IDENTIFYING ISSUES IMPACTING PRODUCTIVITY

OF BOX JACKING PROJECTS

by

BHAUMI BHAVAN CHAURASIA

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ABSTRACT

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Bhaumi Bhavan Chaurasia

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Jacking is a trenchless construction technique used for installing underground pipeline system. Jacking method is more widely used for upgrading under capacity culverts and drainage structures under roads and railroad tracks. Also, this method is used for installing underground pipelines such as watermains, sewers etc.in populated and developed urban areas. In this method, culverts (segments) are installed through the ground from an entry shaft to an exit shaft. During the excavation and spoil removal processes, workers are required to be inside the pipe, this is essentially what separates pipe jacking trenchless construction method from microtunneling technology. The minimum recommended diameter for pipes installed by jacking is 42 in. as it may not be possible for a person to enter smaller diameter pipes.

Pipe/box jacking projects often have to face schedule delays or loss of productivity due to inherent uncertainties in identifying unmarked under laid structures, type of soil and groundwater conditions. The contractor usually relies on the judgments, from experienced engineers and experts in forecasting productivity. This leads to development of imprecision cost estimates, and as a result, bidding price for box jacking projects is usually kept on a higher side.

The main objective of this study is to identify and quantify productivity related issues in box jacking trenchless construction method based on case studies and the expert opinion of contactors, engineers and various Department of Transportation's (DOT'S) professionals involved in pipe/box jacking trenchless construction operations, using Analytic Hierarchy Process (AHP) method to rank the opinions.

This study identifies six (traffic control, safety & security, availability of box storage & handling, type of spoil removal system, size of box & weight of box) factors and parameters that contractors and engineers can consider to avoid delays and improve jacking productivity. Ranking of these factors is expected to help in improving the productivity of the box jacking process by planning and executing in a more efficient manner. This research builds up the basics for modeling box jacking productivity operation during various conditions.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

This chapter presents a brief introduction to jacking trenchless construction technique and describes the steps involved in jacking process and how various factors influence its productivity. Box jacking (BJ) process involves the installation, repair, renewal and replacement of pipelines with minimum surface and subsurface disruptions thereby improving safety and cost-effectiveness of pipeline installation and renewal (Najafi and Gokhale, 2005).

1.1 INTRODUCTION

An increase in demand for installation of new utility systems in urban areas has increased the necessity for innovative and economical systems to go underneath and alongside in-place facilities (Najafi and Gokhale, 2005). Environmental concerns, social (indirect) costs, new and more stringent safety regulations, difficult underground conditions (containing natural or artificial obstructions, high water table, etc.) and new developments in equipment have increased demand for trenchless technology. Trenchless technology methods include all methods to install and renew underground utility systems with minimum disruption of the surface or subsurface (Najafi and Gokhale, 2005).

Box jacking is a trenchless technology method for the installation of prefabricated segments through the ground from a drive shaft to a reception shaft (Najafi et. al., 2005). This method was first used at the end of 19th century. New capabilities like extended drive length, upgraded line and grade accuracy, enhanced joint mechanisms, and face stabilizing shields were added to pipe jacking by European and Japanese companies in mid 1950s and 1960s (Najafi et. al., 2005).

The pipe jacking (PJ) is a repetitive operation where the system allows one-pass pipe installation from a jacking to a reception shaft. After carefully mounting and aligning the hydraulic jack in the entry shaft pit a pipe section is then inserted between the jacking ring (thrust ring) and boring head or hand shield. After making necessary corrections the machine performs a drive stroke pushing the pipe along the desired axis and grade. This cycle is repeated until first pipe section reaches at reception shaft. Figure.1.1 shows a typical pipe jacking shaft and jacking frame.

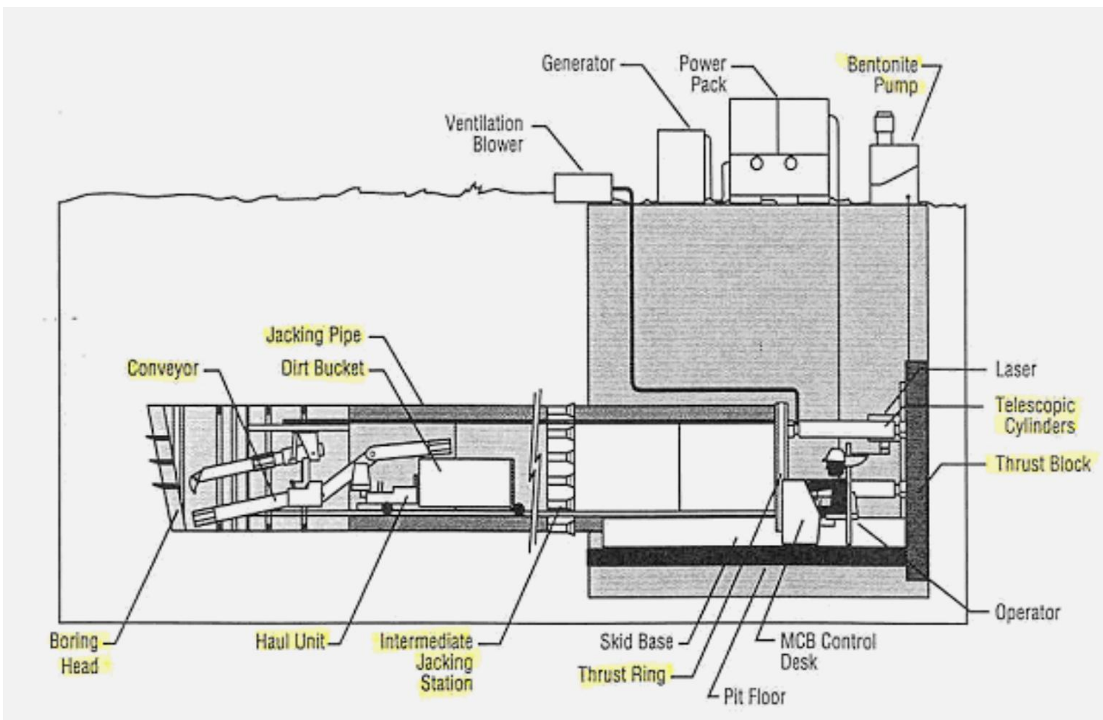

Figure.1.1: Typical Components of a Pipe Jacking Operation

(Iseley and Gokhale, 1997)

As the main jacks push the pipeline into the ground, a thrust wall, located behind the main jacking system, distributes the reactionary force into the walls of the shaft and the ground surrounding the shaft. If the shaft is not designed adequately to support the jacking forces, shaft failure can occur. Shaft failure is a serious and significant problem on pipe jacking projects in the United States today that results in a large number of construction claims, which have significant monetary value (Marshall et al., 1998). Jacking force predictions are therefore crucial to adequately design thrust blocks and jacking shafts to avoid shaft failures.

In longer projects a series of intermediate jacking station (IJS) can also be incorporated into the pipeline at a distance behind the main jacking machine. This helps to overcome large frictional component and share the loading capacity handled by main jacks. IJS shells are fabricated to the exact outer diameter of the jacking pipe and are machined to exert the thrust from the hydraulic jacks to the load-bearing end of the jacking pipe (Marshall et al., 1998). IJS are long lead-time items and must be ordered well in advance of construction.

1.2 Background

Culvert Management Manual (2003) by Ohio Department of Transportation (ODOT) defines culverts as "any structure that conveys water or forms a passageway through an embankment and is designed to support a superimposed earth load or other fill material plus live load with a span, diameter, or multi-cell less than 10 ft. when measured parallel to the centerline of the roadway." Culverts are one of the important components of the highway infrastructure. Culvert construction in the United States became increasingly necessary with the freeway construction projects initiated under the Eisenhower administration (1953-1961) and the signing by President Eisenhower in 1956 of the National Defense Interstate Highway Act. Originally, the culverts were designed with a 50-year life cycle (Camp et. al., 2010) and were installed using open trench excavation methods while a highway was under construction. Engineered fill was used to bury the culvert as the highway embankment was constructed. The backfill was typically native materials, compacted in lifts with undocumented quality control. To replace these aging culverts or to install new culverts open trenching of the existing highway is not possible. Culvert replacement with trenchless methods is the only solution and of the entire available options pipe jacking is the most commonly used method to install new or replace almost any size of culvert (Camp et. al., 2010). Pipe jacking (PJ) is a trenchless tunneling method used for installation of prefabricated (box or circular) pipelines and culverts with minimal disruption to traffic, adjacent property, or services on the surface. This technology was first introduced by the United States some 50 years ago (Hideki, 2008). In the 1950s and 1960s, new capabilities were added to pipe jacking by European and Japanese companies, including extended drive length, upgraded line and grade accuracy, enhanced joint mechanism, new pipe materials, and improved excavation and face-stabilizing shields. These developments as well as the improved operator skills and experience have enabled pipe jacking to be a popular trenchless technology (Jung et al., 2007).

1.3 Comparison of Pipe Jacking and Open Cut

One can install a new pipeline (subsurface utilities) irrespective of its shape by two general categories, the traditional open trench method or by using trenchless technology which is more advanced way. Open trench construction process involves excavating the ground along the entire length of the pipeline which is also a major disadvantage of this process and when the proper depth is reached, selected bedding material is placed into the bottom of the trench.

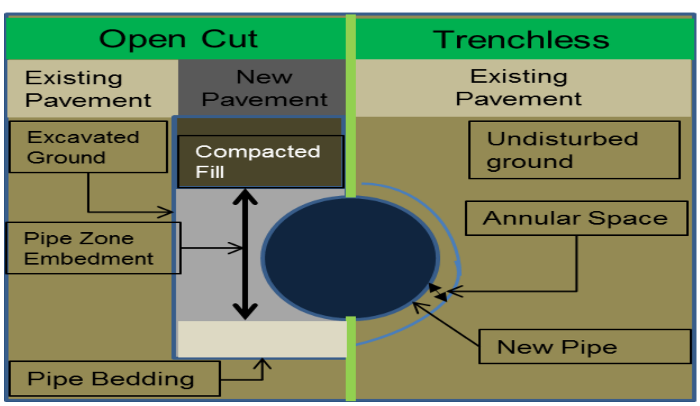

Figure.1.2: Comparison of Pipe Jacking and Open Cut

The new pipe is laid onto the bedding, and the open trench is backfilled in layers and compacted as shown in Figure 1.2. When PJ compared to open cut has many advantages and is popularly used for culvert rehabilitation and repair because of its advantages in terms of speedy installation and minimal environmental impacts and low social costs (Jung et al., 2007). Table 1.1 further compares several planning elements that are common for the rehabilitation or installation of subsurface utilities.

Table 1.1: Project Elements for PJ and Open Cut (Nido, 1999)

Planning Element	**Trenchless Construction**	**Conventional Open Cut**
Schedule	Hours/Day	Days/Weeks
Excavation	Depending on method – minimal or none required	Entire length of installation must be exposed
Traffic Control	Minimal – if any	Usually required
Utility Support	Typically not required	Often required
Site Restoration	Depending on method – minimal or none required	Major resurfacing or restoration required
Worker Experience	New technology – limited pool of skilled workers	Proven method – many skilled workers
Safety	Only pits required	Trenchless required

Open cut method is also generally now day's prohibited in environmentally sensitive areas and in locations of with high traffic flow. Trenchless technologies can reduce construction related CO2 emissions by 90%, reducing our carbon footprint on the environment (Sachs and Lightner, 2012). One of the major advantages of PJ over open cut traffic are fewer inconveniences to the general public, the issue of traffic control is of great concern and in many areas closing of a route or street due to construction activities causes disruption to the nearby residence and businesses. Situations like these make pipe jacking more economical than conventional cut and cover techniques.

1.4 Comparison of Pipe Jacking and Box Jacking

Box jacking operation is similar to that of pipe jacking operation, the main difference which separates PJ from BJ process is the shape of the pipe which is to use to jack. In case pipe jacking operations circular segments of pipe are jacked whereas in box jacking operation box or rectangular segment are jacked.

Table 1.2: Comparison of Pipe Jacking and Box Jacking

Criteria	**Pipe Jacking**	**Box Jacking**
Shape of pipe	Circular	Rectangular
Shape of jacking frame	Circular	Rectangular
Soil movement	Comparatively low	Comparatively high
Frictional force	Comparatively low	Comparatively high
Weight of pipe segment	Comparatively low	Comparatively high
Diameter range	48 in. to 72 in.	4 ft by 2 ft to 12 ft by 10 ft
Drive length	Can go long drives	Comparatively shorter drives
Favorable soil	Cohesive soil	Cohesive soil

The shape of the jacking frame and the front shield in pipe jacking operations are circular but in case of box jacking operations they are rectangular in built. The weight of box segments are relatively heavy and the soil movements in box jacking process are expected to be more when compared with pipe jacking. The methods can be further classified by the diameter range, drive length and favorable soil as shown in Table 1.2.

1.4.1 Diameter Range:

Theoretically, there is no limit to the size of pipe or box that can be jacked either by pipe jacking or box jacking process. Table 1.2 indicates the common diameter range for both the process. Since this technique requires people working inside the jacking pipe, the method is limited to person entry pipes. The minimum recommended diameter for pipe installed by PJ or 42 in and for BJ its 4 ft.

1.4.2 Drive Length:

The length of the pipe or box to be jacked is determined by the amount of available jacking thrust and the compressive strength of the pipe or box segment (Source: Purdue, 2012). The jacking thrust can be minimized or managed by providing an adequate over cut, applying sufficient lubrication between the outside surface of the pipe and the bore hole, maintaining accurate line and grade control, using high-quality pipe products, and using intermediate jacking stations. Pipe jacking operations have relatively longer drive lengths when compared with box jacking operations due to the shape of the pipe segments.

1.4.3 Favorable Soil:

Cohesive soils are the most favorable soil conditions for jacking operations (Purdue, 2012). It is possible to use pipe jacking in unstable soil conditions as long as special precautions are taken, such as dewatering and using closed-face machines and earth pressure balance machines to counterbalance the ground pressure but the same cannot be done for box jacking operations. Table1.3 shows the applicability of pipe jacking technique at various soil conditions.

