Crane Unloads Spoil Cart

Figure 3.12 Empty Spoil Cart is Pulled Towards Face of the Tunnel

8. Jacking the box: Figure 3.13 shows how the operator jacks the box. Figure 3.14 shows how a labor guides the operator to start jacking process.

Figure 3.13 Four Jacks Pushing Box

Figure 3.14 Labor Guides Jacking Operation

9. Removing mud rail, air supply line and hose for bentonite supply: Once one box is fully jacked into the tunnel and the jacking process is completely finished, mud rail, air supply line and hose for bentonite supply will be removed. This activity occupies two laborers. Figure 3.15 and 3.16 shows laborers removing the hoses.

Figure 3.15 Labors Removing Bentonite Supply Hoses

Figure 3.16 Cables and Rails Removed

10. Removing Jacking Frame: Once all hoses were removed, two laborers detach the jacking frame from previous jacked box and attach it to the crane. Then, the crane will bring the frame out of the launch shaft.

11. Applying box culvert joint adhesive to the front end of the previously jacked unit: The process of preparation for the new culvert starts with applying culvert joint adhesive to the end of the previously jacked culvert. Figure 3.17 shows the culvert joint sealant.

Figure 3.17 Polymer Modified Concrete Joint Sealant

12. Cleaning the spoil over the guide rail: The next activity is to clean the dirt from the trench box and to prepare it for receiving a new culvert.

3.5.2 *Data Collection*

In addition to data collection for productivity analysis, tests described below were performed as well:

3.5.2.1 Soil Movement Tests:

A total station (surveying tool) was used to measure any surface (pavement) settlement and heave. Four shoulder points were selected as shown in Figure 3.18 (points A, B, C and D). Table 3.3 shows the total station readings.

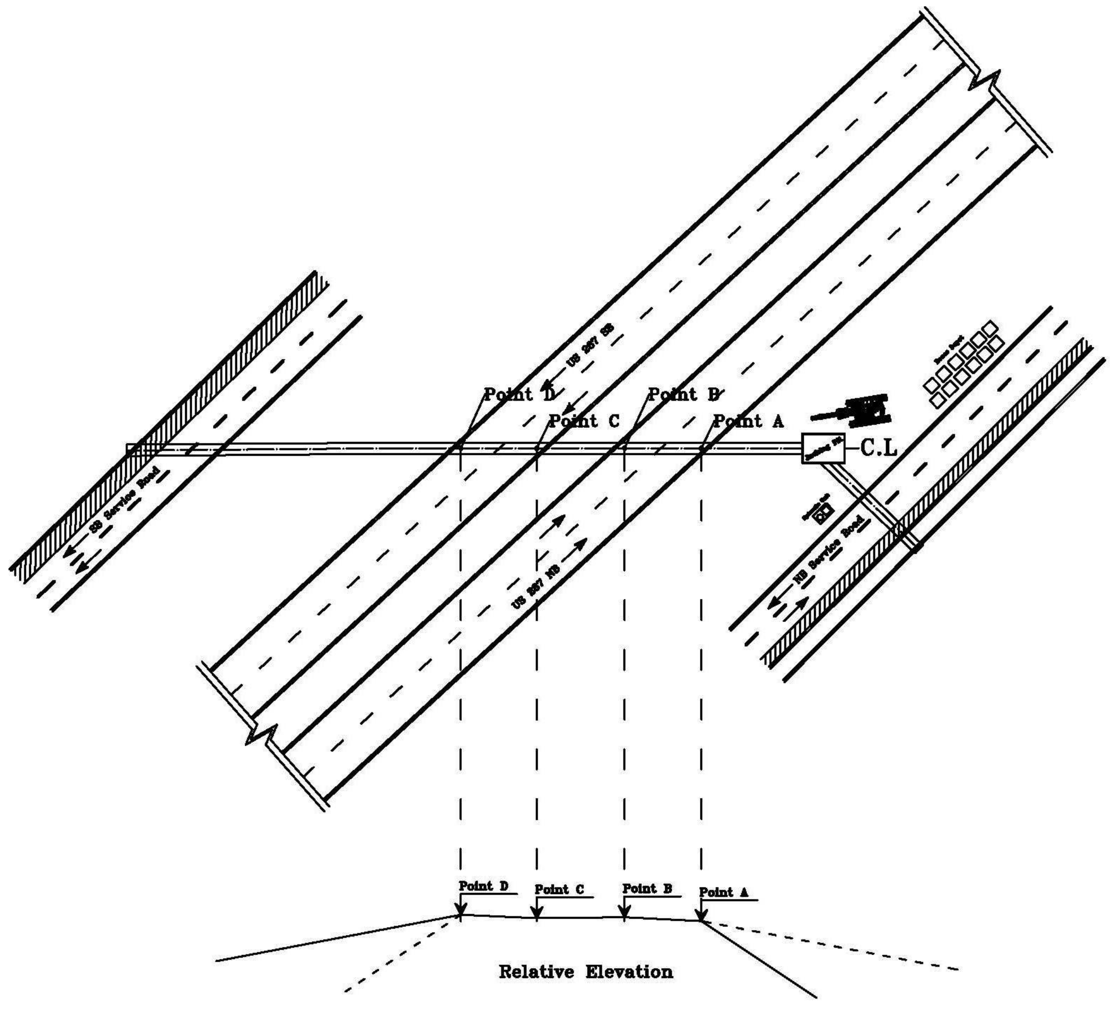


Figure 3.18 Total Station Points

According to Table 3.4, soil deflection along box jacking was less than 0.24 in (0.8 mm). This surface movement is minimal, and can be considered as an effect of temperature in the surface, highway load or instrument reading error, and not contributed by the box jacking operation.

Table 3.4 Total Station Readings

Date	Relative Elevations (ft)			
	Point A	Point B	Point C	Point D
29-Aug-12	11.12	13.59	12.95	15.13
5-Sep-12	11.13	13.58	12.96	15.13
18-Sep-12	11.12	13.60	12.96	15.13
20-Sep-12	11.10	13.59	12.97	15.11
22-Sep-12	11.11	13.57	12.96	15.12
24-Sep-12	11.11	13.58	12.95	15.14
26-Sep-12	11.13	13.58	12.95	15.14
14-Oct-12	11.10	13.57	12.97	15.14
16-Oct-12	11.13	13.61	12.94	15.12
18-Oct-12	11.11	13.60	12.95	15.12
22-Oct-12	11.14	13.58	12.96	15.13
24-Oct-12	11.14	13.60	12.94	15.14

To measure the soil movement in the vicinity of box jacking operation (with 2 ft and 4 ft distance from the tunnel) three 3-in. casings were installed on each side of the highway for inclinometer testing as shown in Figure 3.19 and 3.20. Figure 3.21 shows casings in place on north side of the project. To place these casing a Horizontal Directional Drilling (HDD) rig was used.

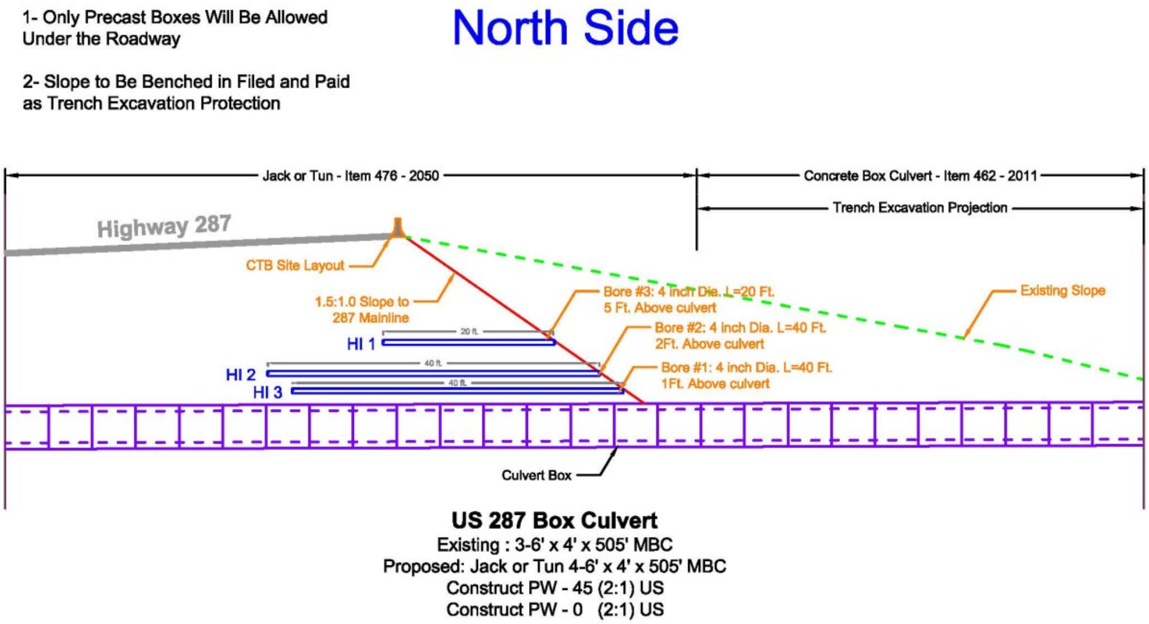


Figure 3.19 Inclinometer Installation Plan North Side

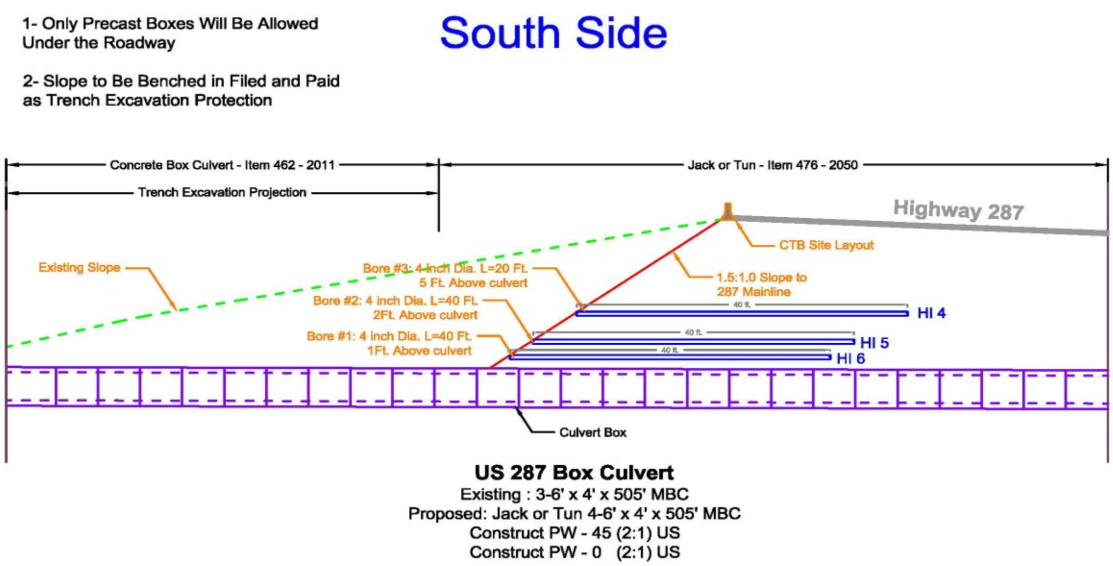


Figure 3.20 Inclinometer Installation Plan South Side

Figure 3.2119: Casings in Place

3.5.3 Load Pressure

Box jacking construction method is a type of trenchless construction methods to install new underground box (culvert) under existing highways. The main parameter in design and construction in this method is the required jacking load. Jacking loads has direct effect on designing thrust block capacity, jacking system, the box thickness and other components, such as distance between jacking stations which has great impact on construction costs. Three main parameters contribute in jacking loads, (1) face pressure, (2) frictional forces, (3) pipe/box string misalignment (Rahjoo, 2012). Frictional forces have the main role among the other parameters. To have a good understanding and prediction about these forces, it is required to have some estimation about friction coefficients and normal pressure over the pipe. Several attempts have been carried out to evaluate soil friction along different pipe materials (Staheli, 2006), some discrepancy exist in method of calculation. In the Vernon project, inclinometer casings were installed and the possible ground movements were recorded to evaluate any unstable regions near culvert entry and exit and critical region between new and old (existing) culvert boxes.

Additionally, pressure from the hydraulic unit which was used to jack boxes was measured using a transducer. The significance of the pressure measurement was to determine maximum jacking load and its relationship to soil type and length of box jacking. The transducer is shown in Figure 3.22. Figure 3.23 presents the data based on reading from transducer in tons over distance in ft. The maximum force was 577 tons. It was found that the force increases with length of the box jacking. As shown in Figure 3.27, it was found that the intermediate jacking station (IJS, see Najafi, 2010) has a major impact in reducing the total force loads at the launch shaft.

Figure 3.20 Pressure Transducer

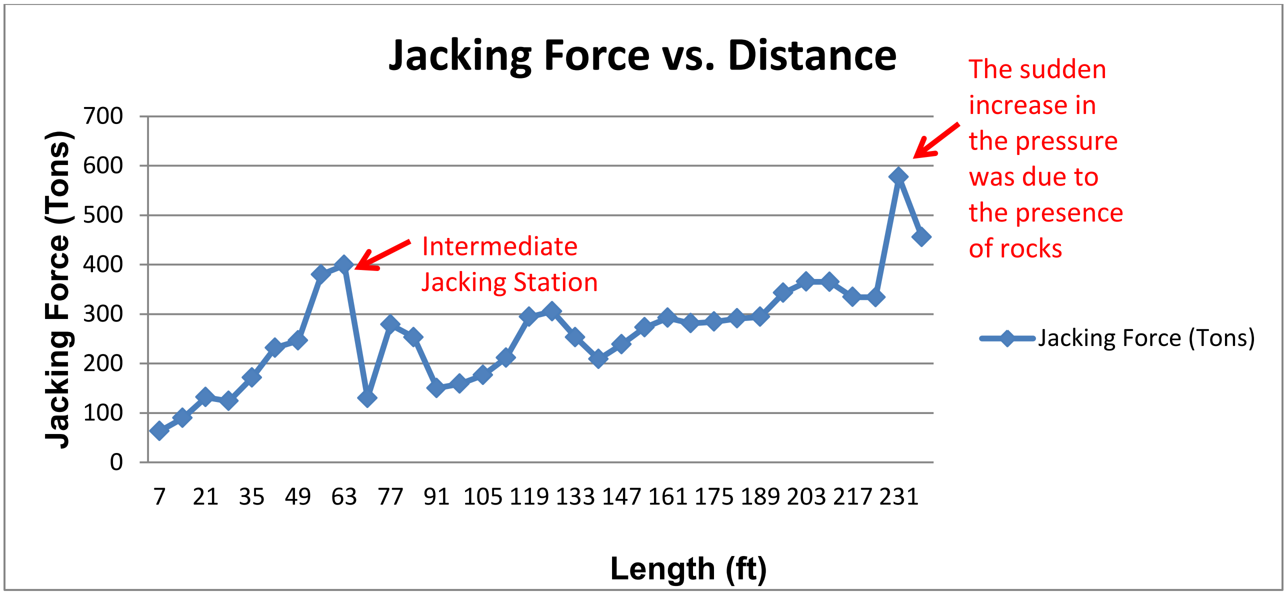


Figure 3.213 Jacking Force vs. Distance

3.6 Chapter Summary

In this chapter the research methodology was described. Details of MicroCYCLONE, a simulation tool were provided. MPDM and Work Sampling as other methods for analyzing the productivity and efficiency were described. The instrumentation and data collection for the case study project was presented.