Table 1.3: Applicability of Pipe Jacking Methods for Different Soil Conditions

(Najafi and Gokhale, 2005)

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

1.5 Method Description

After the construction of entry shaft is completed, hydraulic jacks are installed to the proposed line and grade. A laser guidance system is also installed and point of reference is established to maintain a continuous check on the line and grade of the subject pipeline. Depending on the excavation method the face is cut under the protection of a shield using a Tunnel Boring Machine (TBM) or Hand excavation. As the shield advances the excavation the spoil removal process begins, where it is hoisted and tipped off on the surface. As shown in Figure1.3 simultaneously a prefabricated pipe section is installed between the shield and jacking frame (thrust frame).The purpose of the jacking frame is to provide a 360-degree surface against the pipe to minimize inducement of point pressure and hence reduce the chances of pipe breakage. The prefabricated pipes (box or circular) are usually made of high-strength concrete to withstand the high jacking forces.

Generally speaking their wall thickness is usually determined by finding the maximum jacking forces required to complete the drive. As the shield drives further more into the soil each pipe section is lowered in to the entry shaft and then joined to the previous one by jacking the section forward this sequence is shown in Figure1.4 and Figure 1.5 respectively.

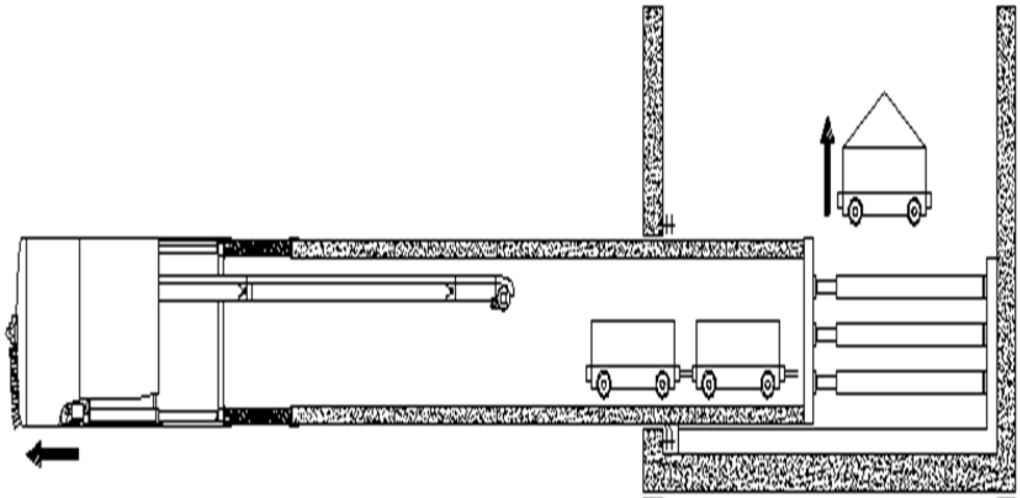

Figure.1.3: Hydraulic Jacks are Pulled Back and Mud Cart is Hoisted

(Frenke, 2010)

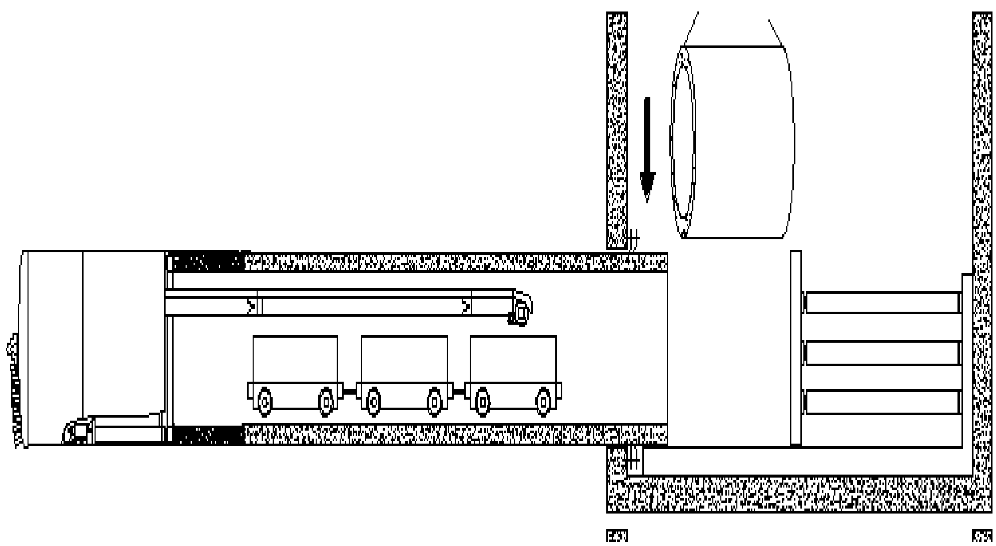

Figure.1.4: Pipe Segment is Lowered into the Entry Shaft

(Frenke, 2010)

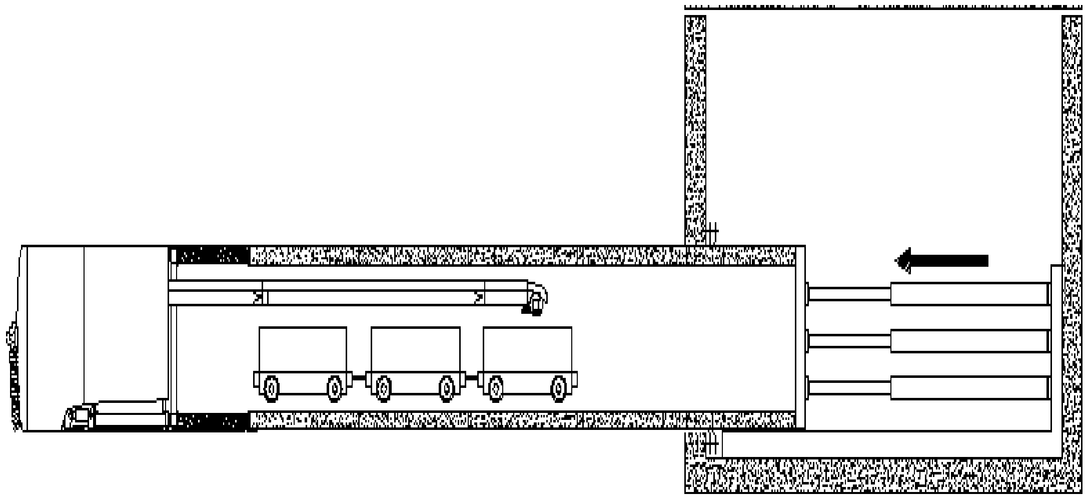

Figure.1.5: Jacks are Completely Extended

(Frenke, 2010)

This process is repeated until the complete line is installed. After successful installation of the pipe line the overcut produced during excavation is grouted to avoid soil settlement. To minimize the likelihood of the occurrence of ground settlement, various ground treatment works can be employed, including jet grouting, silica/cement grouting, grouting using tube-a-manchettes, dewatering, and ground freezing (Geotechnical Services Ltd., 2004). The site can be restored as required after the removal of TBM from the exit shaft. In case of longer tunnels, intermediated jacking stations can be used to reduce the jacking force. Friction reducing agent such as bentonite also can be used to reduce friction between the outside diameter of the pipe and the surrounding ground. This system reduces the friction force and increases the productivity. In the case of unstable ground conditions, the jacked structure may be installed as a sleeve through which the actual service will later pass or within which an in-situ invert may be constructed. A single sleeve pipe may be used to install a variety of smaller services.

1.6 Box Jacking Productivity

As inferred from the literature review, in box jacking the actual trenching operation rate is based on soil conditions encountered, method of soil excavation and removal, liner materials, as well as the field coordination and skill level of the tunneling personnel. A reasonable productivity range for jacking projects is 33 ft to 60 ft per shift with a four or five person crew (Najafi, 2010). So operations which use hand excavation the productivity is relatively low as the crew operates in uncomfortable compressed air zone for most of the time.

1.7 Problem Statement

Box Jacking is an increasingly applied trenchless construction technique in culvert construction in the United States since 1988. The main concern of box jacking contractors is predicting the underground behavior of the machine (Iseley and Gokale, 1997). Presently contractors use their own experience in predicting the productivity of box jacking crew and machines. A need exists for development of a productivity model that helps contractors in forecasting installation time through different soil conditions. This research builds up the basics for modeling the box jacking productivity operation during various difficult scenarios. Accordingly, from this research the contactors will benefit and predict their cost and schedule with more accuracy.

1.8 Research Need

Not much research has been done on box jacking operations. A need exists for development of a box jacking productivity model that helps contractors in forecasting installation time through different soil conditions. This research builds up the basis for developing such a model.

1.9 Objectives and Scope

The scope of this research is to study the different issues affecting/influencing box jacking process based on the expert opinion of contactors, engineers and various professionals involved in box jacking trenchless construction operations. The specific objectives of this thesis are:

- To identify main issues influencing box jacking productivity
- Rank the important issues influencing box jacking productivity
- Develop an analytic hierarchy model to understand the relative interdependency between various factors in predicting box jacking productivity

1.10 Methodology

The research methodology layout concocts of the following steps:

1. Performed literature review to find all articles, papers, and previously done research to identify issues affecting box jacking productivity. Also, to find out available techniques to deal with the current research problem.
2. Performed field observations of box jacking projects.
3. Developed questionnaire and sent to selected engineers, various DOT's and box/pipe jacking contractors.
4. Filtered and analyzed data to establish its hold good factor.
5. Ranked and sorted data collected as per their relative importance using Analytical Hierarchy Process (Saaty,1980).
6. Performed quantitative analysis by developing pair-wise comparison matrix. This matrix gives ratio scale (weighting) and a consistency index ratio, in the form of Eigen vectors and Eigen value.
7. Discussed results and specified conclusions and work for future research.

1.11 Chapter Summary

This chapter provided an introduction to box jacking (BJ) trenchless construction technique and describes the steps involved in BJ process and how various factors influence its productivity. A need to document unaccounted productivity issues in BJ process was highlighted. The methodology selected would explore productivity in the overall box jacking process. This research builds upon the past research on pipe jacking productivity operations in various conditions.

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CHAPTER 2

LITERATURE SEARCH

This chapter provides a literature review on the subject of factors affecting box jacking productivity and Analytical Hierarchy Process (AHP) in general. Extensive research has been done on trenchless construction methods, identifying and evaluating issues in installation and their impacts on productivity. Analytical hierarchy is a powerful tool to model complex systems, such as trenchless construction; therefore, it is believed that there is potential in applying AHP to analyze the factors impacting the productivity of trenchless construction methods. This literature search also covers the research that has been conducted previously on ranking of productivity factors and developing of productivity models for various trenchless construction methods.

2.1 Jacking Productivity

As mentioned earlier, the reasonable productivity range for pipe jacking projects is 33 ft to 60 ft per shift with a four or five person crew (Najafi, 2010). For box jacking projects the productivity range is between 16 ft to 25 ft per shift with a four or five person crew. This range is highly variable due to the factors that can affect productivity, such as presence of groundwater, unanticipated obstructions such as boulders or other utilities, and changed conditions such as encountering wet silty sand after selecting equipment for stable sandy clay (Gokhale et al., 1997). The cost of operation, soil settlement and at times low productivity are the main drawbacks of this wonderful operation.

2.2 Parameters Affecting Trenchless Construction

According to Iseley and Gokhale (1997) factors that can affect trenchless productivity include the presence of groundwater, unanticipated obstructions such as boulders or other utilities, and changed conditions such as encountering wet silty sand after selecting equipment for stable sandy clay. Nido (1999) identifies the factors influencing micro-tunneling productivity based on expert opinion, Allouche et al. (2000) in his research states that subsurface conditions and pipe diameter are the two main factors affecting productivity in trenchless construction projects. Salem et al. (2003) identifies factors affecting auger boring and mentions that mico-tunneling and auger boring productivity factors are common. Hegab (2003) developed a statistical productivity model and classified soil according to its shear strength, in to three categories for micro-tunneling operations using factors stated by Nido (1999) in his research and these factors are listed in Table 2.1.

Table 2.1: Factors Affecting Microtunneling Productivity (Nido, 1999)

Cutter head	Straight vs. curved alignment
Soil condition	Use of lubrication
Separation equipment	Crew/operator experience
Accurate geotechnical investigation	Drive length
Use of intermediate jacks	Pipe section length
Use of high pressure water jets at the excavation face	Pipe material
Obstruction & unusual condition	Shaft design
Groundwater conditions	Technical support
Slurry flow rate	Restrictions to working hours
Rotating cutter torque	Depth of Installation

2.2.1 Crew and Operator Experience

An experienced team of crew and operator can highly affect the productivity rate for pipe jacking tunneling operations (Manabe et al., 1999) the same stands true for box jacking operations. Crew's experience can impact the preparation time and correction time involved in box installation. In other words, the crew's and the operator's skills can directly affect the productivity of the project. Manabe et al. (1999) proposed an automatic direction control technique to reduce the effect of the operator on the machine's performance and the use of this technology should enable an unskilled operator to work with great accuracy (Hegab, 2003).

2.2.2 Restrictions to Working Hours

Productivity loss due to the restrictions in working hours occupy a unique place in the spectrum of claims in construction and are one of the major and unique claims requests sorted by contractors and sub-contractors (Rashad, 2010). In trenchless excavation process it is advised to perform continuous operations and also does not allows for the soil above the box section to settle. By having restrictions to working hours it causes productivity variations

2.2.3 Technical Support

Box jacking can be performed by two different excavation process by hand mining and mechanical excavation method. While performing hand mining it is recommended to have an experienced superintendent or project engineer who could from his experience and technical knowledge guide the crew when encountered with unknown soil conditions or sudden influx of water or to make corrections on grade and line alignment of the line. During mechanical excavation it is recommended to have a representative from the machine manufacturer present on site to provide training and observe the operator's performance (Hegab, 2003). Periodical technical visits by the machine manufacturers are recommended for all projects to ensure quick problem solving (Wilkinson, 1999). Technical support can reduce the number of problems that result from the misunderstanding of the nature of the box jacking equipment. In other words, it impacts productivity indirectly.

2.2.4 Design and Size of the Drive Shaft

The site must provide space for storage and handling of box and spoil and adequate space for the shaft. The size of the jacking shaft is determined by the box segment length, width, height and jacking shield dimensions, jacking system dimensions, thrust wall design, pressure rings, and guide rail system. For example, the drive shaft size for a pipe jacking project using pipe 60 in. in diameter with segments 10 ft in length would require a 12 ft wide and 25 to 32 ft long shaft, depending on selection of jacking and excavation equipment.

2.2.5 Soil Types

During interviews and literature search it was very evident from the responses that type of soil involved during box jacking operation plays a major role in calculating jacking productivity. In this study the soil types were classified as:

1. Non-cohesive soil (soil with very high sand content)
2. Cohesive soil (soil with very high clay content)
3. Mixed soils
4. Fill material
5. Solid rock
6. Boulders & cobbles

The types of soil conditions and their relative parameters are essential decisive success parameter in determining productivity of the box jacking process. Interpreting the soil investigation report and contractor's experience with local soil conditions affects the jacking equipment selection and operation (Koirala, 2001).

2.2.6 Drive Length

In jacking operations drive length is the length or distance a box segments can be jacked or pushed in one pass. It depends on a number of interrelated and variable factors such as the stability and friction characteristics of the geology to be tunneled through, the self-weight and strength of the box segments, its size, the type of excavation method, and the available jacking reaction. The major constraint will be the nature of the ground and the ground water characteristics. However, the distance that can be achieved is optimized by the use of a range of techniques such as use of intermediate jacking stations and use of lubrication during jacking process.

2.2.7 Box Segment Length

Box segment length affects the size of the entry shaft and the preparation time for the entire line. Increasing the box section length increases the diameter, construction time, and construction cost of the shaft. The cost impact may be reduced if fewer box sections are handled. Increasing the box section influences as well the selection of jacks because longer box sections need jacks with a longer stroke. Accordingly, the box section length affects the productivity of the pipe jacking process primarily through preparation time and aligning segments for drilling (Hegab, 2003) the same stands true for box jacking operations.

2.2.8 Geotechnical Investigations

A proper geotechnical investigation would help to determine what type of soil lies along the intended alignment. An accurate geotechnical investigation enables the contractor to select suitable equipment and to select the best arrangement for the box jacking machine to maximize productivity.

2.2.9 Use of Lubrication

Lubrication in the box jacking process is used to reduce or minimize the friction between the box and the soil and to support the annular space around the boxes to prevent ground settlement. Decreasing the friction between the soil and the boxes increases the productivity. Lubrication has several uses that facilitate the box jacking process. It improves the stability of the tunnel face, reduces permeability of soil around the machine, reduces cutting head needed power, and reduces the needed jacking forces (Milligan, 2000). Grout can be either cement or cement bentonite. Any of these two types can be used; but, the second one is preferred for slow setting (Tallard, 1996).

2.2.10 Box Material

Boxes that are used for the box jacking process have special characteristics. These boxes are higher in longitudinal strength compared to traditional box because of the jacking effect during installation. The effect of box material on productivity can also appear in the friction between the box and the soil. However, the lubrication around the box line during the box jacking process minimizes that effect. In other words, there should not be a significant productivity effect due to box material as long as it is fabricated and installed properly. However, projects that use fiberglass box appear to achieve higher production rates than with similarly sized concrete box. This could have occurred due to easier handling of fiberglass pipe and because fiberglass pipe is supplied in longer lengths than other materials (Klein, 1996). The same stands true for boxes.

2.2.11 Shaft Design

Shaft (pit) design includes shaft size, layout, and diameter. Entry and reception shafts dimensions depend on machine size, box dimensions, and site conditions. Shaft dimensions. which typically range from 8 to 20 ft in length or diameter, are minimized to reduce cost and surface disruptions. Research has been conducted to compare the effect of changing the shaft diameter from 14 ft to 8 ft. This change minimized traffic disruption but had an insignificant decrease in overall cost (Lamb et al., 1993).

2.2.12 Using Appropriate Machine Type

The type of machine selected can affect the productivity and the complexity of the operation. Pipe jacking machines is generally either Earth Pressure Balance (EPB) or slurry. EPB machines are less complex but do not perform well below the water table (Hegab, 2003). Slurry machines are complex but can work under the water level. These machines are circular in shape and hence cannot be used for box jacking operations.

2.2.13 Groundwater Conditions

The presence of groundwater influences the decision and construction of shaft design, type of excavation and spoils removal system to be used and depth of installation. Additional grouting around the shaft eye may be needed to reduce groundwater effect when breaking in and out of the entry and the exit shafts (Smith, 2002). Generally, it is recommended to drive with totally wet or dry face because mixed soil disturbs machine performance (Hegab, 2003).

2.2.14 Obstruction or Unusual Soil Conditions

Obstructions, unusual soil conditions such as old foundations or structures or trees, sudden change in soil condition along the bore path are considered unforeseen ground conditions. Unforeseen conditions are challenging to box jacking machines and excavating crew. Accurate and intensive soil investigations can miss some obstructions but reduce the probability of a sudden discovery of them (Brierley et al., 2000; Koirala, 2001; Hegab, 2003).

2.2.15 Depth of Installation

Based on our field observations it was noted that the cycle time associated spoil removal process increases with increase in depth of installation. An increase in the depth of installation can affect the time associated with the construction of the shafts.

2.2.16 Straight and Curved Alignment

Performing box jacking for curved alignment is more technical and time consuming than for a straight alignment. In case of curved alignment special factors such as box joints, and specialized guiding systems are required. As the curvature of bore path and the number of curves along the selected bore path affect the laser guidance (Hegab, 2003). The laser guidance system consists of a mounted laser system on the entry shaft and an electronic target attached at the end of the box jacking machine. In box jacking operations the distortion of the laser line increases significantly because of the curved alignment. Curved alignment also increases the risk of having gaps between boxes allowing water or soil to leak inside the box line, especially with sharp curvatures. Therefore, surveyor's support is needed for every box segment which increases the preparation time. Hence, it is recommended to get the drive or the bore path as straight as possible.

2.2.17 Technical Assistance

Box jacking operation involves lot of complexities hence it is very important to have a team of experts on site such as representative from the machine manufacturer to provide training and observe the operator's performance. Such assistance and support can reduce the number of problems that result from the misunderstanding of the nature of the box jacking equipment. In other words, it impacts productivity indirectly (Hegab, 2003).

2.2.18 Use of Intermediate Jacking Station

Intermediate jacking stations are installed at periodic intervals between the box segments to allow selective propelling of individual segments along the box string. Intermediate jacking stations are used when frictional force or resistance between soils are expected to exceed the capacity of main jacks or the rating of the jacking box. In order to redistribute the total required jacking force on the box line, intermediate jacking stations are frequently used between the launch pit jacking rig and the tunnelling machine. The use of intermediate jacking stations also overcomes excessive the jacking force requirement issue. All the issues impacting box jacking productivity will be ranked and analyzed by using Analytical Hierarchy process.

2.3 Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) is a multi-criteria decision-making method developed by (1989). It is a powerful tool for decision makers to model complex problems in hierarchical structures showing the relationships of the goals, objectives, sub-objectives, and alternatives (Saaty 1980). AHP is composed of several existing concepts and techniques such as hierarchical structuring of complexity, pair wise comparisons, redundant judgments, an eigenvector method for deriving weights, and consistency considerations (Forman and Selly 1999). Forman and Selly (1999) also noted that the power of AHP has exceeded the sum of all the concepts and techniques listed above. It has been applied to solve unstructured problems in a variety of decision-making situations, ranging from simple personal decisions to complex capital-intensive decisions.

The foundation of AHP is the well-defined mathematical structure of consistent matrices and their right-eigenvector's ability to generate true or approximate weights (Mirkin 1979). In a later work by Saaty (1994), he summarized three basic principles behind AHP: decomposition, comparative judgments, and hierarchical composition or synthesis of priorities. The decomposition principle is applied to analyze and decompose a complex problem into a hierarchy of different structures. Then pairwise comparisons are carried out based on comparative judgments principle to evaluate all combinations of elements in a hierarchical structure. The principle of hierarchical composition is applied to compute the 'local' and 'global' priorities of each element (Satty 1994).

In multi-criteria decision-making problems, decision makers meet the challenge of constructing a hierarchy that considers the impact on all objectives. The decision becomes more difficult when the hierarchy of the decision criteria depends on ideas, feelings, and emotions. AHP is a popular way of constructing the hierarchy even when the decision depends on feelings and emotions. AHP provides a quantified numeric scale for prioritizing decision alternatives. A decision-making process starts by establishing the decision objectives and separating them into those that are essential and those that are preferred. This step is followed by eliminating those alternatives that do not meet the essential objectives and evaluating those alternatives that do meet the essential criteria/objectives. AHP can be used to evaluate and rank alternatives that meet the essential requirements. AHP application is simple and can be carried out in four steps:

1. Situation analysis where the problem, the criteria, and the alternatives are identified.
2. Hierarchy design where the elements of the problem are structured into a hierarchy.
3. Evaluation where the overall priority of each alternative is calculated based on a pair-wise weights comparison of the decision criteria.
4. Ranking and decision making based on the results of the previous steps.

According to a comprehensive survey by Zahedi (1986), AHP is suitable for any situation that requires structuring, measurement, and synthesis; therefore, the number and diversity of AHP applications have grown rapidly. An extensive summary of areas of AHP application is summarized below:

- Choice - the selection of one alternative from a given set of alternatives, usually where there are multiple decision criteria involved.
- Ranking - evaluate a set of alternatives with multi-criteria, and sort out an order of alternatives following the general preference from most to least.
- Prioritization/Evaluation – prioritization involves determining the relative weight of a set of alternatives and evaluation means making an estimate or measurement for an alternative. Since it is more difficult to evaluate an alternative with multiple dimensions

than just compare one thing to another, an evaluation is often performed as a prioritization.

- Resource allocation – determining the relative effectiveness of resources toward different objectives of an organization, helping the organization synthesize the often conflicting objectives and subjective information.
- Benchmarking – comparing the processes in one's own organization with those of the best organizations, and finding out how other organizations operate their processes, set the right goals and realize those goals.
- Quality management – dealing with the multidimensional aspects of quality, and providing a way to quantify the qualitative factors.
- Public policy – making competing constituencies regarding to a public policy decision better understand each other, and developing "win-win" solutions.
- Strategic planning – assisting an organization to select the best strategies and allocating relevant resources to implement the chosen strategy.
- Construction Industry - has been used in several applications such as pre-bid qualification (Al-Harbi and Kamal, 2001), selection of delivery methods (Khalil, 2002), conflict resolution (Satty, 1982) and maintenance management (Shen, 1998).

Each application is unique, and, even when the hierarchy can be used in several situations, the evaluation process depends on the situation and the decision maker. The previous applications of AHP in quality management and construction industry provide insights for conducting this research. As factors involved in trenchless construction are multidimensional, AHP is a suitable approach to structure the hierarchical factor elements and measure the relative importance weights for each of them. Also, as some of the factor elements impacting the box jacking construction are subjective, AHP is a good way to quantify these elements. In the next chapter, the structure, function and process of AHP in relation to this study is briefly presented with details for the factors affecting productivity in box jacking trenchless construction.

2.4 Chapter Summary

This chapter provided an introduction to box jacking productivity and provides a literature review on the subject of factors affecting box jacking productivity and Analytical Hierarchy Process (AHP) in general. This chapter covered the various researches that has been conducted previously on ranking of productivity factors and developing of productivity models for various trenchless construction methods. Extensive research has been done on trenchless construction methods, identifying and evaluating issues in installation and their impacts on productivity and it is believed that there is potential in applying AHP to analyze the factors impacting the productivity of trenchless construction methods.

CHAPTER 3

METHODOLOGY

This chapter discusses the research methodology used for identifying and evaluating various issues influencing box jacking productivity. The study involves seven major phases as shown in Figure 3.1. The research methodology layout concocts of the following steps:

1. Performed literature review to find all articles, papers, and previously done research to identify issues affecting box jacking productivity. Also, to find out available techniques to deal with the current research problem.
2. Performed field observations of box jacking projects.
3. Developed questionnaire and sent to selected engineers, various DOT's and box/pipe jacking contractors.
4. Filtered and analyzed data to establish its hold good factor.
5. Ranked and sorted data collected as per their relative importance using Analytical Hierarchy Process (Saaty,1980).
6. Performed quantitative analysis by developing pair-wise comparison matrix. This matrix gives ratio scale (weighting) and a consistency index ratio, in the form of Eigen vectors and Eigen value.
7. Discussed results and specified conclusions and work for future research

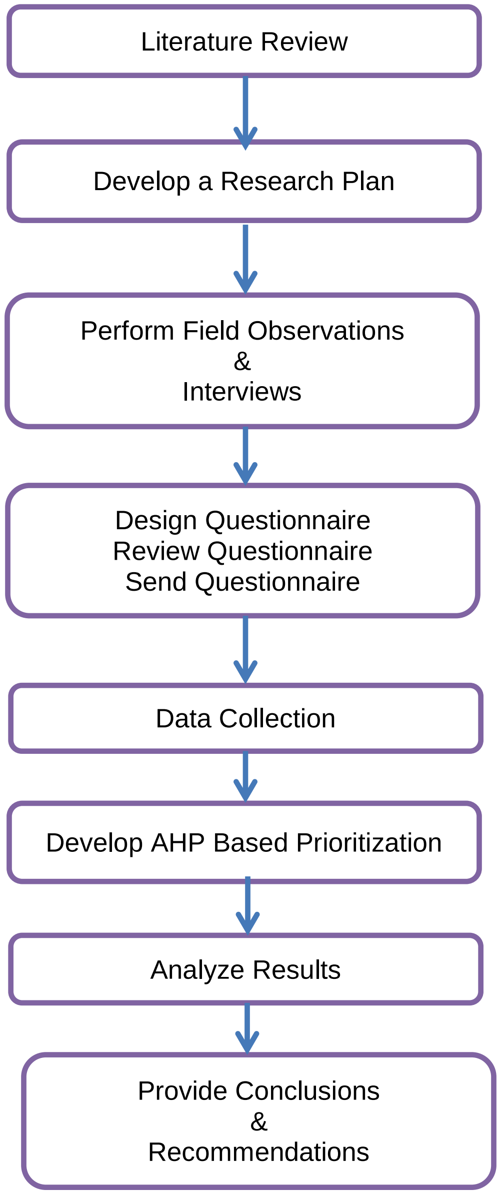


Figure.3.1: Methodology of the Study

3.1 Field Study

Once a detailed literature review was performed it was established that live jacking projects observation are required in order to validate findings from the previous step. The Center of Underground Infrastructure Research and Education (CUIRE) at The University of Texas at Arlington in coordination with the Texas department of Transportation (TxDOT) helped in identifying two culvert jacking projects.