CHAPTER 4

RESEARCH RESULTS

4.1 Introduction

In this chapter, results and findings of this research are presented. The results are categorized in three sections: 1) MicroCYCLONE, 2) MPDM, and 3) Work Sampling. At the end of this chapter, a discussion of findings is provided.

4.2 MicroCYCLONE

4.2.1 Collecting Data

To prepare the MicroCYCLONE simulation, the first step was to collect data from the case study project. All activities during box jacking in the TxDOT project in Vernon, Texas, were carefully observed. Table 4.1 presents all the activities in a cyclic order. Additionally, using a digital video camcorder, duration of each cycle was measured and the distribution for the duration was identified. Figure 4.1 shows the duration for jacking each box, and Table 4.2 shows the minimum and maximum duration for each activity. Based on the distribution for cycles, a uniform distribution was selected for activities.

Table 4.1 Box Jacking Cyclic Activity

Activity Type	No.	Name
COMBI	1	RIG BOX TO CRANE
COMBI	2	BRING BOX FROM STOCKPILE
COMBI	3	PLACE JACKING FRAME INTO TRENCH
COMBI	4	PLACE RAILS AND ALIGNMENT
COMBI	5	EXCAVATE
COMBI	6	REMOVE JACKING FRAME & HOSES
COMBI	7	MIX LUBRICATION
NORMAL	26	JACK BOX SECTION
NORMAL	27	PLACE BOX INTO SHAFT
NORMAL	28	SWING CRANE

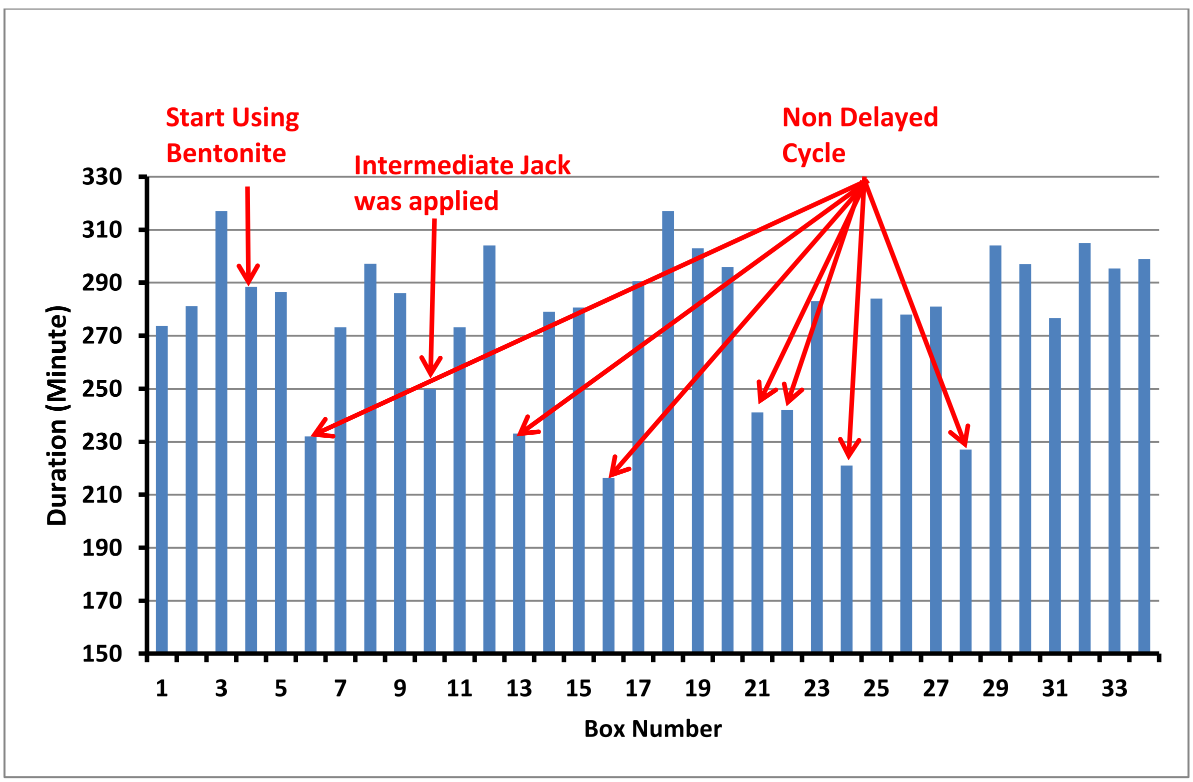


Figure 4.1 Duration for Jacking Each Box

Table 4.2 Minimum and Maximum Duration for Each Activity

Number	Activity	MINIMUM DURATION (Minute)	MAXIMUM DURATION (Minute)
1	RIG BOX TO CRANE	2.3	3.3
2	BRING BOX FROM STOCKPILE	2.4	3.4
3	PLACE JACKING FRAME INTO TRENCH	24.5	42.8
4	PLACE RAILS AND ALIGNMENT	15.5	33.8
5	EXCAVATE	97.6	169.2
6	REMOVE JACKING FRAME & HOSES	24.9	37
7	MIX LUBRICATION	2.3	3.5
26	JACK BOX SECTION	24.2	33.3
27	PLACE BOX INTO TRENCH	3.7	5.1
28	SWING CRANE	2.3	3.3
Total		216.3	317.1

4.2.2 MicroCYCLONE Diagrams and Flow charts

The flow of activities was designed based on the relationships among all activities. Because of the complex nature of the box jacking process with different types of resources and multiple interactions among them, it was essential to first design a cycle for each resource and then combines it with other resources to construct the main cycle. After defining the resources, the next step was to identify work tasks related to each resource. Determining the logic of resource processing was the next step to designing the model for MicroCYCLONE. This process was followed in the case study project and is similar to other box jacking projects; therefore, the designed model can be used for other box jacking processes by modifying the durations and resources.

4.2.3 Resource Identification

As discussed earlier, the main step for designing a model is to identify resources. After identifying the main resources, the duration of each activity should be measured by observation at the jobsite. Based on project observation, the main resources are:

1. Reinforced Concrete Box (RCB) sections: A total of 34 boxes with dimensions of 6 ft x 4 ft x 7ft were used in this project.
2. Crew A: Consisted of one labor helping rig boxes to crane and helping the operator to place boxes in the shaft.
3. Crew B: Consisted of two labors placing the box in the correct direction to attach jacking frame, connect slurry and air hoses, and prepare for jacking operation to start.
4. Crew C: Consisted of three labors excavating in the tunnel. Two labors of this crew excavated the tunnel, while the other filled the bucket (cart) and transported outside the tunnel.
5. Supervisor: One supervisor always supervised the operations.
6. Crane: One excavator (Caterpilar Model 330 CL) was available on the jobsite to hoist the culverts and placed them into the shaft. The same excavator was used take the spoil out of the trench and unloaded it.
7. Hydraulic jacks: A set of four hydraulic jacks, each with 8-inch diameter, were used.
8. Lubrication: After four boxes were jacked, a mud mixer was filled up with bentonite lubrication. Crew A filled the mixer.

Based on these resources, the following cycles were developed. The main row of activities is shown in Figure 4.2. The main row starts from taking RCB from stockpile and placing it into launch shaft. Then the crane placed jacking frame and hoses and air supply line into launch shaft followed by crew C starting excavation from within the RCB. After completing 2 ft of excavation, RCB was jacked by four hydraulic jacks. Removing hoses and jacking frame were the last activities shown in the main row.

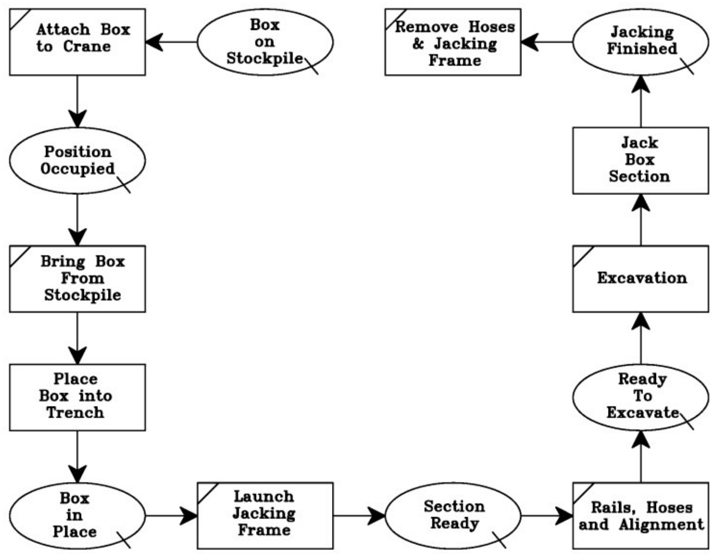


Figure 4.2 Cycle for Placing and Jacking RCB

Figure 4.3 shows the cycle for tunnel excavation and the jacking cycle. Figures 4.4 and 4.5 show the availability of Crew A and Crew B. Crew A with one labor helped to rig RCB to crane, bringing it from stockpile and then mix lubrication. Crew B with two labors helped in placing and removing jacking frame and air supply and bentonite hoses.

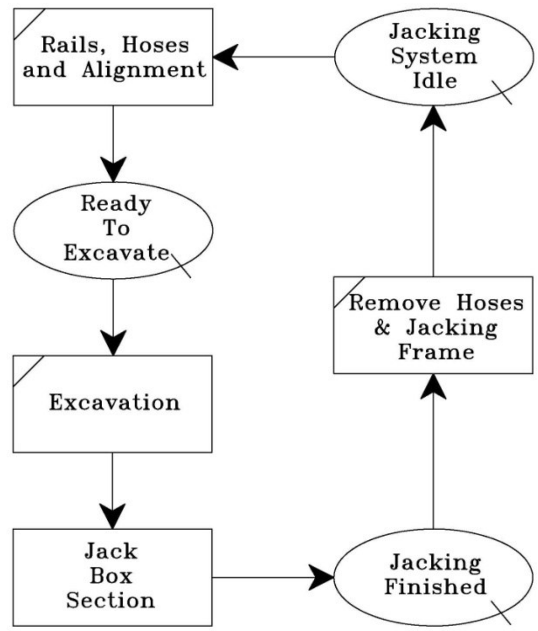


Figure 4.3 Excavation and Jacking Cycle

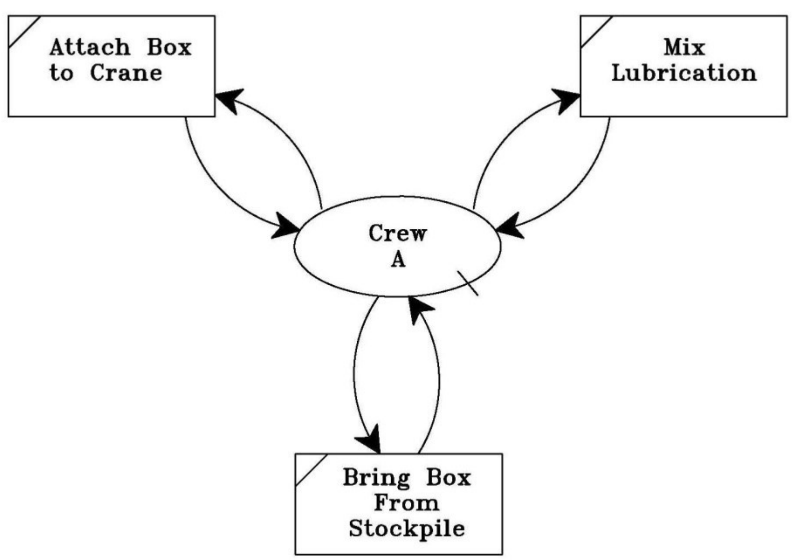


Figure 4.4 Crew A Activities

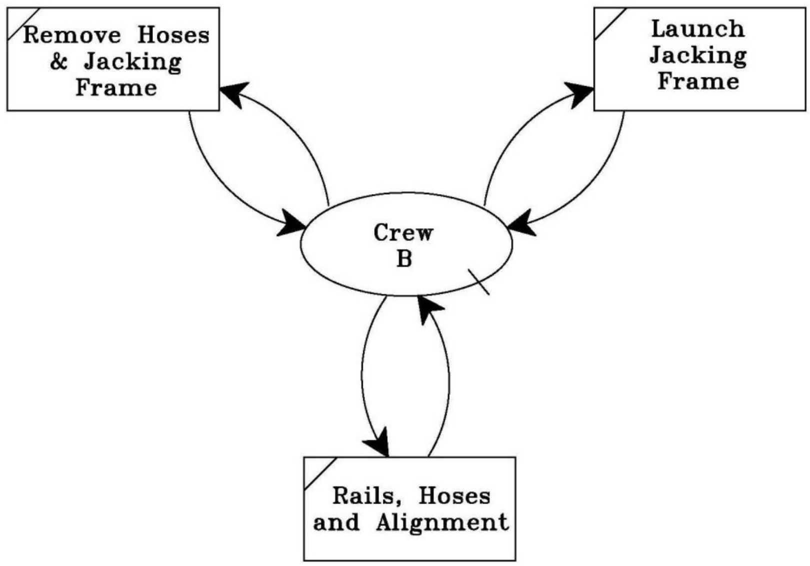


Figure 4.5 Crew B Activities

Figure 4.6 shows the cycle for mixing lubrication. In this activity, after every four jacked RCB, crew A mixes bentonite with water to mix lubrication.