3.2 Case Study I

The first field observation was in Dallas, TX. The Figure 3.2 below shows the site layout of the mentioned project located at the intersection of IH 635 and Josey lane.

Figure.3.2: Site layout at IH 635 and Josey Lane

(Source: Google Maps)

The scope of the project was to jack two pre-cast culverts of dimension 8 x 8 x 6 feet at 32 feet below the surface. The total length of the installation was 132 feet and the spacing between the two culverts was 4 feet. AR Daniel Construction Services, Inc (ARDCS) was the sub-contractors hired to construct the new parallel pre-cast culvert line.

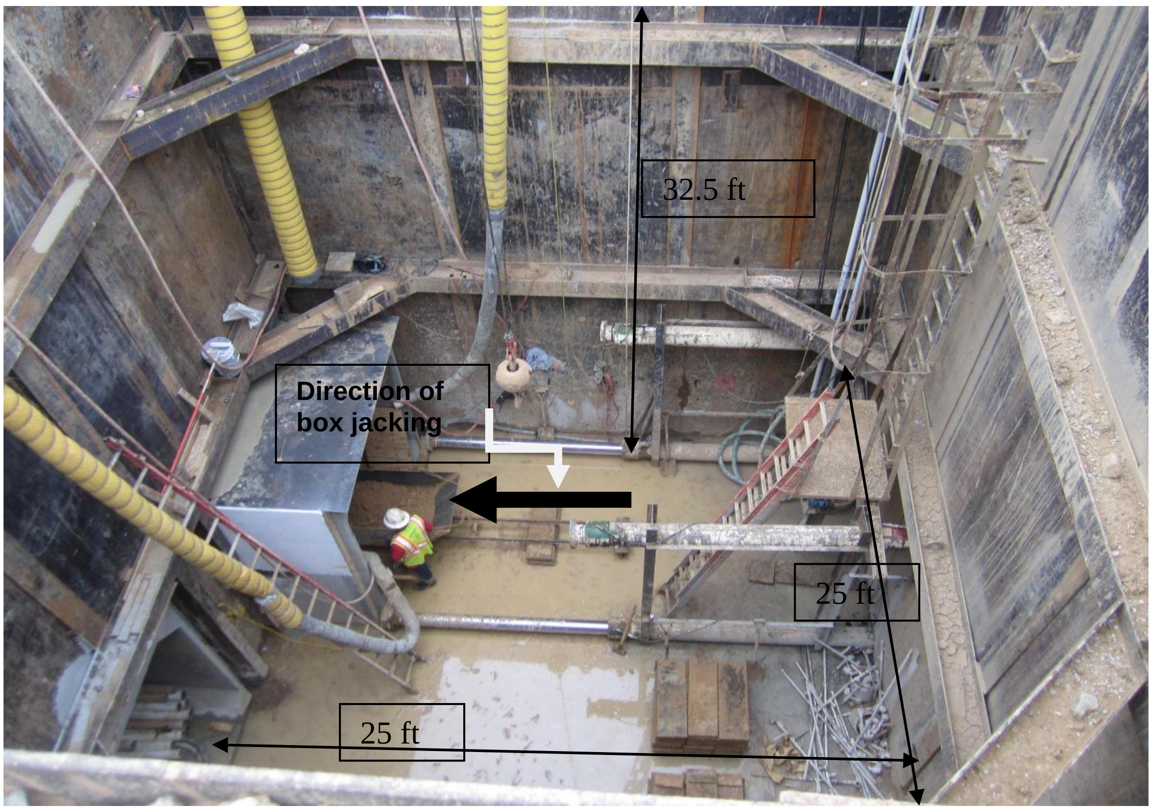


Figure.3.3: Inside View of the Entry Shaft

3.2.1 Working Shaft

Large jacking forces are required to push large culvert sections through unknown ground conditions. The design and construction of the jacking shaft are therefore critical to the success of the project. The dimensions of the entry shat pit, as measured on the site were 25 x 25 feet, with the excavation depth of about 32.5 feet as shown in Figure 3.3. ARDCS used two circular reinforced concrete columns embedded deep into thrust bed as thrust walls. The basic feature of the thrust bed and thrust wall is to provide all necessary reactions needed for resisting the pushing or jacking forces exerted by hydraulic jacks, as the segment is jacked. The front shield which acts as a cutting edge was fabricated from mild steel plates and anchored to the front end of the first unit (header unit). The rear shield which was fabricated from mild steel plates was fixed on the rear ends of the first and remaining units as can be seen in Figure 3.3. Due to the adverse water conditions at the pit, ARDCS installed a de-watering system and pressure collars, and performed grouting of soil where ever needed.

3.2.2 Jacking Operation

We observed large precast segment of 8 x 8 x 6 feet manufactured by Rinker Materials being raised from the ground and carefully placed between the hydraulic jacks and front shield as shown in Figures 3.4 and 3.5 respectively. The first segment was pushed by hydraulic jacks making the front shield to penetrate into the soil; this was followed by manual excavating of the soil at the front shield. As the jacking face was excavated, the soil was transported through the inside of the culvert to the drive shaft, where it was removed and disposed of to the ground surface before the next stage of pushing began.

This process is captured in Figure 3.6 and 3.7 respectively. A team of six labors performed the difficult excavation process using pneumatic and normal shovels. ARDCS used plywood of ¾ inch in thickness as a joint cushion and a polymer modified concrete EVERGRIP 990 as a joint between the segments. After each box segment was installed, the rams of the jacks were retracted such that another segment can be placed in position for the jacking cycle to begin again. Of the four hydraulic jacks, initially only the lower two jacks were used to induce pressure to push the segments into the ground

Figure.3.4: A Segment Being Lifted by Mobile Crane from Ground Surface to be Placed in the Entry Shaft

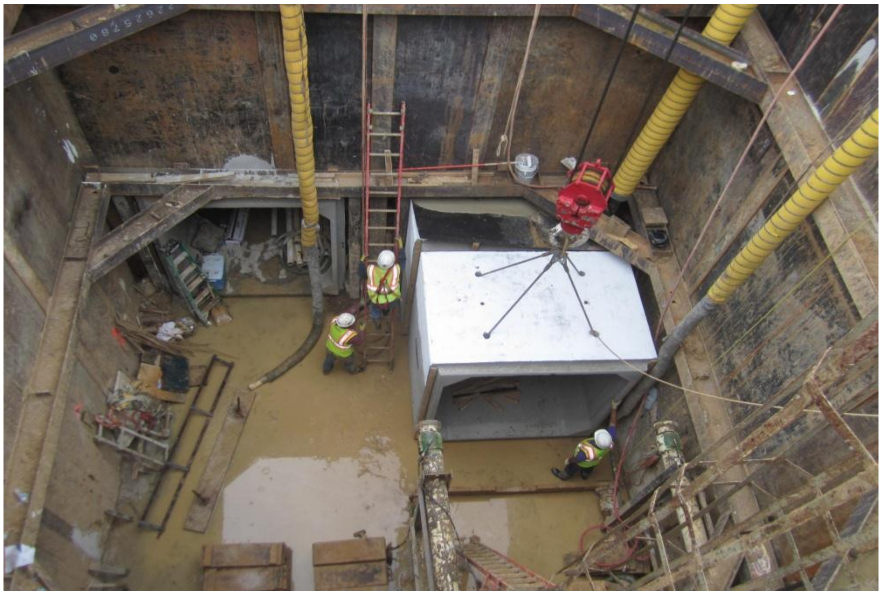


Figure.3.5: Placing Box Segment on the Guide Rails

Figure.3.6: Soil Loaded On a Bucket at the Rear End of the Jacking Pit

Figure.3.7: Bucket Filled with Soil Lifted to be Unloaded at Ground Surface

All four hydraulic jacks will be operational only when the frictional force starts to dominate the working capacity of the lower jacks. Bentonite solution will be used as a lubricating agent to reduce the frictional forces between the soil and the surface. The top half surface of the culvert was coated with plastic paint so that it does not absorb water from the Bentonie solution as shown in Figure 3.5.

The alignment and levels of the jacked boxes were monitored using laser guided system and plumb bob before and after every jacking operation. In case of misalignment, successive corrections were done by steering the hydraulic jacks located at the working shaft. It must be noted that, irrespective of the alignment tolerance limits mentioned in the design guidelines, the ultimate criterion is that the joint deflect must not go above the value used in calculation of box design load.

In total, 44 numbers of segments were installed weighing 11.301 tons each. The jacking forces used for pushing each unit ranged from 50 tons to 531 tons. The average jacking rate during an eight hour shift was 18 feet/shift.

3.2.3 Lessons Learned from Case Study I

Pitching issue of the header unit was one of the main reasons for the loss of productivity on this project. The subsoil at the jacking path was establish to be poor and comprised of mainly soft silty clay. Furthermore, during the jacking operation, the water table was found to be higher than expected level. As a result, ARDCS experienced gradual settlement of the first unit (header unit) during the initial jacking process. In order to maintain the bed level as per the design requirements, a seal slab of 2 inch concrete bed was laid to maintain the bed level as shown in Figure 3.8 and Refer Figure 3.9 for wooden pilot tunnel section detail. ARDCS stated that this method solved the problems of pitching and settlement of culvert and also acted like a guiding rail system.

Figure 3.8: Concrete Bed (Mat) Laid to Maintain Design Bed Level

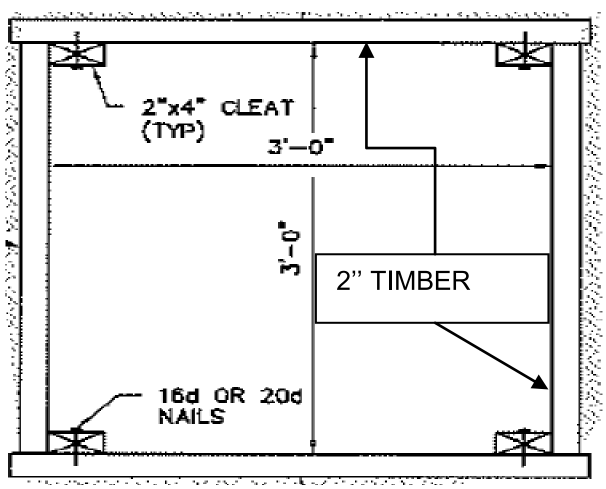


Figure.3.9: Wooden Pilot Tunnel Section

(Source: Stiver Engineers)

3.2.4 Issues Found - Ground Movement Issue at Pavement

During culvert jacking, ground movement can occur due to instability of the face or from elastic unloading of ground caused by excavation. Any tunneling method will create ground movement, which may be significant or trivial. The parameters which govern the soil movement are depth, sub–soil condition, location, type of bracing system used, water intrusions, and the skill set of the construction team must also be taken into consideration.

When asked what type of ground movement can be expect and what movement are accepted ARDCS, from his 30 years of experience in culvert jacking, pointed that 80% of the ground movement he had witnessed was settlement; and the heaving of pavement he had witnessed was due to dragging of soil at the top span of the culvert and the acceptable limits of ground movement are generally stated in the specifications.

3.3 Case Study II

The second field observation was performed in Vernon, TX. The Figure 3.11 below shows the site layout of the mentioned project located on highway embankment of US 287.

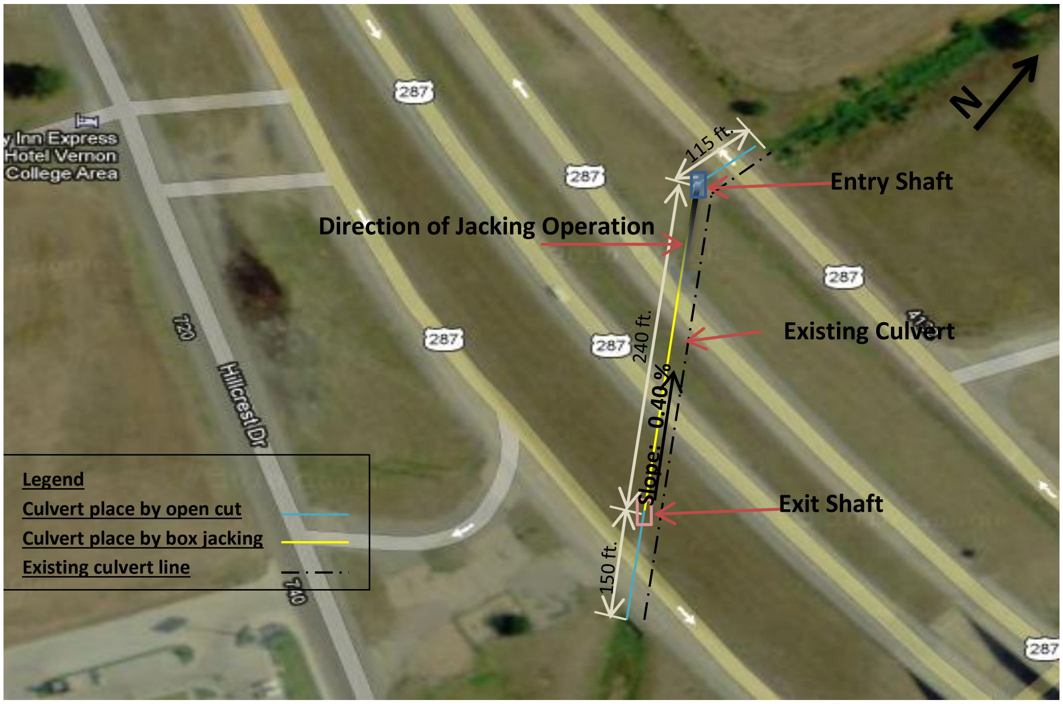


Figure.3.10: Site layout at US 287, Vernon TX

(Source: Google Maps)

The scope of this project was to install/jack 240 feet of 6 by 4 by 7 feet pre-cast box culvert segments and lay 265 feet of 6 by 4 by 7 by feet pre-cast box culvert segments by open cut method. The purpose of this project was to alleviate the flood problem. Three rows of 6 by4 feet drainage culverts were previously constructed and a need to install another 6 by 4 feet culvert by jacking method to facilitate the flow of back water was identified. To check the existing soil information three borehole geotechnical investigations were performed.

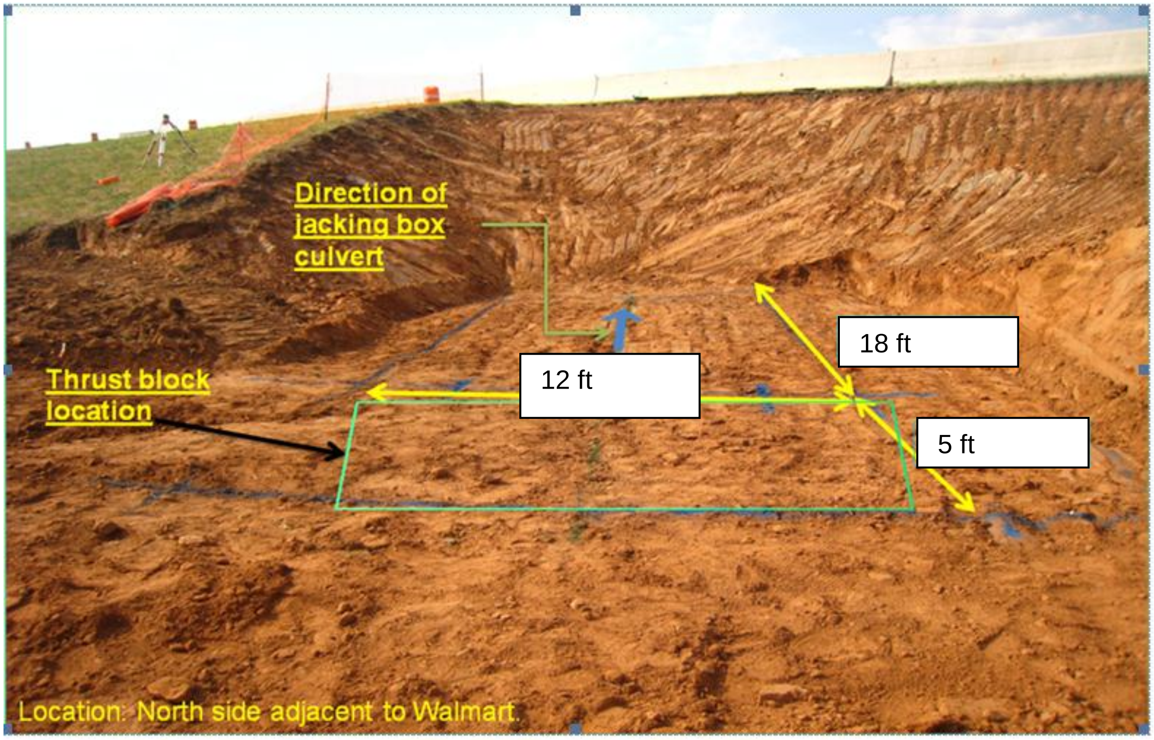


Figure.3.11: Layout for Entry Shaft Top Base Preparation (Phase-1)

The construction process started with preparation of entry shaft at the north side of the project. The entry shaft preparation was divided in two phases. First phase involved embankment excavation and marking the area to be dug in second phase. As shown in total as show in Figure. 3.11. A part of the first phase also involved preparation of thrust block, the purpose of thrust block is to provide support against the force exerted by hydraulic jacks to jack culvert segments into place behind the jacking shield. After the preparation of the thrust block is completed the second phase of entry shaft preparation began where a trench is placed on the entry shaft location and systematically a pit is dug of 18 x 12 x 12 feet in dimension. Once the entry shaft is excavated and leveled two guide rails are set up over wooden block as shown in the Figure 3.12 entry shaft is excavated.

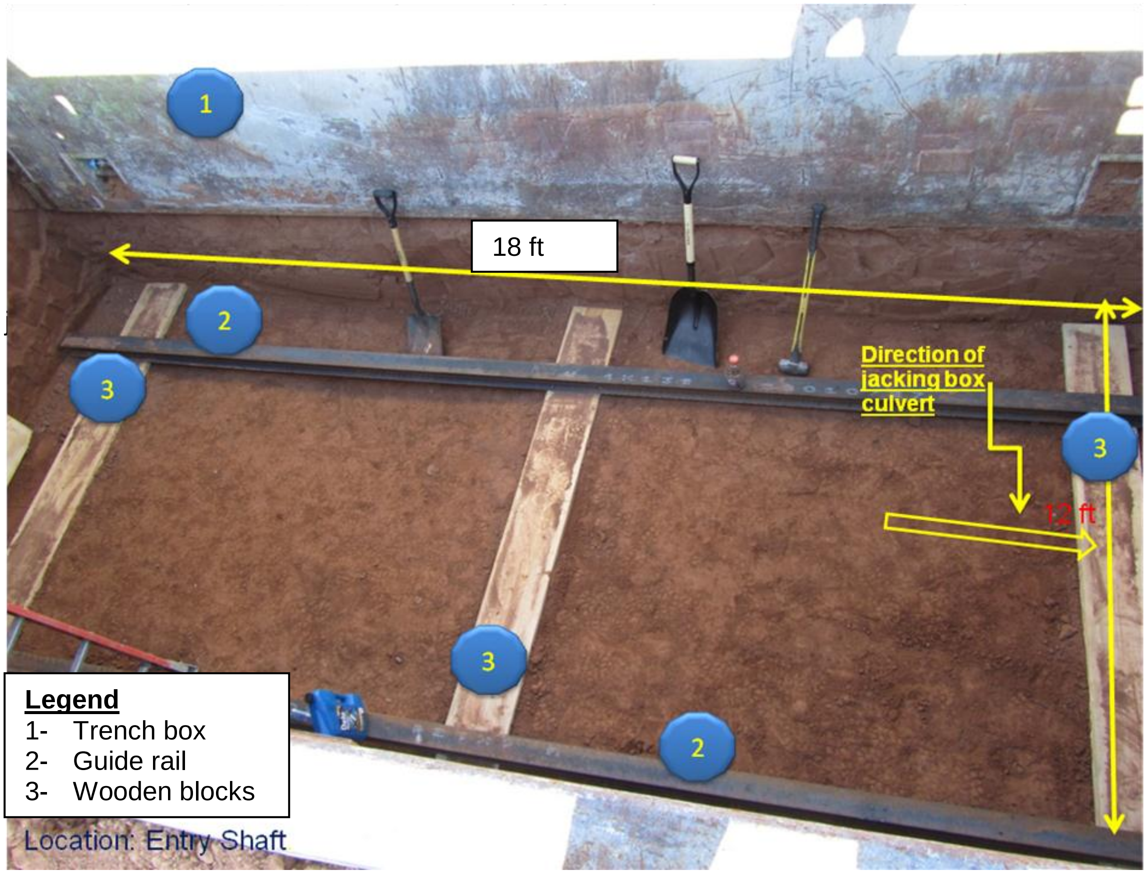


Figure.3.12: Layout For Entry Shaft Bottom Base Preparation (Phase-2)

Once the sub-base or the bottom base of entry shaft is leveled and cleaned concrete was poured to create an 8 inch slab as shown in Figure 4.4. The embedded rails inside the concrete slab are used to set line and grade of the culvert.

Figure.3.13: Concrete Slab Being Prepared at the Entry Shaft (Phase-2)

After the construction of entry shaft a laser guidance system was installed as shown in Figure 3.14 and Figure 3.15 for a close-up view and point of reference was established to maintain a continuous check on the line and grade of the subject culvert line. The completion of previous steps initiates the cyclic procedures in box jacking process. Where a pre-cast culvert is hoisted and transported towards the entry shaft and then lowered into the entry shaft where two helpers guide into the jacking direction this process is shown in Figure 3.16 and Figure 3.17 respectively.

Figure.3.14: Laser Guidance System Can Be Seen Here In the Yellow Circle

Figure.3.15: Close-Up View of Laser Guidance System

Figure.3.16: Excavator Is Lifting a Culvert and Transporting It to the Entry Shaft

Figure.3.17: Excavator Lowers the Into the Entry Shaft and Two Helpers Guide the Into the Jacking Direction

In the next step a jacking frame was hosted into the entry shaft pit and placed in indirect contact with the box to be jacked. Wooden frames are installed between the jacking frame and culvert to avoid direct contact as shown in Figure 3.18. The purpose of jacking frame is to transfer thrust loads applied by jacks to the box and to ensure the jacking force is distributed equally throughout the entire diameter of the jacked box.

Figure.3.18: Excavator Lowers the Into the Entry Shaft and Two Helpers Guide Box Culvert into the Jacking Direction

Once the jacking frame is in place hydraulic jacks are then activated to push forward the segments into the soil. This step initiates the spoil removal process which is similar to the spoil removal process explained for Dallas project located at the intersection of IH 635 and Josey lane case study. In total, 34 numbers of segments were installed. Intermediate jacking station were used to keep the total jacking force below 700 tons and placed between 7th and 8th box culvert segments. The jacking forces used for pushing each unit ranged from 50 tons to 578 tons. The average jacking rate during an eight hour shift was approximately 16 feet/shift. It took 56 days for successful completion for this box jacking project.

3.3.1 Lessons Learned from Case Study II

Initially the project was anticipated to finish in 36 days but it got delayed as the subsoil at the jacking path was established to be poor which caused pitching and settlement of culvert segments. A special wooden pilot tunnel was constructed as shown in shown in Figure 3.10 in order to maintain the bed level as per the design requirement. An interesting contrast between the projects was that, despite the difference in the installation depth and the difference in the size of the culvert, the actual rate of installation of culvert were measured to be same.

3.3 Case Study Summary

Based on the data collected from the above field observations, research studies and interaction with professionals involved in box jacking operations few more issues were identified which substantially played a major role in box jacking operations. The factors affecting micro-tunneling productivity identified by Nido (1999) and Hegab (2003) were further tailored as per the requirements and suggestions from the industry professionals and this resulted in addition of six new issues. The issues were further sub-categorized in five divisions as shown in Table 3.1:

- General factors
- Soil types & soil related factors
- Surface establishment factors
- Box dimension factors
- Box installation factors

Table 3.1: Issues Impacting Box Jacking Productivity

Division	No.	Issues
General factors	1	Crew/ operator experience
	2	Restrictions to working hours
	3	Technical assistance
Surface establishment factors	4	Traffic control
	5	Safety and security
	6	Availability of box storage & handling
	7	Type of spoil removal system
	8	Availability of grade & line control system
	9	Availability of box jacking load monitoring equipment
Soil related factors	10	Ground water condition
	11	Friction force
	12	Drive length
	13	Obstruction or unusual soil conditions
	14	Availability of soil investigation report
	15	Type of Soil
Box dimensions	16	Box material
	17	Shape of box
	18	Size of box
	19	Weight of box
	20	Box segment length
Box installation factors	21	Depth of installation
	22	Type of joint between boxes
	23	Straight alignment
	24	Curved alignment
	25	Use of intermediate jacking station
	26	Use of lubrication
	27	Shaft design (size, layout, structural integrity)

3.4 Dependency between Factors

The dependency amongst the different factors influencing box jacking productivity was evaluated to gain an understanding of the relationships and interdependencies between the different factors. The dependency amongst factors was not considered in their ranking. This interdependency is one of the major challenges in modeling the productivity of box jacking operation. For better understanding of the effects of the factors mentioned earlier on productivity, the survey participants were asked to provide their expert opinion on the relationships and dependencies of the various factors on each other.

In this research, AHP used a three level hierarchy based model that aligned the factors impacting productivity of box jacking operation as shown in Figure 3.19. The hierarchy was arranged in a descending order from the overall goal to the criteria, and then sub-criteria. The hierarchy was then symmetrically evaluated using pairwise comparisons of various criteria, matrix manipulation and eigenvalue computation to obtain a final score for each of the alternatives. AHP provided a systematic methodology to organize tangible and intangible factors and provided a structured, yet relatively simple, analysis algorithm to the decision making problem (Yang and Allouche, 2010).

Based in the characteristics of the factors, level 1 of AHP consisted of two parts: soil and ground related factors and box related factors. The soil and ground related factors included three parts as level 2, namely Soil Related Factors, Surface Establishment Factors, and General Factors. The box related factors were sub-categorized as box dimensions and box Installation Factors as of the level 2 categories. Level 3 was formed by 27 factors from the inventory dataset. Figure 3.19 and Table 3.2 and 3.3 show the structure of the AHP including abbreviations for each factor.