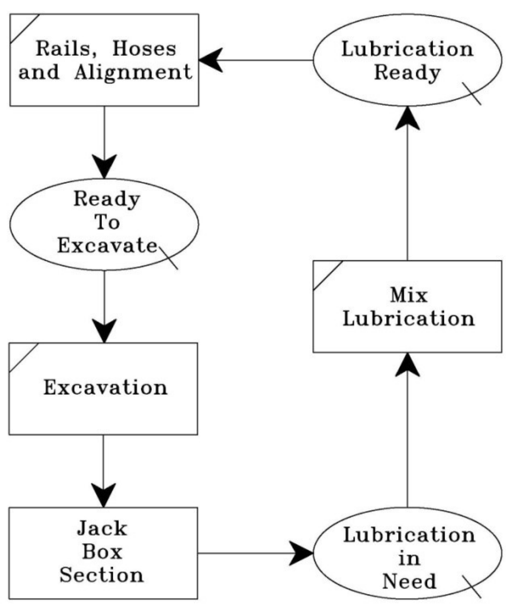


Figure 4.6 Lubrication Cycle

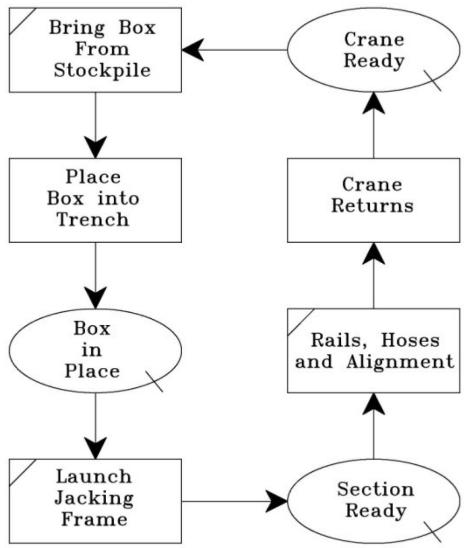


Figure 4.7 Crane Cycle

Figure 4.7 shows the activity where crane was involved. Crane brought the RCB from stockpile and placed it into the launch shaft. Next, it brought jacking frame and placed it into shaft with bentonite hoses and air supply lines. Crane also removed jacking frame, hoses and lines after jacking was completed. Figure 4.8 shows the counter (flag) which was placed after removing jacking frame. Technically one cycle is finished after jacking is completed and jacking frame and hoses are removed.

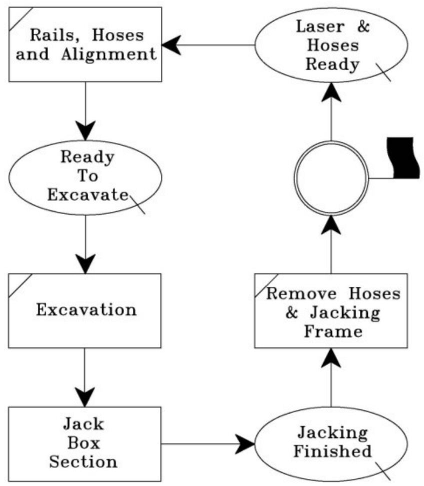


Figure 4.8 Counter (Flag) after Removing Hoses and Jacking Frame

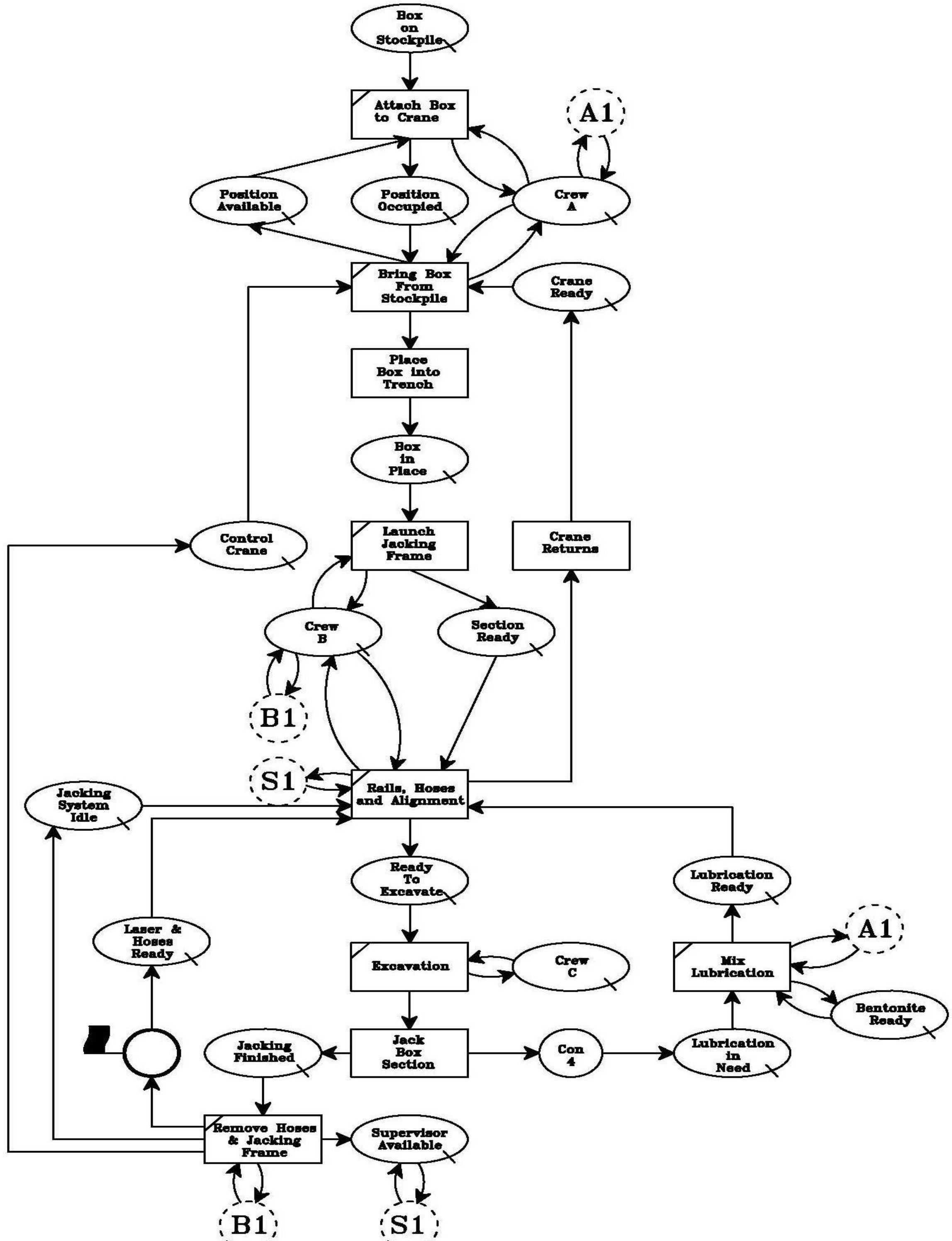


Figure 4.9 Complete Cycles for Box Jacking Operation

4.2.4 MicroCYCLONE Model

Based on the cycles described previously, the input code for MicroCYCLONE simulation was developed as below:

Input Code

```
Line 1: NAME BOX JACKING PROCESS LENGTH 10000 CYCLES 34
Line 2: NETWORK INPUT
Line 3: 1 COM 'ATTACH BOX TO CRANE' SET 1 PRE 8 9 11 FOL 10 11
Line 4: 2 COM 'BRING BOX FROM STOCKPILE' SET 2 PRE 10 11 20 25 FOL 9 11 27
Line 5: 3 COM 'PLACE JACKING FRAME INTO TRENCH' SET 3 PRE 13 21 FOL 13 19
Line 6: 4 COM 'RAILS AND ALIGNMENT' SET 4 PRE 12 13 14 17 19 22 FOL 12 13 24 28
Line 7: 5 COM 'EXCAVATION' SET 5 PRE 23 24 FOL 23 26
Line 8: 6 COM 'REMOVE JACKING FRAME & HOSES' SET 6 PRE 12 13 15 FOL 12 13 14 25 31
Line 9: 7 COM 'MIX LUBRICATION' SET 7 PRE 11 16 18 FOL 11 17 18
Line 10: 8 QUE 'BOX ON STOCKPILE'
Line 11: 9 QUE 'POSITION AVAILABLE'
Line 12: 10 QUE 'POSITION OCCUPIED'
Line 13: 11 QUE 'CREW A'
Line 14: 12 QUE 'SUPERVISOR AVAILABLE'
Line 15: 13 QUE 'CREW B'
Line 16: 14 QUE 'JACKING SYSTEM IDLE'
Line 17: 15 QUE 'JACKING FINISHED'
Line 18: 16 QUE 'LUBRICATION IN NEED'
Line 19: 17 QUE 'LUBRICATION READY' GEN 4
Line 20: 18 QUE 'BENTONITE READY'
Line 21: 19 QUE 'SECTION READY'
Line 22: 20 QUE 'CRANE READY'
Line 23: 21 QUE 'BOX IN PLACE'
Line 24: 22 QUE 'LASER AND HOSES READY'
Line 25: 23 QUE 'CREW C'
Line 26: 24 QUE 'READY TO EXCAVATE'
Line 27: 25 QUE 'CONTROL CRANE'
Line 28: 26 NOR 'JACK BOX SECTION' SET 26 FOL 15 30
Line 29: 27 NOR 'PLACE BOX INTO TRENCH' SET 27 FOL 21
```

```
Line 30: 28 NOR 'CRANE RETURNS' SET 28 FOL 20
Line 31: 30 FUN CON 4 FOL 16
Line 32: 31 FUN COU FOL 22 QUA 1
Line 33: DURATION INPUT
Line 34: SET 1 UNI 2.4 3.4
Line 35: SET 2 UNI 2.3 3.3
Line 36: SET 3 UNI 24.5 42.8
Line 37: SET 4 UNI 15.5 33.8
Line 38: SET 5 UNI 97.6 169.2
Line 39: SET 6 UNI 24.9 37
Line 40: SET 7 UNI 2.3 3.5
Line 41: SET 26 UNI 24.2 33.3
Line 42: SET 27 UNI 3.7 5.1
Line 43: SET 28 UNI 2.3 3.3
Line 44: RESOURCE INPUT
Line 45: 34 'BOX SECTION' AT 8
Line 46: 1 'POSITION' AT 9
Line 47: 1 'LABOR' AT 11
Line 48: 1 'SUPERVISOR' AT 12
Line 49: 1 'CRANE' AT 20
Line 50: 1 'CRANE CONTROL SIGNAL' AT 25
Line 51: 2 'LABOR' AT 13
Line 52: 1 'LUBRICATION READY SIGNAL' AT 17
Line 53: 1 'BENTONITE READY SIGNAL' AT 18
Line 54: 1 'JACKING SYSTEM' AT 14
Line 55: 3 'LABOR' AT 23
Line 56: 1 'CABLE HOSE LASER READY SIGNAL' AT 22
Line 57: ENDDATA
```

Table 4.3 shows the simulation time and productivity per time unit for each cycle. Based on this table, the highest productivity is 0.004462 boxes per minutes and the lowest productivity rate is 0.003551 boxes per minutes. Table 4.4 shows CYCLONE passive elements statistics.

Table 4.3 Simulation Time and Productivity for Each Cycle

BOX JACKING PROCESS		
PRODUCTIVITY INFORMATION		
Simulation Time (Minute)	Cycle No.	Productivity (Box Per Minute)
224.1	1	0.004462
542.8	2	0.003684
844.9	3	0.003551
1111.6	4	0.003598
1359	5	0.003679
1560.5	6	0.003845
1787.1	7	0.003917
1994.3	8	0.004011
2192.8	9	0.004104
2469	10	0.00405
2669.9	11	0.00412
2921.8	12	0.004107
3167.4	13	0.004104
3459.6	14	0.004047
3757.4	15	0.003992
3950.3	16	0.00405
4261.3	17	0.003989
4500.2	18	0.004
4705.4	19	0.004038
4899.9	20	0.004082
5205.8	21	0.004034
5509.3	22	0.003993
5718.3	23	0.004022
5911.9	24	0.00406
6139	25	0.004072
6451.9	26	0.00403
6659.6	27	0.004054
6898.6	28	0.004059
7199.8	29	0.004028
7427.7	30	0.004039
7711.6	31	0.00402
7978.4	32	0.004011
8284.6	33	0.003983
8537.1	34	0.003983

Table 4.4 CYCLONE Passive Elements Statistics

BOX JACKING PROCESS									
CYCLONE PASSIVE ELEMENTS STATISTICS INFORMATION									
Type	No.	Name	Average Units Idle	Max. Idle Units	Times not empty (Minute)	% Idle	Total Simulation Time (Minute)	Average Wt Time (Minute)	Units Remaining
QUEUE	8	BOX ON STOCKPILE	16.4	34	7981.5	93.49	8537.1	1930.7	0
QUEUE	9	POSITION AVAILABLE	0	1	0	0	8537.1	0	1
QUEUE	10	POSITION OCCUPIED	1	1	8097.4	94.85	8537.1	238.2	0
QUEUE	11	CREW A	1	1	8074.9	94.59	8537.1	104.9	1
QUEUE	12	SUPERVISOR AVAILABLE	0.8	1	6706.2	78.55	8537.1	97.2	1
QUEUE	13	CREW B	1.7	2	8537.1	100	8537.1	134.1	2
QUEUE	14	JACKING SYSTEM IDLE	0.2	1	1351	15.83	8537.1	38.6	1
QUEUE	15	JACKING FINISHED	0	1	0	0	8537.1	0	0
QUEUE	16	LUBRICATION IN NEED	0	1	0	0	8537.1	0	0
GEN	17	LUBRICATION READY	1.9	4	6999.9	81.99	8537.1	424.7	2
QUEUE	18	BENTONITE READY	1	1	7926.6	92.85	8537.1	880.7	1
QUEUE	19	SECTION READY	0	1	0	0	8537.1	0	0
QUEUE	20	CRANE READY	0.7	1	6107.1	71.54	8537.1	174.5	1
QUEUE	21	BOX IN PLACE	0	1	0	0	8537.1	0	0
QUEUE	22	LASER AND HOSES READY	0.2	1	1351	15.83	8537.1	38.6	1
QUEUE	23	CREW C	2.5	3	8478.3	99.31	8537.1	546.4	3
QUEUE	24	READY TO EXCAVATE	0	1	0	0	8537.1	0	0
QUEUE	25	CONTROL CRANE	0	1	2.6	0.03	8537.1	0.1	1

4.3. Method Production Delay Model

The Method Productivity Delay Model (MPDM) is developed by Dr. James Adrian (Adrian, 2004). This model is a tool for planners and contractors to measure, predict, and improve the productivity of construction projects. As Adrian explained, the model consists of three major parts as shown below:

Collection of data: in this step all delays related to project should be measured on site. Delays are categorized into five groups: 1) Environmental Delay, 2) Equipment Delay, 3) Labor Delay, 4) Material Delay, and 5) Management Delay.

Model Processing and structuring: In this step, occurrences of each delay and probability of occurrences were identified and Relative Severity was calculated. Finally, according to collected data from previous step, Expected percentage delay time per production cycle for each delay was calculated.

Data Implementation: The MPDM non delay productivity rate and the overall productivity rate represent measurements which are used to identify ideal productivity rate and can be used by planners and contractors to compare the results with actual productivity. Implementation of data can help contractors focus on critical delays that cause the most overall delay on a project, and decrease duration of projects by improving or eliminating that specific delay.