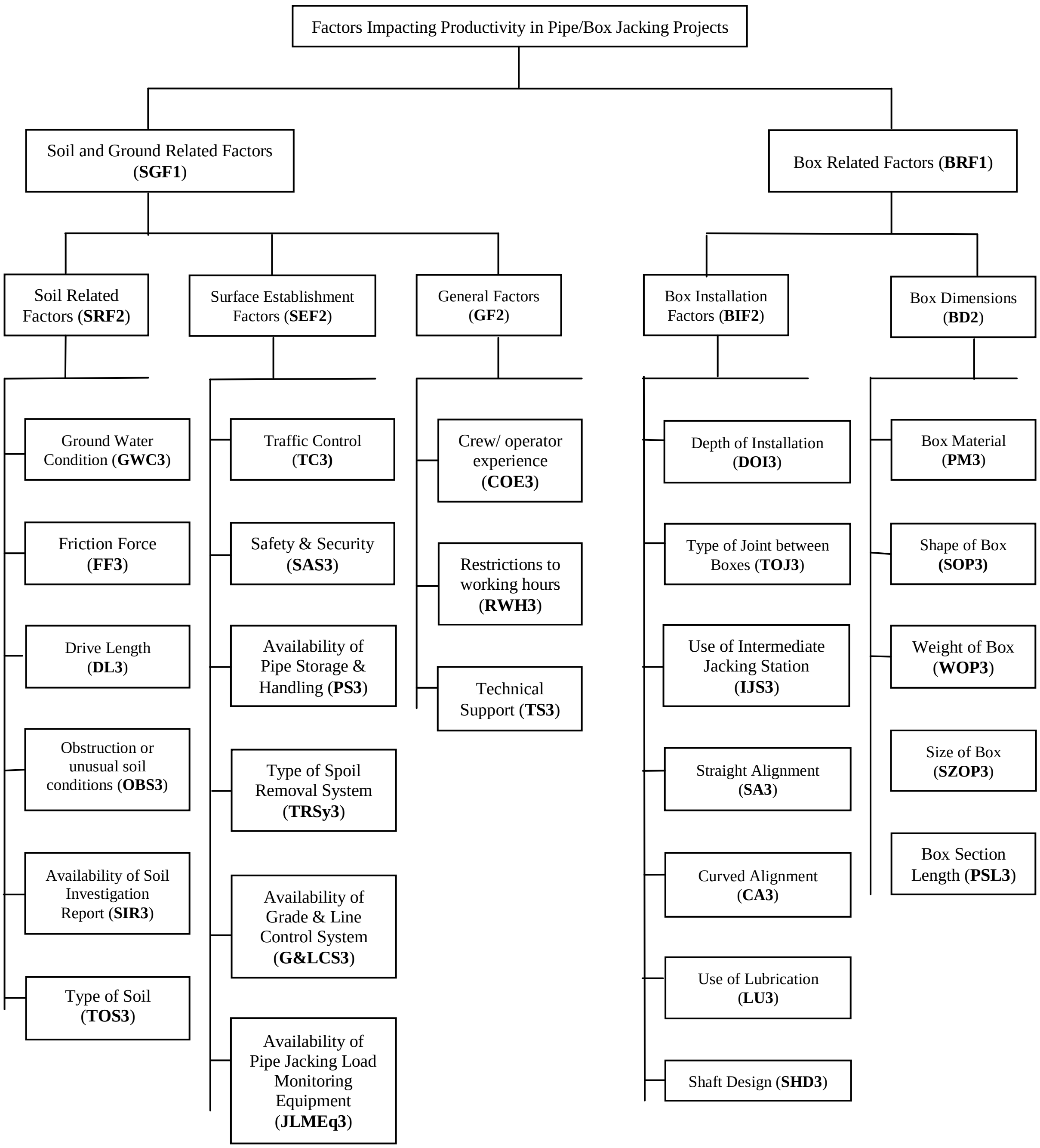


Figure 3.19: AHP for Rating Issues Impacting Box Jacking Productivity

Table 3.2: Definitions for the Rating Scale Used for Pairwise Comparison

AHP Level1	Division	No.	Issues	Abbreviations	AHP Level
Soil & ground related factors (**SGF**1)	General factors (**GF2**) AHP level 2	1	Crew/ operator experience	COE3	3
		2	Restrictions to working hours	RWH3	3
		3	Technical Support	TS3	3
	Surface establishment factors (**SEF2**) AHP level 2	4	Traffic control	TC3	3
		5	Safety and security	SAS3	3
		6	Availability of box storage & handling	PS3	3
		7	Type of spoil removal system	TSRSy3	3
		8	Availability of grade & line control system	G&LCS3	3
		9	Availability of box jacking load monitoring equipment	JLMEq3	3
	Soil related factors (**SRF2**) AHP level 2	10	Ground water condition	GWC3	3
		11	Friction force	FF3	3
		12	Drive length	DL3	3
		13	Obstruction or unusual soil conditions	OBS3	3
		14	Availability of soil investigation report	SIR3	3
		15	Type of soil	TOS3	3

Table 3.3: Definitions for the Rating Scale Used for Pairwise Comparison

AHP Level1	Division	No.	Issues	Abbreviations	AHP Level
Box related factors (**PRF**1)	Box Dimensions **(PD2)** AHP level 2	16	Box material	PM3	3
		17	Shape of box	SOP3	3
		18	Size of box	SZOP3	3
		19	Weight of box	WOP3	3
		20	Box section length	PSL3	3
	Box Installation Factors **(PIF2)** AHP level 2	21	Depth of Installation	DOI3	3
		22	Type of joint between boxes	TOJ3	3
		23	Straight alignment	SA3	3
		24	Curved alignment	CA3	3
		25	Use of intermediate jacking station	IJS3	3
		26	Use of lubrication	LU3	3
		27	Shaft design (size, layout, structural integrity)	SHD3	3

3.5 Industry Survey

Questionnaires are a helpful method of collecting a wide range of information from large number of respondents. To rank the identified issues affecting box jacking productivity a survey questionnaire was designed. The following steps were followed in developing the questionnaire:

- Read books and articles on how to develop questionnaire
- Determined the type of data we need
- Established goals and objectives of the survey
- Choose the type of questions to be asked
- Design the layout (introduction & sequence) of the questionnaire
- Test the questionnaire and improvise suggestions
- Check quality of respondents

Refer to Appendix A for the questionnaire. The objective of this questionnaire was to understand the productivity issues faced by the professionals involved in pipe/box jacking operation and to rank them as per their experience and opinion. The survey was distributed to engineers, owners, contractors, and sub-contractors who are experts in the field of pipe/box jacking operation and the participants were requested to investigate the factors that influence the pipe/box jacking operation. The main purpose of the survey was to identify and rank the factors affecting the productivity of box jacking operation by importance and to also determine their interdependency based on the expert opinion of engineers, contractors, and practitioners in the industry. This knowledge is expected to help in improving the productivity of the box jacking construction process through planning and execution of a more efficient construction operation.

The questionnaire was divided into five sections. The first section contained questions about respondent's contact information and experience in the industry. The second section asked the respondent about their preferred methods of evacuation and installation and their operation productivity factors. In the third section, the respondents were asked to rank the various productivity related factors. The fourth section asked the respondents to investigate the possible dependency amongst the various box jacking productivity related factors. The final section addressed the favorable soil conditions for the box jacking operation.

The responses from the survey have been analyzed and reported under five categories that illustrate the physical and industry demographics of respondents, use of excavation methods in the industry, ranking of factors affecting productivity, dependency among the factors, and favorable soil conditions.

3.5.1 General Survey Results

The survey form was sent to 42 experts and practitioners via e-mails and Linkedin. The general response rate was 24%. The Figure 3.20 below shows responses from the survey.

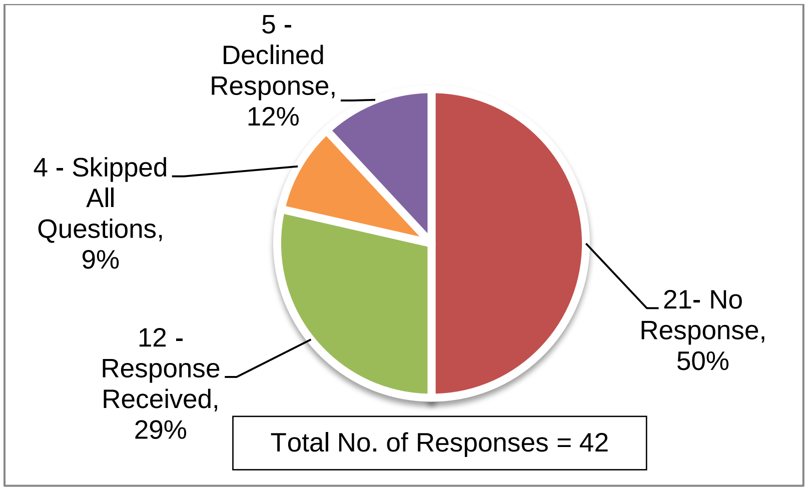


Figure 3.20: Responses from Survey

3.5.2 Physical and Industry Demographics

The survey respondents were spread across 8 states across the United States as shown in Figure 3.21. The survey respondents were from various levels in the trenchless construction industry and sampled from a vast range of industry experience, from 1 to 30 in terms of years and have together performed over 600,000 linear feet of pipe jacking operation. The distribution of level of survey participants is represented in Figure 3.22 and the range of experience is illustrated in Figure 3.23 (a) and 3.23 (b).

Figure 3.22: Map of United States indicating Survey Respondent's Location.

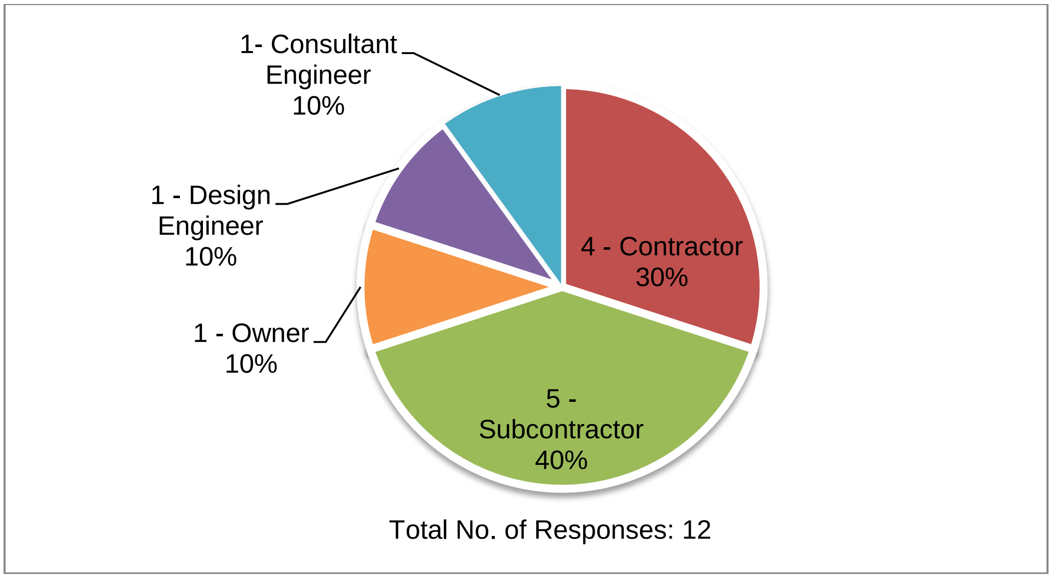
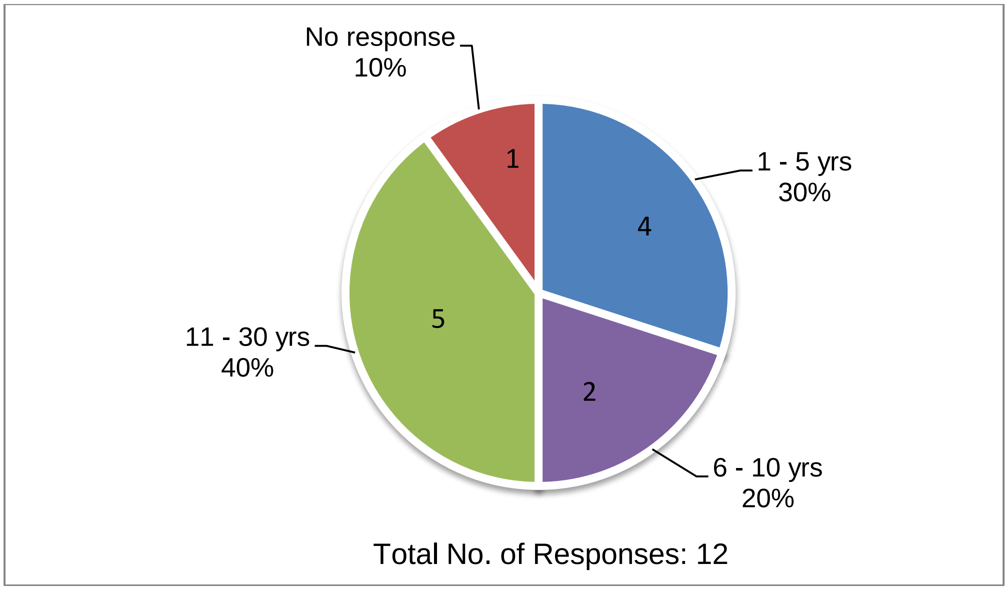
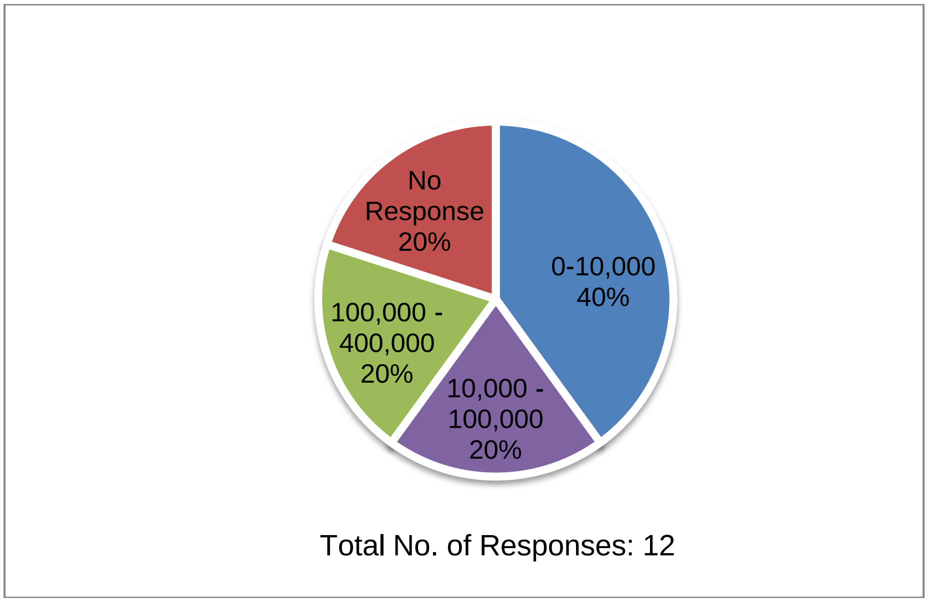


Figure 3.22: Distribution of Survey Respondents



(a)



(b)

Figure 3.23: Distribution of Experience Range of Survey Respondents
(a) By years of relevant experience (b) By linear feet pipe jacking operation performed

3.5.3 Box Installation

The survey results demonstrated that circular pipe installation and rectangular box installation are used in conjunction during pipe installation operation, but more than two-thirds of the installation is circular. A vast majority (89%) of the respondents also indicated that circular pipe installation is more productive than rectangular box installation as the circular pipe installation reduces the risk of skin friction by providing a natural shape to support top of excavation until the pipe jacking operation is completed. It also helps in spoil removal during mechanical excavation. The results from the survey can be seen in Figure 3.25.

Table 3.4 describes the responses from the survey participants when asked to provide the pipe (box and circular sections) installation average productivity for your operation in feet per shift for each of the excavation methods.

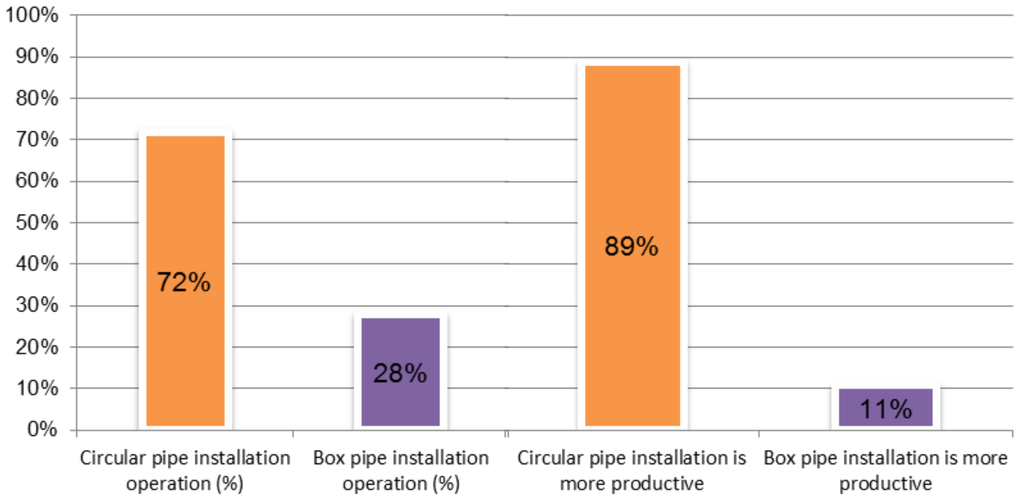


Figure 3.24: Comparison of Circular pipe and Rectangular Box installation

(Based on Individual Responses)

Table 3.4: Survey Responses about Productivity of Pipe Jacking Operations

(Based on Individual Responses)

Type of Soil Condition	Type of Excavation Process Used	Depth of Installation (ft)	Length of Installation (ft)	Shape of Pipe	Average Productivity (ft/shift)
Fill material	Hand Mining	10 ft - 15 ft	161 - 250 ft	Circular	30
Non-cohesive soil	Hand Mining	10 ft - 15 ft	61 - 100 ft	Box	20
		7 ft	161 - 250 ft	Circular	17
		10 ft - 15 ft	> 250 ft	Box	16
Cohesive soil	Hand Mining	10 ft - 15 ft	> 250 ft	Box	18
	Mechanical Excavation	10 ft - 15 ft	61 - 100 ft	Circular	50
Mixed phase	Mechanical Excavation	31 ft - 35 ft	> 250 ft	Circular	> 52
Non-cohesive soil	Mechanical Excavation	16 ft - 20 ft	> 250 ft	Circular	> 52
		10 ft - 15 ft	> 250 ft		
		10 ft - 15 ft	161 - 250 ft		

Note: Each shift is 8 hours

3.5.4 Ranking of Issues

The survey participants were asked to rank the importance of each issue on the basis on their impact on productivity on a scale of 1 to 5, with a weight of 5 meaning maximum impact and weight of 1 meaning no impact. The rank for each of the issue was obtained by taking a Rating Average of responses for each of the factor.

$$\overline{x_j} = \frac{\sum_{i=1}^{n_j} w_1^5 x_{ijw}}{n_j} \qquad [3.1]$$

where,

$\overline{x}_j$ = Rating Average for j th factor.

n_j = Total number of responses for the j th factor.

w_1^5 = Rating scale from 1 to 5.

x_{ijw} = Number of responses with rating w for the j th factor.

To represent the variance in expert opinions, the Mean Deviation was used. The Mean Deviation is defined as the mean of the absolute deviations of a set of data about the data's mean. Mean Deviation is used to represent the average variation of the responses from the mean.

$$MD_j = \frac{\sum_{i=1}^{n_j} |x_{ij} - \overline{x_j}|}{n_j} \qquad [3.2]$$

where,

MD_j = Mean Deviation for j th factor.

x_{ij} = Response of i th participant for j th factor.

$\overline{x}_j$ = Rating Average for j th factor.

n_j = Total number of responses for the j th factor.

The Mean Deviation was preferred in this case since we are only interested in the deviations of the rating and not whether they are above or below the mean score. The results of equations [3.1] and [3.2] are represented in Table 4.2.

3.5.5 Response Analysis using Pairwise Comparisons

Based on the questionnaire, the pairwise computations were applied to process the received responses. Each of the Level 1, Level 2, and Level 3 factors were compared pairwise against each other with respect to the goal based on the scale shown in Figure 4.1 and rating scale as defined in Table 4.5. The total number of comparisons for each of the AHP Level is derived from the formula in Equation 3.3 and detailed in Table 3.5.

$$Number\ of\ Pairwise\ comparisions = C(n,k) = n!/(k!\,(n-k)!) \qquad [3.3]$$

where, n is the number of factors being compared.

Table 3.5: Total Number of Pairwise Comparisons for AHP

AHP Level	Sub - Level	# of Factors	# of Comparisons
1	1	2	1
Total			**1**
2	1-1	3	3
	2-1	2	1
Total			**4**
3	1-1-1	3	3
	1-1-2	6	15
	1-1-3	6	15
	2-1-1	7	21
	2-1-2	5	10
Total			**54**
Total Number of Comparisons			**59**

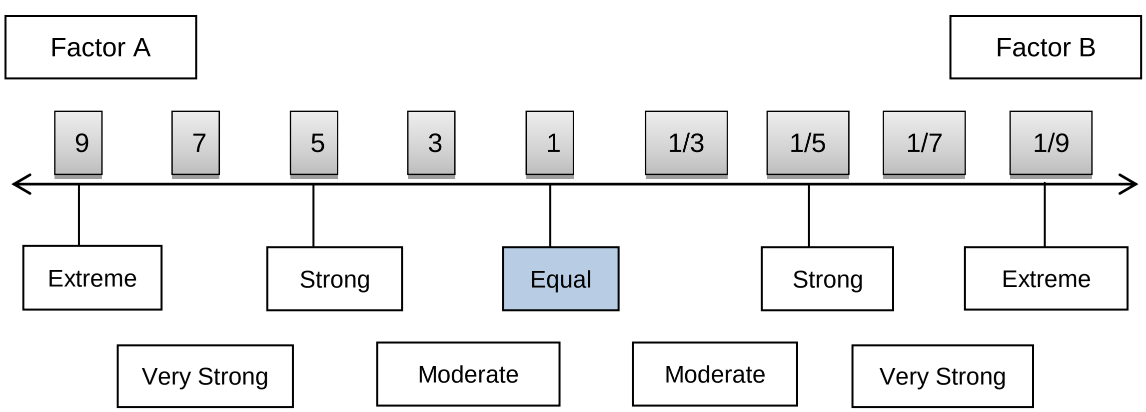


Figure 3.25: Scale for Pairwise Comparison in AHP

Table 3.6: Definitions for the Rating Scale used for Pairwise Comparison

Rating	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one element over the other
5	Strong importance	Experience and judgment strongly favour one element over the other
7	Very strong importance	One element is favoured very strongly over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation

3.5.6 Weights and Consistency Ratio Calculations

To calculate the weight of each factor, the pairwise comparison ratings are arranged in a $N = \mathrm{n\,X\,n}$ matrix and the Eigen Vector of the matrix is computed using the steps defined below:

Matrix N for n=3 factors,
$$\begin{bmatrix} 1 & a_{12} & a_{13} \\ a_{12}^{-1} & 1 & a_{23} \\ a_{13}^{-1} & a_{23}^{-1} & 1 \end{bmatrix} \qquad [3.4]$$

Sum of Columns $\quad S_{C1} \quad S_{C2} \quad S_{C3}$

The matrix N is then normalized to $|\boldsymbol{N}|$ using Equation 3.5 and the first normalized principal **Eigen Vector $\boldsymbol{X1}$** is calculated using the Equation 3.6 below:

$$|\boldsymbol{N}| = \begin{bmatrix} \frac{1}{S_{C1}} & \frac{a_{12}}{S_{C2}} & \frac{a_{13}}{S_{C3}} \\ \frac{a_{12}^{-1}}{S_{C1}} & \frac{1}{S_{C2}} & \frac{a_{23}}{S_{C3}} \\ \frac{a_{13}^{-1}}{S_{C1}} & \frac{a_{23}^{-1}}{S_{C2}} & \frac{1}{S_{C3}} \end{bmatrix} \quad \boldsymbol{X1} = \begin{bmatrix} \frac{\sum row_1}{n} \\ \frac{\sum row_2}{n} \\ \frac{\sum row_3}{n} \end{bmatrix} \qquad [3.5 \text{ and } 3.6]$$

Next, normalized matrix $|\boldsymbol{N}|$ is squared and the next iteration of Eigen Vector $\boldsymbol{X2}$ is calculated until the difference $\boldsymbol{X_{k+1}} - \boldsymbol{X_k}$ is negligible.

$$X_2 \rightarrow |\boldsymbol{N}|^2 \qquad [3.7]$$

Next, the largest **Eigen Value $\boldsymbol{\lambda_{max}}$** is calculated using Equation 3.8 (Saaty, 1980).

$$\boldsymbol{\lambda_{max}} = \boldsymbol{S_{C1}.x_1} + \boldsymbol{S_{C2}.x_2} + \boldsymbol{S_{C3}.x_3} \qquad [3.8]$$

If $\lambda_{\max} = n$, then the judgments have turned out to be consistent. The difference between $\lambda_{\max}$ and $\mathbf{n}$, if any, is an indication of the inconsistency in the judgments. A Consistency Index **CI** is calculated using the Equation 3.9 (Saaty, 1980).

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad [3.9]$$

Finally, a Consistency Ratio **CR** is calculated using the Equation 3.10 (Saaty, 1980) by dividing the Consistency Index for the set of judgments by the index for the corresponding Random Matrix as defined by Saaty. The values of Random Index **RI** are listed in Table 3.7.

$$Consistency\ Ratio\ (\boldsymbol{CR}) = \frac{Consistency\ Index\ (\boldsymbol{CI})}{Random\ Index\ (\boldsymbol{RI})} \qquad [3.10]$$

Table 3.7: Random Index (RI) Values As Computed By Saaty (1980)

n	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

Saaty suggests that if the Consistency Ratio exceeds 0.1, the set of judgments may be too inconsistent to be reliable. A CR of 0 means that the judgments are perfectly consistent. As a rule of thumb CR <= 0.1 indicates sufficient consistency.

3.6 Chapter Summary

This chapter presented a detailed explanation on the seven major stage research methodologies conducted for this study. The first part included literature search. The second part involved development of research plan. The third part included design of a survey questionnaire that was sent to pipe/box jacking experts. Finally, the use of Rating Average and AHP to rank issues affecting box jacking productivity and general survey results were discussed. Figure 3.1 shows a flowchart of the research methodology.

CHAPTER 4

RESEARCH RESULTS

This chapter summarizes the results of the research conducted for the purpose of this thesis to understand in depth the factors affecting productivity of box jacking including the dependency among these factors.

4.1 Case Study Results

Based on the data collected from the above field observations and interaction with professionals involved in box jacking operations six new issues were identified which substantially played a major role in box jacking operations

Table 4.1: Definitions for the Rating Scale used for Pairwise Comparison

Division	No.	Issues
Surface establishment factors	1	Traffic control
	2	Safety and security
	3	Availability of box storage & handling
	4	Type of spoil removal system
Box dimensions	5	Size of box
	6	Weight of box

4.2 Ranking of Issues

Based on the data collected from the survey questionnaire sent to various professionals involved in box jacking operations it was found that type of soil, shaft design and use of intermediate jacking stations were the top three major factors influencing box jacking as shown in Figure 5.1.

4.3 Pairwise Comparison

Based on the questionnaire, pairwise computations were applied to process the received responses, and the weights obtained from the calculations using for each of the factors in AHP are shown in the Table 4.2 and Table 4.3 respectively.