Halpin & Riggs (1992) explained MPDM as an accessible method to relatively low-level field personnel because of its simplified measures. Although this method is very simple to calculate and there are a few chances of error, it can raise doubts in the very long cycle or very short cycle processes because the judgment of the data collector is also involved (Halpin & Riggs, 1992).

Table 4.5 shows the data collected at the jobsite by observation and measuring the actual duration for each and every activity, and Table 4.6 illustrates the calculations to refine the delays related to each category. During observation at the jobsite, first the duration for each activity in all cycles was measured and compared to the non-delay cycles which shows the delay occurred in each category. By knowing the reasons of delay and the duration of activities from Table 4.5, the amount of delay can be found. The main factor to allocate reasonable percentage to each delay is understanding the reasons for delay. For example, in cycle #7, the project faced 40.4 minutes delay because during the jacking, bentonite hoses broke. First, it was labors mistake to not secure the hose joint completely. The contractor had to change the hose and clean the site. During the bentonite hose repair, other crews and equipment were idle and caused the 40.4 minutes delay. In this case, the delay caused because of labor fault and old equipment, but management could prevent this delay by checking the joint before using the bentonite hose, and by assigning an experienced labor to this task. Hence, for this specific activity, a total of 25% delay was recognized as labor delay, 25% equipment delay and the rest (50%) was identified as a delay caused by management. This issue was discussed with the site superintendent, and he agreed with these delay responsibilities.

Table 4.5 Data Collected at the Jobsite (Refer to Table 4.2 for Activity Descriptions)

Activity #	Activity	Cycle 1 (Min)	Cycle 2 (Min)	Cycle 3 (Min)	Cycle 4 (Min)	Cycle 5 (Min)	Cycle 6 (Min)	Cycle 7 (Min)	Cycle 8 (Min)	Cycle 9 (Min)
1	BRING BOX FROM STOCKPILE	2.6	3.3	2.6	2.7	3.4	2.4	2.9	3.3	3.2
2	RIG BOX TO CRANE	2.5	3.3	3.3	2.8	2.6	2.7	2.5	3	3
3	PLACE JACKING FRAME INTO TRENCH	41.3	32.6	38.2	31.5	29.7	42.8	34.5	39.8	33.7
4	PLACE RAILS AND ALIGNMENT	19.7	17.3	18.7	33.8	22.1	16.5	17.3	25.8	16.2
5	EXCAVATE	141.6	154	138	149.3	155.2	99.9	139.4	148.9	152.6
6	REMOVE JACKING FRAME & HOSES	29.3	27.5	37	29.1	32.6	34.1	36.2	34	33
7	MIX LUBRICATION	2.8	3.2	2.6	2.6	3.1	2.3	3	3.2	3.1
26	JACK BOX SECTION	26.2	32.5	27.5	28.5	29.9	24.3	30.2	31.2	33.3
27	PLACE BOX INTO TRENCH	4.6	4.5	4.2	5.1	5.1	4.5	4.1	4.7	4.7
28	SWING CRANE	3.1	2.9	2.3	3.1	2.8	2.5	3.1	3.2	3.3
	Total	273.7	281.1	274.4	288.5	286.5	232	273.2	297.1	286.1
Activity #	Activity	Cycle 10 (Min)	Cycle 11 (Min)	Cycle 12 (Min)	Cycle 13 (Min)	Cycle 14 (Min)	Cycle 15 (Min)	Cycle 16 (Min)	Cycle 17 (Min)	Cycle 18 (Min)
1	BRING BOX FROM STOCKPILE	3.1	3	2.9	2.5	2.4	2.4	2.9	2.4	2.9
2	RIG BOX TO CRANE	2.3	3.2	2.8	2.9	2.3	2.6	2.5	2.3	2.3
3	PLACE JACKING FRAME INTO TRENCH	40.3	37.9	42.6	33.6	27.9	35.4	34.3	38.2	38.6
4	PLACE RAILS AND ALIGNMENT	25.9	16.4	27.4	21	20.7	24.8	15.5	19	26.8
5	EXCAVAE	116.1	142.5	161.2	98.3	152.9	143	97.6	159.3	169.2
6	REMOVE JACKING FRAME & HOSES	28.4	28.7	24.9	32	34	31.9	25.9	28.2	34.6
7	MIX LUBRICATION	2.7	2.9	2.6	2.7	3.2	3	2.8	3.2	3.5
26	JACK BOX SECTION	24.2	31.2	32.8	32.1	27.9	30.4	28.5	30.6	31.6
27	PLACE BOX INTO TRENCH	4.3	4.2	3.7	4.9	4.9	3.9	3.8	4.5	4.7
28	SWING CRANE	2.5	3.2	3.1	3.1	2.9	3.2	2.5	2.8	2.9
Total		249.8	273.2	304	233.1	279.1	280.6	216.3	290.5	317.1

Table 4.6 Total Delays per Delay Category (Minutes)[2]

Cycle #	Duration	Environ-mental Delay	Equipment Delay	Labor Delay	Material Delay	Management Delay	Notes	Minus Mean Non-Delay Time
Cycle 1	273.7	--------	30%	70%	--------	--------	--	40.9
		--------	12.27	28.63	--------	--------		
Cycle 2	281.1	100%	--------	--------	--------	--------	--	48.3
		48.3	--------	--------	--------	--------		
Cycle 3	274.4	--------	50%	--------	--------	50%	--	41.6
		--------	20.8	--------	--------	20.8		
Cycle 4	288.5	50%	--------	50%	--------	--------	--	55.7
		27.85	--------	27.85	--------	--------		
Cycle 5	286.5	40%	--------	30%	--------	30%	--	53.7
		21.48	--------	16.11	--------	16.11		
Cycle 6	232	--------	--------	--------	--------	--------	Non-Delay Cycle	0.8
		--------	--------	--------	--------	--------		
Cycle 7	273.2	--------	25%	25%	--------	50%	--	40.4
		--------	10.1	10.1	--------	20.2		
Cycle 8	297.1	--------	50%	50%	--------	--------	--	64.3
		--------	32.15	32.15	--------	--------		
Cycle 9	286.1	50%			--------	50%	--	53.3
		26.65			--------	26.65		
Cycle 10	249.8	--------	--------	--------	--------	--------	Non-Delay Cycle	17
		--------	--------	--------	--------	--------		
Cycle 11	273.2	--------	50%	50%	--------	--------	--	40.4
		--------	20.2	20.2	--------	--------		
Cycle 12	304	50%	--------	--------	--------	50%	--	71.2
		35.6	--------	--------	--------	35.6		
Cycle 13	233.1	--------	--------	--------	--------	--------	Non-Delay Cycle	0.3
		--------	--------	--------	--------	--------		
Cycle 14	279.1	100%	--------	--------	--------	--------	--	46.3
		46.3	--------	--------	--------	--------		
Cycle 15	280.6	--------	50%	50%	--------	--------	--	47.8
		--------	23.9	23.9	--------	--------		
Cycle 16	216.3	--------	--------	--------	--------	--------	Non-Delay Cycle	16.5
		--------	--------	--------	--------	--------		
Cycle 17	290.5	70%	--------	--------	--------	30%	--	57.7
		40.39	--------	--------	--------	17.31		
Cycle 18	317.1	70%	--------	--------	--------	30%	--	84.3
		59.01	--------	--------	--------	25.29		
Total	4936.3	305.58	119.42	158.94	0	161.96		

[2] A total of 18 boxes was analyzed as a representation of the 34 boxes installed

Table 4.7 presents MPDM processing form. In this table, production total time (row A) is calculated by adding all non-delayed cycles. The mean cycle time was obtained by equation (4.1) (Adrian, 2004)

Mean Cycle Time = $\frac{\textbf{Production Total Time}}{\textbf{Number of Cycle}}$ Equation (4.1)

Row C is a number of delays which occurred in all cycles.

Row D is a total delays time which can be obtained from Table 4.5. To calculate specific delay for each category, a percentage of the delay is multiplied by the amount of total delay time in that cycle. By adding all delay times related to that category, a total added time in Table 4.7 row C was obtained.

Row E, probability of occurrence, can be calculated by dividing occurrences by overall number of cycles in Row B. Equation (4.2) shows the formula to calculate the probability (Adrian, 2004).

Probability of occurrences = $\frac{\textbf{occurrences}}{\textbf{Overall number of cycles}}$ ……………..…………Equation (4.2)

Relative severity, Row F, is calculated based on the total added time, occurrences and overall productions mean cycle time. Equation (4.3) shows how to calculate the relative severity (Adrian, 2004).

Relative Severity =

$\frac{\textbf{Total Added Time (ROW D)}}{\textbf{Overall productions mean cycle time (ROW B)} * \textbf{Number of occurrences (ROW C)}}$…………………Equation (4.3)

Expected delay time per production cycle in Row (G) is calculated by relative severity times the probability of occurrences. Equation (4.4) shows the calculation (Adrian, 2004).

Expected delay time per production cycle =

Relative severity (Row F) * Probability of occurrences (Row E)……………..……Equation (4.4)

Ideal productivity happens when the amount of delay in all cycles is zero. Therefore, the ideal productivity is calculated by Equation (4.5) (Adrian, 2004).

$$\text{Ideal Productivity} = \frac{\mathbf{60\ \mathit{Minutes\ per\ Hour}}}{\mathbf{\mathit{Mean\ cycle\ time\ in\ non\ delayed\ production\ cycle}\ (\mathit{Row\ A})}} \text{.......Equation (4.5)}$$

So, ideal productivity for this project is:

Ideal Productivity= 60 / 232.8 = 0.258 unit (box) per hour

and 0.258 * (22 hours per working day) = 5.676 box per working day (24 hours or two shifts of 12 hours each)

Probability of productive work =

$$\mathbf{1-(E_{Environment}+E_{Equipment}+E_{Labor}+E_{Material}+E_{Management})} \text{..................Equation (4.6)}$$

Where (Adrian, 2004):

$E_{Environment}$ = Expected environmental delay time

$E_{Equipment}$ = Expected equipment delay time

E_{Labor} = Expected labor delay time

$E_{Material}$ = Expected material delay time

$E_{Management}$ = Expected management delay time

Table 4.7 MPDM Processing Form

MPDM Processing					
	Production Total Time	Number of cycles	Mean Cycle time	$\sum[\|(\boldsymbol{Cycle\ Time}) - (\boldsymbol{Nondelay\ Cycle\ Time})\|] / \boldsymbol{n}$	
(A) Non Delay Production Cycles	931.2	4	232.8	8.65	
(B) Overall Production Cycles	4936.3	18	274.2	43.36	
Delay Information					
	Environment	Equipment	Labor	Material	Management
(C) Occurrences	8	6	7	0	7
(D) Total Added Time	305.58	119.42	158.94	0	161.96
(E) Probability of Occurrence	0.444	0.333	0.389	0	0.389
(F) Relative Severity	0.139	0.073	0.083	0	0.084
(G) Expected % Delay Time Per Production Cycle	6.17	2.43	3.22	0	3.27

The variability of method productivity is calculated from the unpredictability of both non-delay productivity cycle and the total overall productivity cycles. The variability of method productivity can be measured by equation (4.7) and (4.8) (Adrian, 2004).

Ideal Cycle Variability =

$$\frac{(Nondelay\ cycle\ time - Mean\ nondelay\ cycle\ time) \div Number\ of\ nondelay\ cycle\ time}{Mean\ nondelay\ cycle\ time}$$ ...Equation (4.7)

Overall Cycle Variability =

$$\frac{(Overall\ cycle\ time - Mean\ nondelay\ cycle\ time) \div Number\ of\ total\ cycles}{Mean\ overall\ cycle\ time}$$ ……………………………Equation (4.8)

Overall method productivity = (Ideal productivity)*(probability of productive work) Equation (4.9)

According to equation (4.6), (4.7), (4.8) and (4.9):

Probability of Productive work = 1- (0.0617+0.0243+0.0322+0.0327) = 0.85

Overall Method Productivity = 0.258 * 0.85 =0.219

So 0.219 * (22 hours per working day) = 4.81 box per working day

According to these equations and results, the *ideal productivity* will occur when there is no delay and productivity is 0.258 box per hour which means one culvert can be jacked in 3.87 hours or 5.68 culverts per working day (24 hours or two 12-hour shifts), while the *overall productivity* is 0.219 which means 4.56 hours is needed for one culvert to be jacked, or 4.81 culverts per working day. The average delay per each box calculated to be 0.67 hour or 40 minutes.

4.4 Work Sampling

4.4.1 Field rating

Work sampling is a method to measure the efficiency of a crew by observation at the jobsite. To determine the effectiveness of a crew, random observations should be made and Table 4.8 shows the data observed. Additional observations are provided in Appendix B presenting more data collected. The average efficiency is shown in Table 4.9. The Efficiency in this method is measured by dividing the number of labors working by the number of labors observed (Equation 4.10) (Adrian, 2004).

Field Rating Productivity = (Labors Working / Labors Observed) * 100…………………..Equation (4.10)

Table 4.8 Work Sampling, Field Rating

Work Sampling- Field Rating 1			
Project: Jack & Bore Project		Location: Vernon, TX - US 287	
Contractor: AR Daniel Construction			
Date: 9/18/2012		Prepared by: Hossein Tavakoli	
Observation	Labors Observed	Labors Working	Labors Not Working
1	4	3	1
2	4	4	0
3	4	4	0
4	4	3	1
5	4	3	1
6	4	4	0
7	5	4	1
8	5	5	0
9	5	5	0
10	5	5	0
11	5	3	2
12	5	4	1
13	4	3	1
14	4	4	0
15	4	3	1
16	4	3	1
17	5	4	1
18	5	4	1
19	5	3	2
20	4	3	1
Total	89	74	15
%Working		83.15	

Table 4.9 Average Efficiency for Field Rating Method

Work Sampling -Field Rating 1	83.15
Work Sampling -Field Rating 2	88.42
Work Sampling -Field Rating 3	84.34
Work Sampling -Field Rating 4	75.64
Work Sampling -Field Rating 5	92.41
Average	84.79

4.4.2 Productivity Rating

The data collected at the jobsite include effective labors, contributory labors, and nonproductive or non-effective labors and this data are shown in Table 4.10. Additional tables in Appendix B present more data. The average efficiency is shown in Table 4.11. Equations 4.11, 4.12, and 4.13 show the formulas to measure productivity in this method (Adrian, 2004).

Labor Rating Factor = $\frac{EM}{TMO}$ ………………………………………………..…Equation 4.12

Productivity Rating = $[(\frac{EM}{TMO}) + (\frac{EM*CM}{(TMO)^2})]*100$ ……………………….…….Equation 4.13

Or,

Productivity Rating = $\frac{(LRF \times CM)+EM}{TMO}$……….…………………………………Equation 4.14

Where,

TMO= Total Labors Observed,

EM = Effective Labors,

And CM = Contributory Labors

Table 4.10 Work Sampling, Productivity Rating

Work Sampling- Productivity Rating 1				
Project: Jack & Bore Project		Location: Vernon, TX - US 287		
Contractor: AR Daniel Construction				
Date: 9/19/2012		Prepared by: Hossein Tavakoli		
Observation	Observed Labors	Effective Labors	Contributory Labors	Non Effective Labors
1	5	4	1	0
2	5	3	2	0
3	5	2	2	1
4	4	3	1	0
5	4	3	1	0
6	4	3	1	0
7	5	4	1	0
8	4	3	1	0
9	5	2	2	1
10	5	3	2	0
11	5	3	2	0
12	4	2	2	0
13	5	3	2	0
14	5	2	2	1
15	5	4	1	0
16	5	4	1	0
17	5	4	0	1
18	5	3	2	0
19	4	4	0	0
20	4	2	1	1
Total	93	61	27	5
% Efficiency			84.6341	

Table 4.11 Average Efficiency for Productivity Rating Method

Work Sampling -Productivity Rating 1	84.63
Work Sampling -Productivity Rating 2	82.81
Work Sampling -Productivity Rating 3	84.28
Work Sampling -Productivity Rating 4	81.11
Work Sampling -Productivity Rating 5	81.59
% Average Efficiency	82.88

4.5 Discussion of Results

A total of 34 boxes were jacked in the case study project. The final results are shown in Table 4.12. Based on the actual activities and durations observed from the jobsite with considering different resources available, the cycles were identified and the coding for prototype model was developed. Table 4.3 illustrates the productivity for each box culvert and Table 4.4 shows the results from the MicroCYCLONE simulation model. Figure 4.10 presents productivity of box installation over time, simulated by MicroCYCLONE, based on actual project conditions.

Table 4.12 Productivity Information

BOX JACKING PROCESS			
PRODUCTIVITY INFORMATION			
Total Simulation Time Unit (Minute)	Cycle No.	Productivity (Box per Hour)	Productivity (Box per Day)
8537.1	34	0.239	5.26

According to Figure 4.10 and Table 4.3, the highest productivity was in the first box with the amount of 0.268 boxes per hour which means the first culvert was jacked in 3 hours and 44 minutes. The lowest productivity shown in Figure 4.10 is for box #3 with 0.213 boxes per hour which means the third box was jacked in 4 hours and 41 minutes. The main reason for decreasing in productivity is in the first three culverts, lubrication was not used. In the box jacking normally the first three boxes are covered with steel plate on top to prevent from soil collapsing at the tunnel face and at the box joint locations. In addition, steel plate makes soil around the box more smooth thereby reducing friction. Accordingly, in the simulation, the bentonite starts to pump after the third culvert. After the bentonite is used, the productivity increases and box jacking duration for each culvert box decreases.

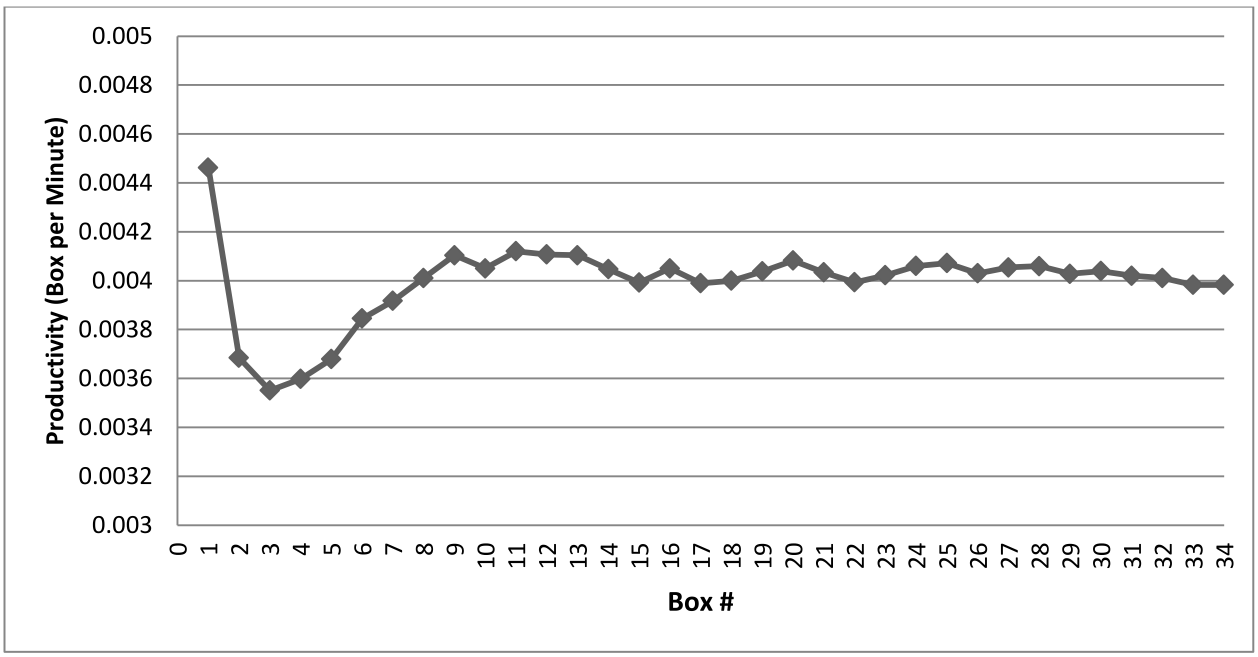


Figure 4.10 Simulated *Productivity* (Box per Minute) of Actual Project

Based on MicroCYCLONE

Figure 4.11 shows the duration of operation per each box. As shown in this figure, the productivity stayed in the range of 0.235 - 0.250 box per hour.

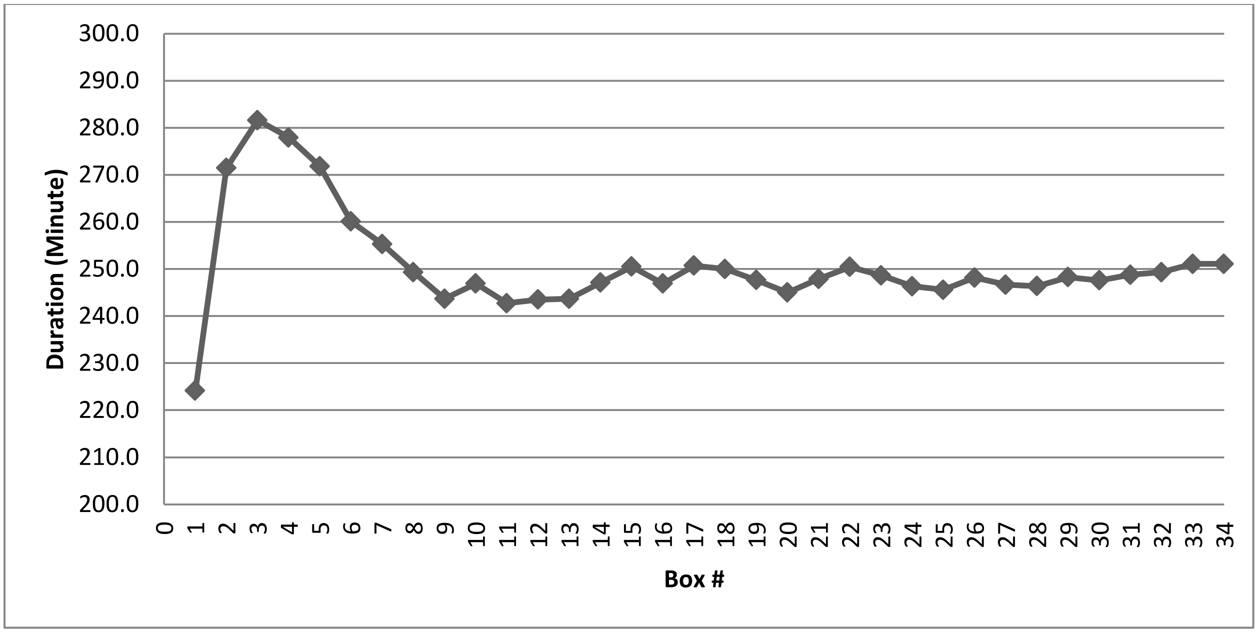


Figure 4.11 Simulated *Duration* of Operation per each Box of Actual Project Based on MicroCYCLONE

The average duration observed at the jobsite was 271.76 minutes for each box with the productivity of 0.221. Comparing average productivity of 0.221 box/hour with the productivity of 0.239 box/hour obtained from MicroCYCLONE, a difference of 0.018 box/hour or 8.14% is obtained, which means the duration calculated by MicroCYCLONE for each cycle is 19 minutes less than the actual duration. This difference is because in the actual situation, many delays occurred which MicroCYCLONE did not consider. Because of the complex nature of box jacking, some delays are unavoidable, and a simulation may consider all the jobsite and project specific condition factors. For example, an accurate geotechnical study assists the contractor to select appropriate equipment and method to maximize productivity.

Luo (2005) studied Microtunneling operation with MicroCYCLONE simulation. He found productivity in the first 4 pipe sections to have an increasing trend, because of necessity of preparation and learning curve at the beginning of the project. According to Abdelhamid (2004), productivity will increase; however, the rate of increase will go down to approximately zero, after the learning curve is completed and not considering other factors impacting productivity. In this thesis, the first three box sections have a decreasing productivity trend, because bentonite lubrication was not used for these first three boxes. After the third box was installed, the productivity started to improve (a total of 0.000653 box per minute) until the 9^{th} box. After the 9^{th} box, the change in productivity is a total of 0.000111 box/minute, or 0.03%, which is near zero. This trend may confirm Abdelhamid's findings that there is a limit for productivity improvement.

A sensitivity analysis was conducted by applying different combinations of labor crews, number of supervisor, and number of crane to determine optimum productivity. Appendix E presents all combinations of one to three labors in crew A, one to three labors in crew B, two to five labors in crew C, one to two supervisors, and one to two cranes. However based on space limitations at jobsite, two cranes are not recommended. According to sensitivity analysis, there are four different options for productivity improvement. All options have the total crew size of seven to nine labors, while in actual project there were a total of six labors. Table 4.13 shows all possible options to evaluate productivity. The highest productivity (0.0041 box / hour) will be achieved by having two labors in crew A, three labors in crew B, two labors in crew C, one supervisor and one crane. The difference between this option and the actual crew size at jobsite is one extra labor in crew A, one extra labor in crew B, and one less labor in crew C. Speaking with the contractor, he mentioned that crew size is optimized based on his experience, considering project location, availability of crews, site logistics, and project and ground specific conditions. For example, increasing the number of labors for crew C (hand mining and filling spoil cart) which is 3 for this project, will have space and congestion issues at the face of tunnel.

By using MPDM, it was found that the average duration for box jacking was 274.2 minutes and the highest duration was 317.1 minutes and lowest duration was 216.3 minutes. The expected percent delay time per production cycle shows that 6.19% of time was due to environmental delay, 3.28% due to management delay, 3.22% due to labor delay and 2.41% due to equipment delay. The projects never faced a delay because of material (box culvert). The probabilities of occurrence of each type of delay are shown in Figure 4.12. According to this figure, the probability of occurrence of environmental delay is the highest and shows with reducing this delay, productivity can be increased. Space permitting, the contractor could use an excavator to and reduce the duration by increasing the productivity in excavation producvity. Also there was a change in the soil type, which was not mentioned in the soil test result and caused delay in the excavation and jacking operations.

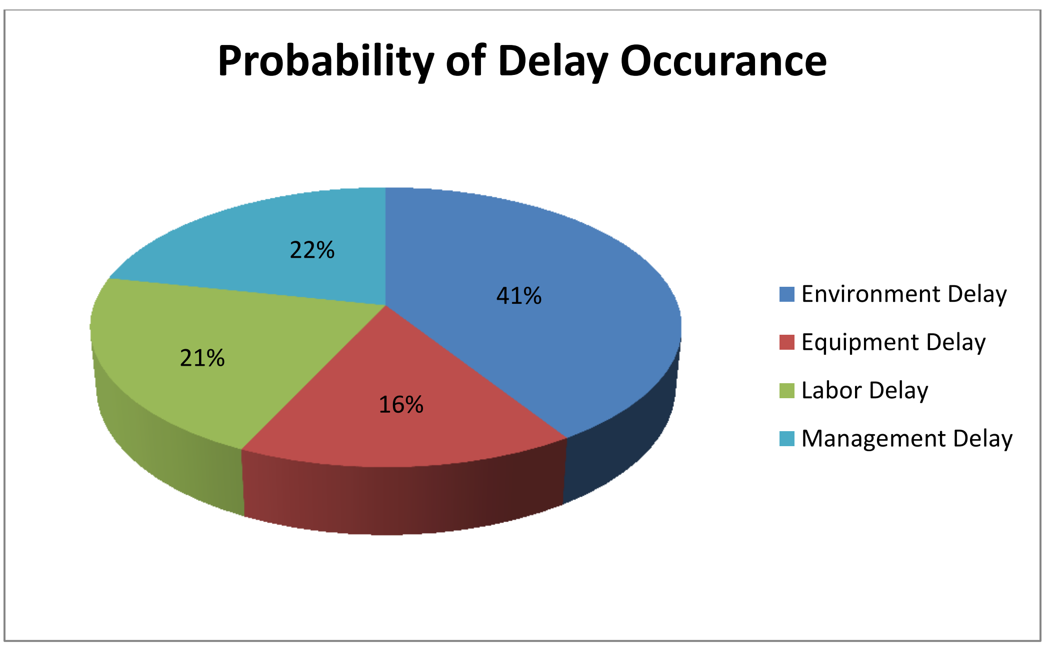


Figure 4.12 Probability of Delay Occurrence

While one of the main resources in box jacking is labor, a work sampling method was applied to identify the efficiency of crews. The results from more than 800 observations at the jobsite are presented in Tables 4.9 and 4.11. Based on these observations, it was found that the average crew efficiency was 83.83%, which is excellent.

To evaluate productivity in this project, two different methods were applied. A model for MicroCYCLONE was built with actual resources and durations for each activity based on observations at the jobsite. By using MicroCYCLONE simulations, the productivity of box jacking in future project was analyzed. Based on MicroCYCLONE, the maximum productivity was identified as 0.249 boxes per hour, minimum was 0.215 boxes per hour, and the average productivity was 0.236 boxes per hour.

The next method studied was the Method Productivity Delay Model (MPDM). Through MPDM, five different delay categories, i.e., Environment Delay, Equipment Delay, Labor Delay, Material Delay and Management Delay, were introduced. Based on the jobsite data, Tables 4.5 and 4.6 were developed. These tables show the amount of delays in percentage and in minutes for each category. Finally, in Table 4.7, MPDM Processing Form, the expected delay per production cycle was calculated. The productivity rate is in a reasonable range from simulation model in MicroCYCLONE and compared to what was observed at the jobsite.

A work sampling method also was developed to recognize productivity of crews. Two different models, field rating and productivity rating, were used to identify productive and nonproductive laborers. Using this model, more than 200 observations were calculated based on the productivity of the crews. These crew productivities are shown in Tables 4.9 and 4.11.

Tables 4.14 and Figure 4.13 compares productivity in each group.

Table 4.13 Productivity Comparison

Productivity (Box per Hour)	
Actual Productivity Observed in Job Site	0.221
MicroCYCLONE	0.239
MPDM	0.220

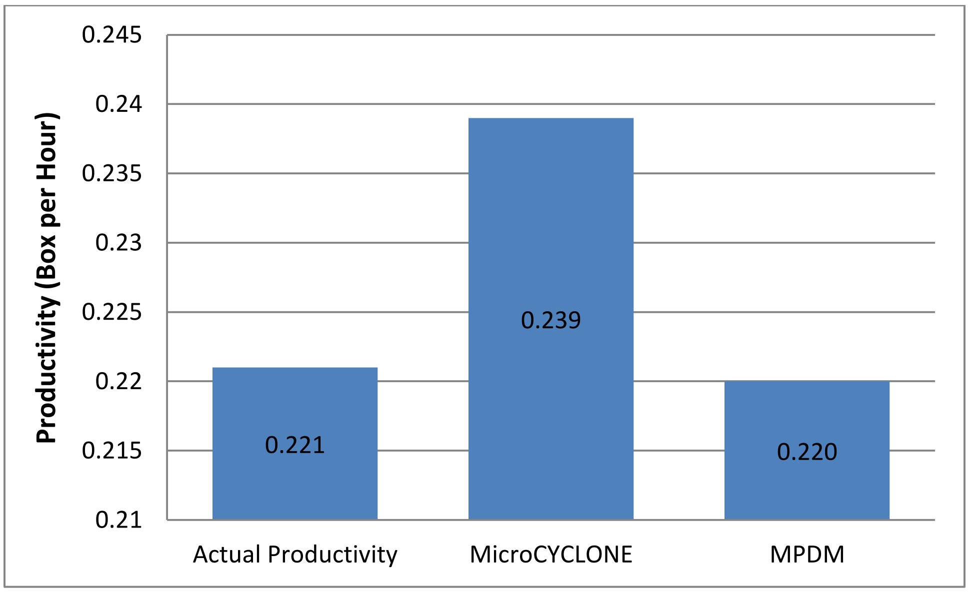


Figure 4.13 Productivity Comparisons

4.6 Chapter Summary

In this chapter the productivity was measured by using two different methods. The productivity of box jacking using MicroCYCLONE simulation was found to be 0.239 boxes per hour which means 5.19 boxes per working day (in two shifts of 12 hours for each shift). The productivity in MPDM measured to be 0.220 boxes per hour which indicates 4.54 culverts can be jacked in a working day. The labor efficiency in work sampling was measured to be 85% to 91% by using work sampling.

CHAPTER 5

CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Overall Summary

In previous chapters, the process of box jacking was described based on an actual project performed in the City of Vernon, near Wichita Falls, Texas. The total length of the project was 240 feet, and the contractor successfully completed the in 25 days, however, the jacking portion of the project took only 7 days (in two 12-hour shifts). The worked was delayed due to addition of pilot tubes, which were not in the original plan, and some equipment and weather issues, as described in this thesis. To achieve objectives if this thesis, MicroCYCLONE simulation and the Method Productivity Delay Model (MPDM) were used.

The productivity of box jacking using MicroCYCLONE Simulation was 0.239 boxes per hour which means 5.25 boxes per working day. The productivity of MPDM measured to be 0.220 boxes per hour which indicates 4.54 culverts can be jacked in a working day. The labors efficiency in work sampling was 84.1% to 90.9%.

According to MPDM Model, the most delays occur because of the environment. The difference in soil type forced the contractor to stop the project and build the pilot tubes, and the second reason for delay in this project was weather conditions. Tunnel excavation and spoil removal is the most time consuming activities for box jacking. This time could be reduced by replacing hand mining with a special excavator. However, due to small size of the culvert box, this may not have been possible. Again, space permitting, a conveyor system could be used to transport spoil.

5.2 Research Limitations

The main limitation in this research is data collection. Although there are many projects using the pipe jacking method, box jacking is used in certain conditions. The other limitation for this project is the difficulty of collecting data during the night, since the contractor was working in two 12-hour shifts. Finally, due to complex nature of trenchless methods, cost plays an important role in resource allocation. In this research, cost was not considered due to the time and resource limitations, but should be considered for future research.

5.3 Recommendations for Future Research

Recommendations for future research can be summarized as below:

- Conduct productivity research on additional box jacking projects possibly with use of excavators for tunnel excavation.
- Compare productivity of box jacking with pipe jacking.
- Include costs in the productivity study.
- Investigate impact of soils on productivity

APPENDIX A
CASE STUDY PROJECT FROM BEGINNING TO END

Excavation of Jacking Pit

Truck Hauling Dirt from job Site

Placing Jacking Frame

Leveling and Preparing Jacking Pit

Pouring Concrete on Bottom of Jacking Pit

Pouring Concrete on Bottom of Jacking Pit

Bringing Culvert Box from Stockpile

Preparing First Box and Shield

Preparing First Box and Shield

Setting up Jacking Frame

Setting up Jacking Frame

Jacks in Place

Start Jacking Boxes

Installing Next Segment

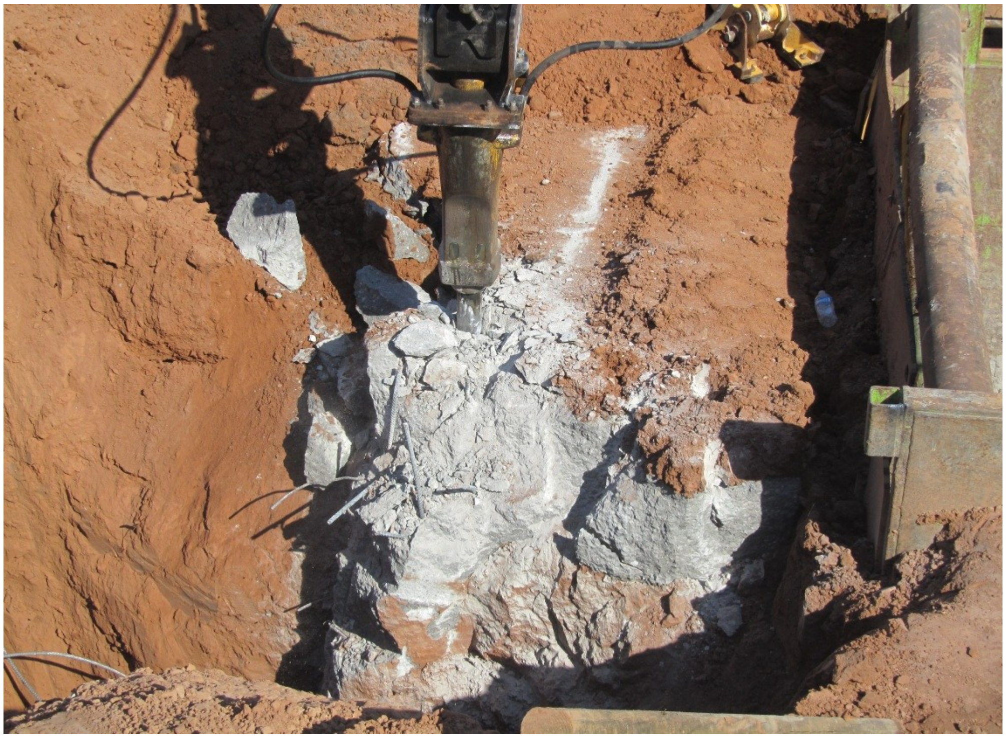
Mixing Lubricant in Mud-Mixer

Installed Rails for Bringing out the Dirt and Pipeline for Lubrication as Going Forward

Rails and Dirt Removing Bucket

Removing Excavated Dirt

First Culvert Reaches the Other Side, End f Jacking Process



Demobilization, Removing Trust Wall

Removing Trust Wall

Demobilization, Removing Jacking Frame and Backfill

Loading Jacks in Truck

APPENDIX B

DATA COLLECTED FOR WORK SAMPLING METHOD

Work Sampling- Field Rating 1			
Project: Jack & Bore Project		Location: Vernon, TX - US 287	
Contractor: AR Daniel Construction			
Date: 9/18/2012		Prepared by: Hossein Tavakoli	
Observation	Labors Observed	Labors Working	Labors Not Working
1	4	3	1
2	4	4	0
3	4	4	0
4	4	3	1
5	4	3	1
6	4	4	0
7	5	4	1
8	5	5	0
9	5	5	0
10	5	5	0
11	5	3	2
12	5	4	1
13	4	3	1
14	4	4	0
15	4	3	1
16	4	3	1
17	5	4	1
18	5	4	1
19	5	3	2
20	4	3	1
Total	89	74	15
%Working		83.15	

Work Sampling- Field Rating 2			
Project: Jack & Bore Project		Location: Vernon, TX - US 287	
Contractor: AR Daniel Construction			
Date: 9/20/2012		Prepared by: Hossein Tavakoli	
Observation	**Labors Observed**	**Labors Working**	**Labors Not Working**
1	5	5	0
2	6	5	1
3	5	5	0
4	5	5	0
5	5	5	0
6	5	4	1
7	4	4	0
8	5	4	1
9	4	4	0
10	6	6	0
11	5	5	0
12	5	5	0
13	5	5	0
14	5	3	2
15	5	3	2
16	4	3	1
17	4	3	1
18	4	2	2
19	4	4	0
20	4	4	0
Total	**95**	**84**	**11**
%Working		**88.42**	

Work Sampling- Field Rating 3			
Project: Jack & Bore Project		Location: Vernon, TX - US 287	
Contractor: AR Daniel Construction			
Date: 9/22/2012		Prepared by: Hossein Tavakoli	
Observation	Labors Observed	Labors Working	Labors Not Working
1	5	5	0
2	5	5	0
3	5	5	0
4	5	5	0
5	3	3	0
6	3	3	0
7	5	3	2
8	3	2	1
9	5	2	3
10	4	2	2
11	4	4	0
12	4	4	0
13	6	5	1
14	5	3	2
15	2	2	0
16	4	3	1
17	4	3	1
18	3	3	0
19	4	4	0
20	4	4	0
Total	83	70	13
%Working		84.34	

Work Sampling- Field Rating 4			
Project: Jack & Bore Project		Location: Vernon, TX - US 287	
Contractor: AR Daniel Construction			
Date: 9/24/2012		Prepared by: Hossein Tavakoli	
Observation	**Labors Observed**	**Labors Working**	**Labors Not Working**
1	6	5	1
2	6	6	0
3	6	5	1
4	5	5	0
5	5	4	1
6	5	4	1
7	4	3	1
8	6	2	4
9	5	2	3
10	5	2	3
11	5	4	1
12	5	4	1
13	2	2	0
14	2	2	0
15	2	1	1
16	1	1	0
17	1	1	0
18	1	1	0
19	3	3	0
20	3	2	1
Total	**78**	**59**	**19**
%Working		**75.64**	

Work Sampling- Field Rating 5			
Project: Jack & Bore Project		Location: Vernon, TX - US 287	
Contractor: AR Daniel Construction			
Date: 9/26/2012		Prepared by: Hossein Tavakoli	
Observation	**Labors Observed**	**Labors Working**	**Labors Not Working**
1	5	4	1
2	5	5	0
3	5	5	0
4	4	4	0
5	5	4	1
6	4	4	0
7	4	4	0
8	4	4	0
9	2	2	0
10	2	1	1
11	5	4	1
12	5	4	1
13	3	3	0
14	3	3	0
15	3	3	0
16	5	4	1
17	5	5	0
18	5	5	0
19	2	2	0
20	3	3	0
Total	79	73	6
%Working		**92.41**	

Work Sampling- Productivity Rating 1				
Project: Jack & Bore Project		Location: Vernon, TX - US 287		
Contractor: AR Daniel Construction				
Date: 9/19/2012		Prepared by: Hossein Tavakoli		
Observation	Observed Labors	Effective Labors	Contributory Labors	Not Effective Labors
1	5	4	1	0
2	5	3	2	0
3	5	2	2	1
4	4	3	1	0
5	4	3	1	0
6	4	3	1	0
7	5	4	1	0
8	4	3	1	0
9	5	2	2	1
10	5	3	2	0
11	5	3	2	0
12	4	2	2	0
13	5	3	2	0
14	5	2	2	1
15	5	4	1	0
16	5	4	1	0
17	5	4	0	1
18	5	3	2	0
19	4	4	0	0
20	4	2	1	1
Total	93	61	27	5
% Productivity			84.6341	

Work Sampling- Productivity Rating 2				
Project: Jack & Bore Project		Location: Vernon, TX - US 287		
Contractor: AR Daniel Construction				
Date: 9/21/2012		Prepared by: Hossein Tavakoli		
Observation	**Observed Labors**	**Effective Labors**	**Contributory Labors**	**Not Effective Labors**
1	4	3	1	0
2	4	2	2	0
3	4	3	1	0
4	3	2	1	0
5	3	2	1	0
6	5	2	2	1
7	5	3	1	1
8	5	4	1	0
9	5	3	1	1
10	3	2	1	0
11	5	2	1	2
12	4	2	2	0
13	5	4	1	0
14	3	2	1	0
15	4	3	1	0
16	5	3	1	1
17	3	3	0	0
18	3	3	0	0
19	4	3	0	1
20	3	2	1	0
Total	**80**	**53**	**20**	**7**
% Productivity			**82.8125**	

Work Sampling- Productivity Rating 3				
Project: Jack & Bore Project		Location: Vernon, TX - US 287		
Contractor: AR Daniel Construction				
Date: 9/22/2012		Prepared by: Hossein Tavakoli		
Observation	**Observed Labors**	**Effective Labors**	**Contributory Labors**	**Not Effective Labors**
1	5	4	1	0
2	4	3	1	0
3	3	2	0	1
4	5	2	0	3
5	4	4	0	0
6	4	3	1	0
7	3	2	0	1
8	4	4	0	0
9	4	3	1	0
10	4	3	1	0
11	4	3	1	0
12	5	5	0	0
13	3	2	1	0
14	4	3	1	0
15	3	2	1	0
16	5	4	1	0
17	5	3	1	1
18	4	2	1	1
19	3	2	0	1
20	4	2	1	1
Total	**80**	**58**	**13**	**9**
% Productivity			**84.2813**	

Work Sampling- Productivity Rating 4				
Project: Jack & Bore Project		Location: Vernon, TX - US 287		
Contractor: AR Daniel Construction				
Date: 9/23/2012		Prepared by: Hossein Tavakoli		
Observation	Observed Labors	Effective Labors	Contributory Labors	Not Effective Labors
1	5	4	1	0
2	5	2	2	1
3	5	4	1	0
4	4	2	2	0
5	4	2	1	1
6	4	3	1	0
7	5	3	1	1
8	4	3	1	0
9	5	3	2	0
10	5	3	1	1
11	5	4	1	0
12	4	2	2	0
13	5	3	1	1
14	5	3	2	0
15	5	4	1	0
16	5	4	1	0
17	5	4	0	1
18	5	3	0	2
19	4	3	0	1
20	4	2	1	1
Total	93	61	22	10
% Productivity			81.1076	

Work Sampling- Productivity Rating 5				
Project: Jack & Bore Project		Location: Vernon, TX - US 287		
Contractor: AR Daniel Construction				
Date: 9/25/2012		Prepared by: Hossein Tavakoli		
Observation	**Observed Labors**	**Effective Labors**	**Contributory Labors**	**Not Effective Labors**
1	5	4	1	0
2	4	2	2	0
3	5	4	1	0
4	5	2	2	1
5	3	2	1	0
6	3	2	1	0
7	5	4	1	0
8	4	2	1	1
9	4	2	2	0
10	3	2	1	0
11	4	4	0	0
12	5	3	1	1
13	3	2	1	0
14	5	3	1	1
15	3	2	1	0
16	4	2	1	1
17	3	2	0	1
18	4	3	0	1
19	5	4	1	0
20	4	2	1	1
Total	**81**	**53**	**20**	**8**
% Productivity			**81.5882**	

APPENDIX C

MICROCYCLONE SIMULATION RESULTS

BOX JACKING PROCESS			
TRACE INFORMATION			
Simulation Time (min)	Activity No.	Type	Operation
2.7	1	COMBI	ATTACH BOX TO CRANE
5.3	2	COMBI	BRING BOX FROM STOCKPILE
8.5	1	COMBI	ATTACH BOX TO CRANE
9.5	27	NORMAL	PLACE BOX INTO TRENCH
40.6	3	COMBI	PLACE JACKING FRAME INTO TRENCH
60.9	4	COMBI	RAILS AND ALIGNMENT
63.6	28	NORMAL	CRANE RETURNS
184.5	5	COMBI	EXCAVATION
212.0	26	NORMAL	JACK BOX SECTION
241.0	6	COMBI	REMOVE JACKING FRAME & HOSES
241.0	31	COUNTER	-
244.1	2	COMBI	BRING BOX FROM STOCKPILE
247.2	1	COMBI	ATTACH BOX TO CRANE
249.0	27	NORMAL	PLACE BOX INTO TRENCH
289.4	3	COMBI	PLACE JACKING FRAME INTO TRENCH
320.0	4	COMBI	RAILS AND ALIGNMENT
323.2	28	NORMAL	CRANE RETURNS

479.8	5	COMBI	EXCAVATION
511.9	26	NORMAL	JACK BOX SECTION
547.1	6	COMBI	REMOVE JACKING FRAME & HOSES
547.1	31	COUNTER	-
550.1	2	COMBI	BRING BOX FROM STOCKPILE
553.0	1	COMBI	ATTACH BOX TO CRANE
554.8	27	NORMAL	PLACE BOX INTO TRENCH
592.8	3	COMBI	PLACE JACKING FRAME INTO TRENCH
620.4	4	COMBI	RAILS AND ALIGNMENT
623.5	28	NORMAL	CRANE RETURNS
771.0	5	COMBI	EXCAVATION
801.9	26	NORMAL	JACK BOX SECTION
835.4	6	COMBI	REMOVE JACKING FRAME & HOSES
835.4	31	COUNTER	-
838.2	2	COMBI	BRING BOX FROM STOCKPILE
841.0	1	COMBI	ATTACH BOX TO CRANE
842.7	27	NORMAL	PLACE BOX INTO TRENCH
877.8	3	COMBI	PLACE JACKING FRAME INTO TRENCH
901.6	4	COMBI	RAILS AND ALIGNMENT
904.5	28	NORMAL	CRANE RETURNS
1040.9	5	COMBI	EXCAVATION
1070.3	26	NORMAL	JACK BOX SECTION

1070.3	30	CONSOLIDATE	-
1073.0	7	COMBI	MIX LUBRICATION
1101.8	6	COMBI	REMOVE JACKING FRAME & HOSES
1101.8	31	COUNTER	-
1104.5	2	COMBI	BRING BOX FROM STOCKPILE
1107.1	1	COMBI	ATTACH BOX TO CRANE
1108.9	27	NORMAL	PLACE BOX INTO TRENCH
1142.5	3	COMBI	PLACE JACKING FRAME INTO TRENCH
1164.7	4	COMBI	RAILS AND ALIGNMENT
1167.5	28	NORMAL	CRANE RETURNS
1298.2	5	COMBI	EXCAVATION
1326.9	26	NORMAL	JACK BOX SECTION
1357.4	6	COMBI	REMOVE JACKING FRAME & HOSES
1357.4	31	COUNTER	-
1359.9	2	COMBI	BRING BOX FROM STOCKPILE
1362.6	1	COMBI	ATTACH BOX TO CRANE
1363.8	27	NORMAL	PLACE BOX INTO TRENCH
1392.0	3	COMBI	PLACE JACKING FRAME INTO TRENCH
1410.1	4	COMBI	RAILS AND ALIGNMENT
1412.6	28	NORMAL	CRANE RETURNS
1522.0	5	COMBI	EXCAVATION
1548.0	26	NORMAL	JACK BOX SECTION

1575.2	6	COMBI	REMOVE JACKING FRAME & HOSES
1575.2	31	COUNTER	-
1577.8	2	COMBI	BRING BOX FROM STOCKPILE
1580.4	1	COMBI	ATTACH BOX TO CRANE
1582.0	27	NORMAL	PLACE BOX INTO TRENCH
1613.7	3	COMBI	PLACE JACKING FRAME INTO TRENCH
1634.5	4	COMBI	RAILS AND ALIGNMENT
1637.2	28	NORMAL	CRANE RETURNS
1760.3	5	COMBI	EXCAVATION
1788.0	26	NORMAL	JACK BOX SECTION
1817.4	6	COMBI	REMOVE JACKING FRAME & HOSES
1817.4	31	COUNTER	-
1819.9	2	COMBI	BRING BOX FROM STOCKPILE
1822.4	1	COMBI	ATTACH BOX TO CRANE
1823.9	27	NORMAL	PLACE BOX INTO TRENCH
1853.1	3	COMBI	PLACE JACKING FRAME INTO TRENCH
1872.0	4	COMBI	RAILS AND ALIGNMENT
1874.6	28	NORMAL	CRANE RETURNS
1988.1	5	COMBI	EXCAVATION
2014.6	26	NORMAL	JACK BOX SECTION
2014.6	30	CONSOLIDATE	-
2017.9	7	COMBI	MIX LUBRICATION

2042.4	6	COMBI	REMOVE JACKING FRAME & HOSES
2042.4	31	COUNTER	-
2044.8	2	COMBI	BRING BOX FROM STOCKPILE
2047.8	1	COMBI	ATTACH BOX TO CRANE
2048.7	27	NORMAL	PLACE BOX INTO TRENCH
2076.2	3	COMBI	PLACE JACKING FRAME INTO TRENCH
2093.9	4	COMBI	RAILS AND ALIGNMENT
2096.3	28	NORMAL	CRANE RETURNS
2203.1	5	COMBI	EXCAVATION
2228.8	26	NORMAL	JACK BOX SECTION
2255.5	6	COMBI	REMOVE JACKING FRAME & HOSES
2255.5	31	COUNTER	-
2258.3	2	COMBI	BRING BOX FROM STOCKPILE
2260.9	1	COMBI	ATTACH BOX TO CRANE
2262.9	27	NORMAL	PLACE BOX INTO TRENCH
2298.6	3	COMBI	PLACE JACKING FRAME INTO TRENCH
2323.3	4	COMBI	RAILS AND ALIGNMENT
2326.2	28	NORMAL	CRANE RETURNS
2465.2	5	COMBI	EXCAVATION
2495.0	26	NORMAL	JACK BOX SECTION
2526.9	6	COMBI	REMOVE JACKING FRAME & HOSES
2526.9	31	COUNTER	-

2529.4	2	COMBI	BRING BOX FROM STOCKPILE
2532.2	1	COMBI	ATTACH BOX TO CRANE
2533.4	27	NORMAL	PLACE BOX INTO TRENCH
2561.4	3	COMBI	PLACE JACKING FRAME INTO TRENCH
2579.4	4	COMBI	RAILS AND ALIGNMENT
2581.9	28	NORMAL	CRANE RETURNS
2690.9	5	COMBI	EXCAVATION
2716.8	26	NORMAL	JACK BOX SECTION
2743.9	6	COMBI	REMOVE JACKING FRAME & HOSES
2743.9	31	COUNTER	-
2746.6	2	COMBI	BRING BOX FROM STOCKPILE
2749.4	1	COMBI	ATTACH BOX TO CRANE
2751.0	27	NORMAL	PLACE BOX INTO TRENCH
2785.0	3	COMBI	PLACE JACKING FRAME INTO TRENCH
2807.6	4	COMBI	RAILS AND ALIGNMENT
2810.4	28	NORMAL	CRANE RETURNS
2942.5	5	COMBI	EXCAVATION
2971.4	26	NORMAL	JACK BOX SECTION
2971.4	30	CONSOLIDATE	-
2974.5	7	COMBI	MIX LUBRICATION
3002.1	6	COMBI	REMOVE JACKING FRAME & HOSES
3002.1	31	COUNTER	-

3004.8	2	COMBI	BRING BOX FROM STOCKPILE
3007.8	1	COMBI	ATTACH BOX TO CRANE
3009.2	27	NORMAL	PLACE BOX INTO TRENCH
3042.6	3	COMBI	PLACE JACKING FRAME INTO TRENCH
3064.8	4	COMBI	RAILS AND ALIGNMENT
3067.6	28	NORMAL	CRANE RETURNS
3197.6	5	COMBI	EXCAVATION
3226.2	26	NORMAL	JACK BOX SECTION
3256.6	6	COMBI	REMOVE JACKING FRAME & HOSES
3256.6	31	COUNTER	-
3259.6	2	COMBI	BRING BOX FROM STOCKPILE
3262.6	1	COMBI	ATTACH BOX TO CRANE
3264.2	27	NORMAL	PLACE BOX INTO TRENCH
3301.2	3	COMBI	PLACE JACKING FRAME INTO TRENCH
3327.6	4	COMBI	RAILS AND ALIGNMENT
3330.6	28	NORMAL	CRANE RETURNS
3474.4	5	COMBI	EXCAVATION
3504.9	26	NORMAL	JACK BOX SECTION
3537.7	6	COMBI	REMOVE JACKING FRAME & HOSES
3537.7	31	COUNTER	-
3540.7	2	COMBI	BRING BOX FROM STOCKPILE
3543.1	1	COMBI	ATTACH BOX TO CRANE

3545.3	27	NORMAL	PLACE BOX INTO TRENCH
3582.9	3	COMBI	PLACE JACKING FRAME INTO TRENCH
3609.9	4	COMBI	RAILS AND ALIGNMENT
3612.9	28	NORMAL	CRANE RETURNS
3758.8	5	COMBI	EXCAVATION
3789.5	26	NORMAL	JACK BOX SECTION
3822.7	6	COMBI	REMOVE JACKING FRAME & HOSES
3822.7	31	COUNTER	-
3825.0	2	COMBI	BRING BOX FROM STOCKPILE
3828.2	1	COMBI	ATTACH BOX TO CRANE
3828.8	27	NORMAL	PLACE BOX INTO TRENCH
3853.9	3	COMBI	PLACE JACKING FRAME INTO TRENCH
3869.8	4	COMBI	RAILS AND ALIGNMENT
3872.2	28	NORMAL	CRANE RETURNS
3969.8	5	COMBI	EXCAVATION
3994.3	26	NORMAL	JACK BOX SECTION
3994.3	30	CONSOLIDATE	-
3997.3	7	COMBI	MIX LUBRICATION
4019.6	6	COMBI	REMOVE JACKING FRAME & HOSES
4019.6	31	COUNTER	-
4022.6	2	COMBI	BRING BOX FROM STOCKPILE
4025.4	1	COMBI	ATTACH BOX TO CRANE

4027.4	27	NORMAL	PLACE BOX INTO TRENCH
4066.5	3	COMBI	PLACE JACKING FRAME INTO TRENCH
4095.5	4	COMBI	RAILS AND ALIGNMENT
4098.6	28	NORMAL	CRANE RETURNS
4250.2	5	COMBI	EXCAVATION
4281.7	26	NORMAL	JACK BOX SECTION
4316.0	6	COMBI	REMOVE JACKING FRAME & HOSES
4316.0	31	COUNTER	-
4318.7	2	COMBI	BRING BOX FROM STOCKPILE
4321.3	1	COMBI	ATTACH BOX TO CRANE
4323.0	27	NORMAL	PLACE BOX INTO TRENCH
4355.9	3	COMBI	PLACE JACKING FRAME INTO TRENCH
4377.5	4	COMBI	RAILS AND ALIGNMENT
4380.3	28	NORMAL	CRANE RETURNS
4508.1	5	COMBI	EXCAVATION
4536.4	26	NORMAL	JACK BOX SECTION
4566.5	6	COMBI	REMOVE JACKING FRAME & HOSES
4566.5	31	COUNTER	-
4569.0	2	COMBI	BRING BOX FROM STOCKPILE
4571.4	1	COMBI	ATTACH BOX TO CRANE
4573.0	27	NORMAL	PLACE BOX INTO TRENCH
4601.8	3	COMBI	PLACE JACKING FRAME INTO TRENCH

4620.5	4	COMBI	RAILS AND ALIGNMENT
4623.1	28	NORMAL	CRANE RETURNS
4735.2	5	COMBI	EXCAVATION
4761.6	26	NORMAL	JACK BOX SECTION
4789.1	6	COMBI	REMOVE JACKING FRAME & HOSES
4789.1	31	COUNTER	-
4791.5	2	COMBI	BRING BOX FROM STOCKPILE
4794.6	1	COMBI	ATTACH BOX TO CRANE
4795.3	27	NORMAL	PLACE BOX INTO TRENCH
4821.5	3	COMBI	PLACE JACKING FRAME INTO TRENCH
4838.2	4	COMBI	RAILS AND ALIGNMENT
4840.6	28	NORMAL	CRANE RETURNS
4942.3	5	COMBI	EXCAVATION
4967.3	26	NORMAL	JACK BOX SECTION
4967.3	30	CONSOLIDATE	-
4970.2	7	COMBI	MIX LUBRICATION
4993.2	6	COMBI	REMOVE JACKING FRAME & HOSES
4993.2	31	COUNTER	-
4996.2	2	COMBI	BRING BOX FROM STOCKPILE
4999.3	1	COMBI	ATTACH BOX TO CRANE
5001.0	27	NORMAL	PLACE BOX INTO TRENCH
5039.4	3	COMBI	PLACE JACKING FRAME INTO TRENCH

5067.6	4	COMBI	RAILS AND ALIGNMENT
5070.6	28	NORMAL	CRANE RETURNS
5219.8	5	COMBI	EXCAVATION
5251.0	26	NORMAL	JACK BOX SECTION
5284.8	6	COMBI	REMOVE JACKING FRAME & HOSES
5284.8	31	COUNTER	-
5287.8	2	COMBI	BRING BOX FROM STOCKPILE
5290.4	1	COMBI	ATTACH BOX TO CRANE
5292.5	27	NORMAL	PLACE BOX INTO TRENCH
5330.7	3	COMBI	PLACE JACKING FRAME INTO TRENCH
5358.5	4	COMBI	RAILS AND ALIGNMENT
5361.5	28	NORMAL	CRANE RETURNS
5509.7	5	COMBI	EXCAVATION
5540.7	26	NORMAL	JACK BOX SECTION
5574.3	6	COMBI	REMOVE JACKING FRAME & HOSES
5574.3	31	COUNTER	-
5576.8	2	COMBI	BRING BOX FROM STOCKPILE
5579.3	1	COMBI	ATTACH BOX TO CRANE
5580.9	27	NORMAL	PLACE BOX INTO TRENCH
5610.4	3	COMBI	PLACE JACKING FRAME INTO TRENCH
5629.5	4	COMBI	RAILS AND ALIGNMENT
5632.1	28	NORMAL	CRANE RETURNS

5746.6	5	COMBI	EXCAVATION
5773.3	26	NORMAL	JACK BOX SECTION
5801.2	6	COMBI	REMOVE JACKING FRAME & HOSES
5801.2	31	COUNTER	-
5803.6	2	COMBI	BRING BOX FROM STOCKPILE
5806.3	1	COMBI	ATTACH BOX TO CRANE
5807.4	27	NORMAL	PLACE BOX INTO TRENCH
5833.1	3	COMBI	PLACE JACKING FRAME INTO TRENCH
5849.5	4	COMBI	RAILS AND ALIGNMENT
5851.9	28	NORMAL	CRANE RETURNS
5951.9	5	COMBI	EXCAVATION
5976.7	26	NORMAL	JACK BOX SECTION
5976.7	30	CONSOLIDATE	-
5979.2	7	COMBI	MIX LUBRICATION
6002.4	6	COMBI	REMOVE JACKING FRAME & HOSES
6002.4	31	COUNTER	-
6005.0	2	COMBI	BRING BOX FROM STOCKPILE
6008.2	1	COMBI	ATTACH BOX TO CRANE
6009.2	27	NORMAL	PLACE BOX INTO TRENCH
6040.9	3	COMBI	PLACE JACKING FRAME INTO TRENCH
6061.7	4	COMBI	RAILS AND ALIGNMENT
6064.4	28	NORMAL	CRANE RETURNS

6187.7	5	COMBI	EXCAVATION
6215.5	26	NORMAL	JACK BOX SECTION
6244.8	6	COMBI	REMOVE JACKING FRAME & HOSES
6244.8	31	COUNTER	-
6247.9	2	COMBI	BRING BOX FROM STOCKPILE
6250.5	1	COMBI	ATTACH BOX TO CRANE
6252.7	27	NORMAL	PLACE BOX INTO TRENCH
6292.1	3	COMBI	PLACE JACKING FRAME INTO TRENCH
6321.4	4	COMBI	RAILS AND ALIGNMENT
6324.5	28	NORMAL	CRANE RETURNS
6477.3	5	COMBI	EXCAVATION
6508.9	26	NORMAL	JACK BOX SECTION
6543.4	6	COMBI	REMOVE JACKING FRAME & HOSES
6543.4	31	COUNTER	-
6545.9	2	COMBI	BRING BOX FROM STOCKPILE
6548.7	1	COMBI	ATTACH BOX TO CRANE
6549.9	27	NORMAL	PLACE BOX INTO TRENCH
6579.2	3	COMBI	PLACE JACKING FRAME INTO TRENCH
6598.2	4	COMBI	RAILS AND ALIGNMENT
6600.8	28	NORMAL	CRANE RETURNS
6714.5	5	COMBI	EXCAVATION
6741.1	26	NORMAL	JACK BOX SECTION

6768.9	6	COMBI	REMOVE JACKING FRAME & HOSES
6768.9	31	COUNTER	-
6771.6	2	COMBI	BRING BOX FROM STOCKPILE
6774.7	1	COMBI	ATTACH BOX TO CRANE
6775.9	27	NORMAL	PLACE BOX INTO TRENCH
6808.8	3	COMBI	PLACE JACKING FRAME INTO TRENCH
6830.5	4	COMBI	RAILS AND ALIGNMENT
6833.2	28	NORMAL	CRANE RETURNS
6961.1	5	COMBI	EXCAVATION
6989.4	26	NORMAL	JACK BOX SECTION
6989.4	30	CONSOLIDATE	-
6992.1	7	COMBI	MIX LUBRICATION
7019.5	6	COMBI	REMOVE JACKING FRAME & HOSES
7019.5	31	COUNTER	-
7022.5	2	COMBI	BRING BOX FROM STOCKPILE
7025.2	1	COMBI	ATTACH BOX TO CRANE
7027.2	27	NORMAL	PLACE BOX INTO TRENCH
7065.1	3	COMBI	PLACE JACKING FRAME INTO TRENCH
7092.5	4	COMBI	RAILS AND ALIGNMENT
7095.6	28	NORMAL	CRANE RETURNS
7242.7	5	COMBI	EXCAVATION
7273.6	26	NORMAL	JACK BOX SECTION

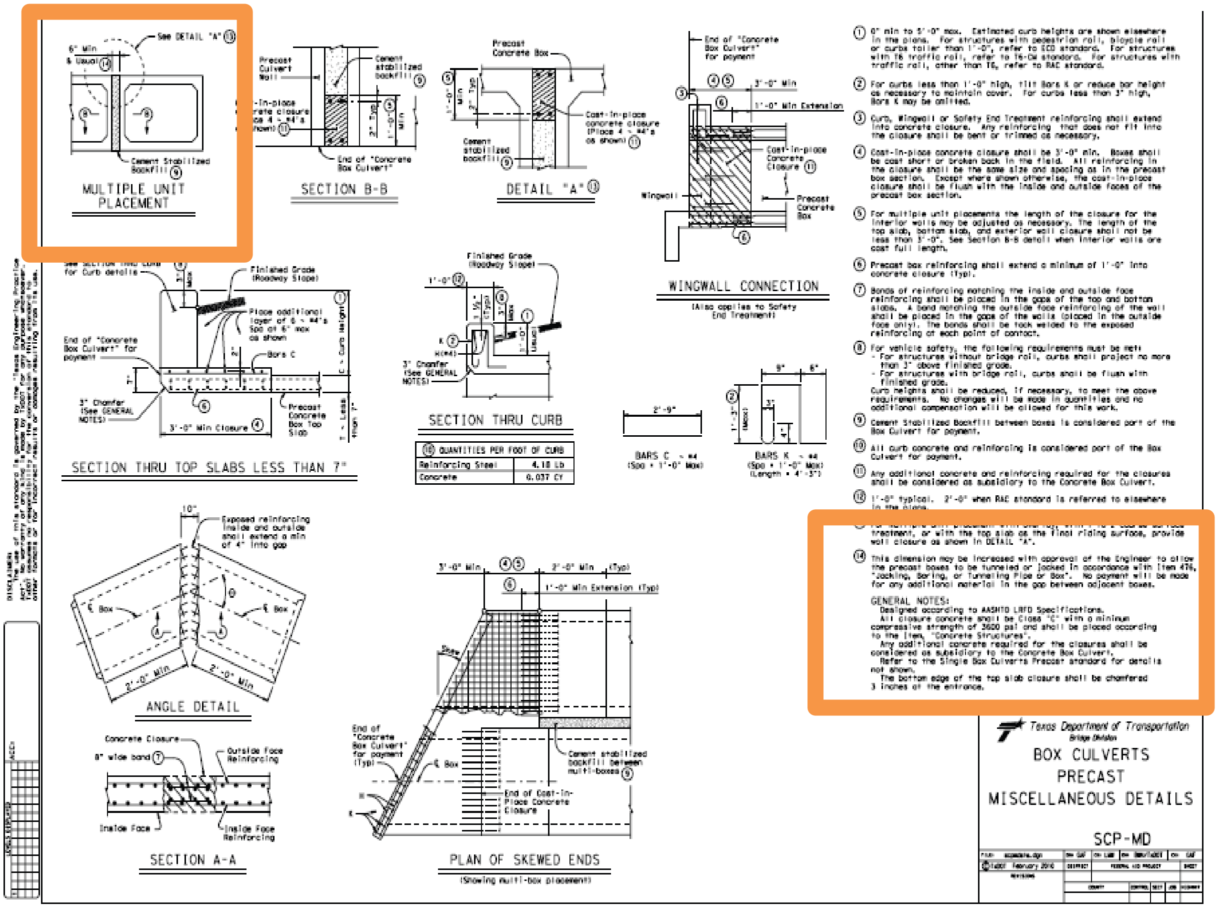
7307.1	6	COMBI	REMOVE JACKING FRAME & HOSES
7307.1	31	COUNTER	-
7309.7	2	COMBI	BRING BOX FROM STOCKPILE
7312.7	1	COMBI	ATTACH BOX TO CRANE
7313.9	27	NORMAL	PLACE BOX INTO TRENCH
7345.7	3	COMBI	PLACE JACKING FRAME INTO TRENCH
7366.6	4	COMBI	RAILS AND ALIGNMENT
7369.3	28	NORMAL	CRANE RETURNS
7492.9	5	COMBI	EXCAVATION
7520.8	26	NORMAL	JACK BOX SECTION
7550.2	6	COMBI	REMOVE JACKING FRAME & HOSES
7550.2	31	COUNTER	-
7553.0	2	COMBI	BRING BOX FROM STOCKPILE
7555.9	1	COMBI	ATTACH BOX TO CRANE
7557.6	27	NORMAL	PLACE BOX INTO TRENCH
7594.0	3	COMBI	PLACE JACKING FRAME INTO TRENCH
7619.4	4	COMBI	RAILS AND ALIGNMENT
7622.4	28	NORMAL	CRANE RETURNS
7763.6	5	COMBI	EXCAVATION
7793.6	26	NORMAL	JACK BOX SECTION
7826.0	6	COMBI	REMOVE JACKING FRAME & HOSES
7826.0	31	COUNTER	-

7828.8	2	COMBI	BRING BOX FROM STOCKPILE
7831.9	1	COMBI	ATTACH BOX TO CRANE
7833.3	27	NORMAL	PLACE BOX INTO TRENCH
7868.4	3	COMBI	PLACE JACKING FRAME INTO TRENCH
7892.2	4	COMBI	RAILS AND ALIGNMENT
7895.1	28	NORMAL	CRANE RETURNS
8031.4	5	COMBI	EXCAVATION
8060.9	26	NORMAL	JACK BOX SECTION
8060.9	30	CONSOLIDATE	-
8063.5	7	COMBI	MIX LUBRICATION
8092.3	6	COMBI	REMOVE JACKING FRAME & HOSES
8092.3	31	COUNTER	-
8095.3	2	COMBI	BRING BOX FROM STOCKPILE
8098.2	1	COMBI	ATTACH BOX TO CRANE
8100.1	27	NORMAL	PLACE BOX INTO TRENCH
8138.6	3	COMBI	PLACE JACKING FRAME INTO TRENCH
8166.8	4	COMBI	RAILS AND ALIGNMENT
8169.8	28	NORMAL	CRANE RETURNS
8319.1	5	COMBI	EXCAVATION
8350.3	26	NORMAL	JACK BOX SECTION
8384.2	6	COMBI	REMOVE JACKING FRAME & HOSES
8384.2	31	COUNTER	-

8386.9	2	COMBI	BRING BOX FROM STOCKPILE
8391.3	27	NORMAL	PLACE BOX INTO TRENCH
8425.3	3	COMBI	PLACE JACKING FRAME INTO TRENCH
8448.0	4	COMBI	RAILS AND ALIGNMENT
8450.8	28	NORMAL	CRANE RETURNS
8583.0	5	COMBI	EXCAVATION
8611.9	26	NORMAL	JACK BOX SECTION
8642.7	6	COMBI	REMOVE JACKING FRAME & HOSES
8642.7	31	COUNTER	-

APPENDIX D

TXDOT 2010 STANDARD SPECIFICATION


MULTIPLE UNIT PLACEMENT
SECTION B-B
DETAIL "A"
WINGWALL CONNECTION
SECTION THRU TOP SLABS LESS THAN 7"
SECTION THRU CURB
ANGLE DETAIL
SECTION A-A
PLAN OF SKEWED ENDS
Texas Department of Transportation
BOX CULVERTS
PRECAST
MISCELLANEOUS DETAILS
SCP-MD

APPENDIX E

SENSITIVITY ANALYSIS

Resource Information					Productivity Information
# of LABOR' at CREW A	# of SUPERVISOR' at SUPERVISOR AVAILABLE	# of LABOR' at CREW B	# of CRANE' at CRANE READY	# of LABOR' at CREW C	Productivity Box Per Minute
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3	2	3	1	2	0.0037
3	2	3	1	3	0.0038
3	2	3	1	4	0.0039
3	2	3	1	5	0.004
3	2	3	2	2	0.0037

3	2	3	2	3	0.0039
3	2	3	2	4	0.0037
3	2	3	2	5	0.0039

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BIOGRAPHICAL INFORMATION

Hossein Tavakoli was born in June, 1981, in Tehran, Iran. He received his bachelor degree in Architecture from Abu Ali Sina University, Hamedan, Iran in 2005, after which he worked as a project coordinator for Shayestgean Counseling Company. He coordinated closely with the Red Cross and helped them build several educational spaces for earthquake victims in the city of Bam, Iran. He then joined the Sangan Sazeh Construction Company as an Assistant Project Manager. He achieved one of his dreams by establishing a construction company, IPK Construction Company, in 2008. He completed several public projects for the City of Tehran and managed several residential and commercial construction projects. With great motivation and enthusiasm for developing higher-level skills and knowledge in the area of construction, he decided to pursue the Master's Degree in Civil Engineering with a focus on Construction Engineering and Management. He was accepted into the graduate program of the University of Texas at Arlington and worked with Dr. Mohammad Najafi who served as his advisor. As a graduate student, he worked on several research projects which provided instruction and explored innovative research in ways to handle HDPE and large-diameter pipeline repair and maintenance. Most importantly, he was able to work with the Texas Department of Transportation through a collaborative program with UTA where he was able to investigate the different applications and methods of trenchless technology like HDD and Pipe/Box Jacking. This study led to the writing of this thesis and inspired a lasting interest in trenchless technology.