Table 4.2: Rating and Weights of Factors for in AHP

(Based on Individual Responses)

AHP Level	Factor	Abbr	Global Weight (%)	Local Weight (%)
Level 1	Box related factors	PRF1	12.5	12.5
	Soil and ground related factors	SGF1	87.5	87.5
	Total		**100%**	**100%**
Level 2	General factors	GF2	38.09	43.53
	Soil related factors	SRF2	42.61	48.69
	Surface establishment factors	SEF2	6.81	7.78
	Total		**87.5% = SGF1**	**100% = SGF1**
	Box installation factors	PIF2	10.42	83.33
	box dimensions	PD2	2.08	16.67
	Total		**12.5% = PRF1**	**100% = PRF1**
Level 3	Crew/ operator experience	COE3	30.43	79.91
	Restrictions to working hours	RWH3	3.99	10.47
	Technical support	TS3	3.67	9.62
	Total		**38.09% = GF2**	**100% = GF2**
	Traffic control	TC3	0.25	3.73
	Safety and security	SAS3	0.24	3.51
	Availability of box storage & handling	PS3	0.82	11.99
	Type of spoil removal system	TSRSy3	3.52	51.64
	Availability of grade & line control system	G&LCS 3	1.73	25.39
	Availability of box jacking load monitoring equipment	JLMEq3	0.25	3.73
	Total		**6.81% = SEF2**	**100% = SEF2**

Table 4.3: Rating and Weights of Factors for in AHP

(Based on Individual Responses)

AHP Level	Factor	Abbr	Global Weight (%)	Local Weight (%)
Level 3	Ground water condition	GWC3	1.52	3.58
	Friction force	FF3	1	2.34
	Drive length	DL3	4.78	11.22
	Obstruction or unusual soil conditions	OBS3	12.21	28.65
	Availability of soil investigation report	SIR3	10.42	24.45
	Type of soil	TOS3	12.68	29.76
	Total		**42.61% = SRF2**	**100% = SRF2**
	Box material	PM3	0.07	3.36
	Shape of box	SOP3	1.07	51.49
	Size of box	SZOP3	0.38	18.42
	Weight of box	WOP3	0.11	5.13
	Box Section length	PSL3	0.45	21.59
	Total		**2.08% = PD2**	**100% = PD2**
	Depth of installation	DOI3	0.26	2.46
	Type of Joint between boxes	TOJ3	0.24	2.34
	Straight alignment	SA3	0.39	3.76
	Curved alignment	CA3	1.11	10.68
	Use of intermediate jacking station	IJS3	2.35	22.58
	Use of lubrication	LU3	3	28.77
	Shaft design (size, layout, structural integrity)	SHD3	3.06	29.41
	Total		**10.42% = PIF2**	**100% = PIF2**

4.4 Favorable Soil Conditions

The survey participants were asked to rank the types of soil from 1 to 5 in terms of their favorability for pipe/box jacking operation with 1 being least favorable and 5 being most favorable in order to determine the overall favorable condition. The average rating of the soil types from the survey results is demonstrated in the Table 4.4 below.

Table 4.4 Favorable Soil Type With Respect to Jacking Operation

(Based on Individual Responses)

Soil Type	Rating Average	Mean Deviation
Non-cohesive soil	4.4	0.78
Cohesive soil	3.9	0.31
Mixed soils	3	0.45
Fill material	2.3	0.33
Solid rock	1.2	0.28
Boulders & cobbles	1.2	0.28

4.5 Chapter Summary

This chapter summarized the results on the data collected in identifying issues affecting productivity of box jacking projects. It aims to provide an overall understanding of the characteristics if the data.

CHAPTER 5

DISCUSSION OF RESULTS

This chapter briefly explains the results on the research conducted by the medium of case studies and survey questionnaire for the purpose of this thesis to understand in depth the issues affecting productivity of box jacking including the dependency among these factors.

5.1 Factors Influencing Box Jacking Productivity

Based on the literature review, field observations and interviews with experts in the field of pipe/box jacking twenty seven factors that impact the productivity of pipe/box jacking operations were consolidated in the questionnaire. The survey participants were asked to rank the importance of each factor on the basis on their impact on productivity on a scale of 1 to 5, with a weight of 5 meaning maximum impact and weight of 1 meaning no impact. The rank for each of the factor was obtained by taking a Rating Average of responses for each of the factor.

The Mean Deviation was preferred in this case since we are only interested in the deviations of the rating and not whether they are above or below the mean score. The results of equations [3.1] and [3.2] are represented in Table 5.1 and Table 5.2 in Figure 5.1 based on individual responses.

Table 5.1: Rating of Factor Impacting Productivity from Survey Responses

(Based on Individual Responses)

Factor	Abbr.	# of Responses	Rating Average	Mean Deviation
Type of soil	TOS	12	4.83	0.28
Shaft design (size, layout, structural integrity)	SHD	11	4.82	0.74
Use of intermediate jacking station	IJS	11	4.82	0.74
Crew/ operator experience	COE	12	4.75	0.42
Obstruction or unusual soil conditions	OBS	12	4.75	0.46
Availability of soil investigation report	SIR	12	4.75	0.46
Type of spoil removal system	TSRSy	12	4.67	0.56

Table 5.2: Rating Of Factor Impacting Productivity from Survey Responses

(Based on Individual Responses)

Factor	Abbr.	# of Responses	Rating Average	Mean Deviation
Shaft design (size, layout, structural integrity)	SHD	11	4.82	0.74
Use of intermediate jacking station	IJS	11	4.82	0.74
Crew/ operator experience	COE	12	4.75	0.42
Obstruction or unusual soil conditions	OBS	12	4.75	0.46
Availability of soil investigation report	SIR	12	4.75	0.46
Type of spoil removal system	TSRSy	12	4.67	0.56
Shape of box	SOP	12	4.58	0.63
Drive length	DL	11	4	0.55
Box material	PM	11	4	0.36
Size of box	SZOP	12	4	0.33
Availability of grade & line control system	G&LCS	12	3.92	0.32
Use of lubrication	LU	12	3.92	0.47
Curved alignment	CA	12	3.67	0.72
Box section length	PSL	12	3.5	0.75
Ground water condition	GWC	12	3.25	0.71
Availability of box storage & handling	PS	12	3.17	0.31
Availability of box jacking load monitoring equipment	JLMEq	12	3.17	0.42
Friction force	FF	12	3.17	0.44
Restrictions to working hours	RWH	12	3	0.17
Straight alignment	SA	12	3	0.17
Type of joint between boxes	TOJ	12	2.83	0.28
Depth of installation	DOI	12	2.58	0.49
Technical support	TS	12	2.25	0.58
Weight of box	WOP	11	2.18	0.68
Safety and security	SAS	11	2	0.91
Traffic control	TC	12	1.92	0.61

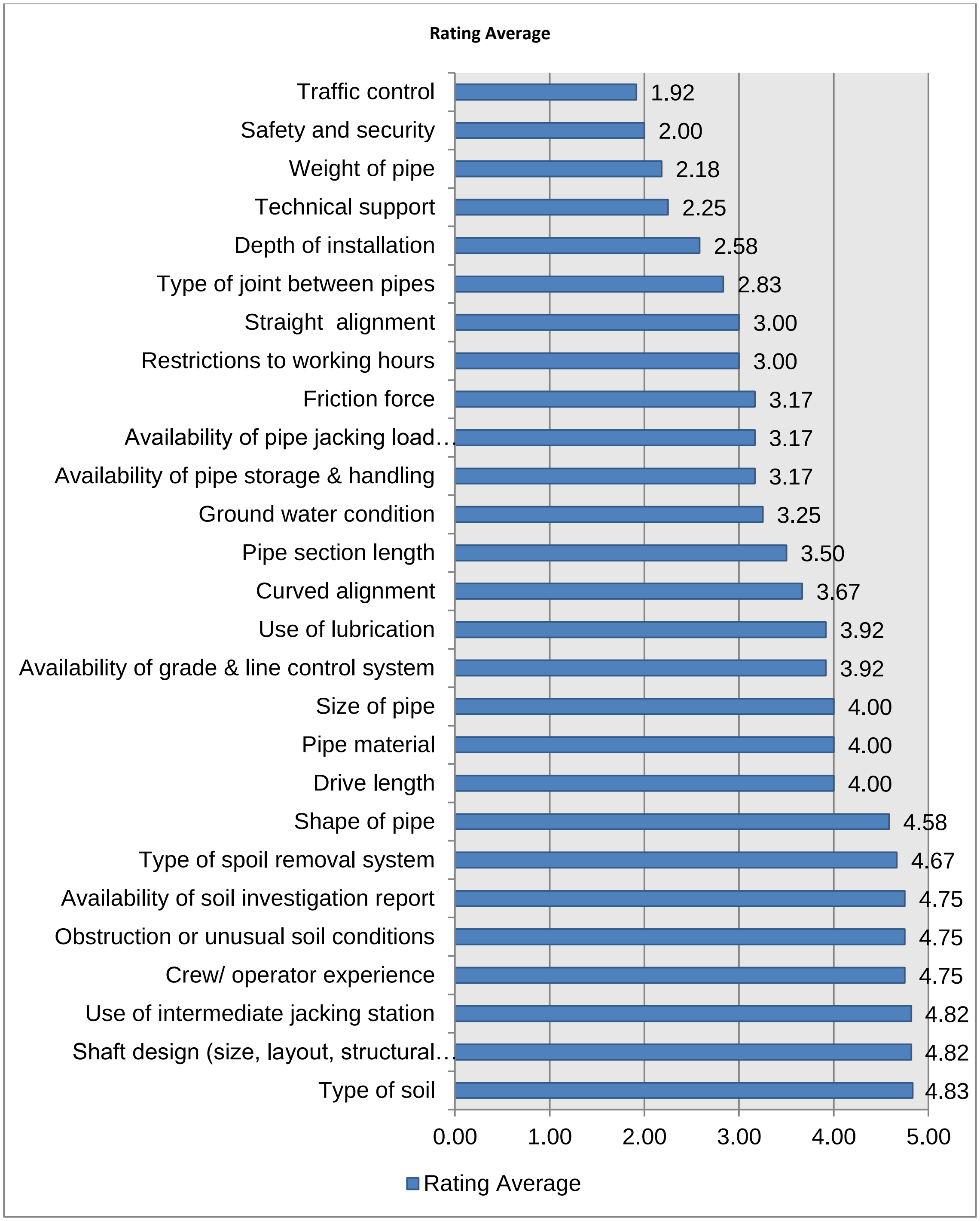


Figure 5.1 Rating Average the Most Influencing Issues on Box Jacking Productivity

(Based on Individual Responses)

For the ease of analyzing the results, the factors were classified in four categories namely general factors, soil related factors, surface establishment factors, and box installation factors as discussed in detail below.

5.1.1 General Factors

The factors namely operator/crew experience, restriction to working hours, and availability of technical support are categorized as General Factors. The operator/crew experience factor had an average rating score of 4.75 with a mean deviation of 0.58, and was the fourth highest ranked factor amongst factors impacting pipe/box jacking operations. The mean deviation of 0.58 indicates that the participant's opinions ranged 0.58 around the average score. The survey results for factors classified as general factors, as can be seen in Figure 5.2 indicated that the crew experience ha the maximum impact, work hours have moderate impact, and technical support has minimal impact on pipe/box jacking operation.

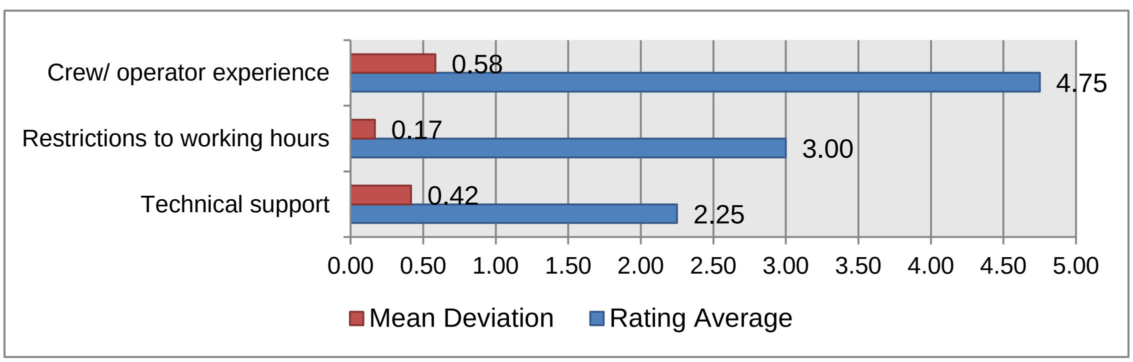


Figure 5.2: Relative Ranking of General Factors Impacting Box Jacking Operation

(Based on Individual Responses)

5.1.2 Surface Establishment Factors

The following factors that the participants were asked to evaluate are classified under Surface establishment factors:

1. Traffic control
2. Safety and security
3. Availability of box storage & handling
4. Availability of box jacking load control equipment
5. Availability of grade & line control system
6. Type of spoil removal system

The responses indicated that the type of soil removal system had the seventh highest impact on productivity with an average rating of 4.67 and mean deviation of 0.56. Traffic control and safety and security have the most minimal impact on pipe/box jacking operation. The availability of grade and line control system has relatively significant impact, while availability of box storage and handling and box jacking load monitoring equipment have moderate impact on the operation. The relative response ratings for each of the factors from the survey are shown in Figure 5.3.

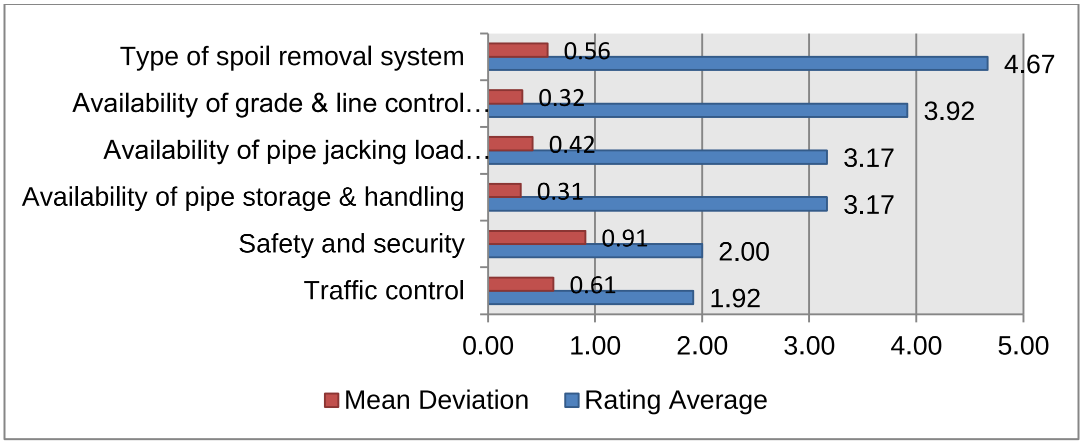


Figure 5.3: Relative Ranking of Surface Establishment Factors Impacting Box Jacking Operation

(Based on Individual Responses)

5.1.3 Soil Related Conditions

The soil factors are considered under the heading of soil related factors:

1. Ground water condition
2. Obstruction or unusual soil conditions
3. Friction force
4. Availability of soil investigation report
5. Drive length

The survey responses as illustrated in the Figure 5.4 below identified type of soil as the factor with highest impact on the box jacking operation with a rating average of 4.83 and a mean deviation of 0.28 in responses. Availability of soil investigation report and obstructions or unusual soil conditions also have equal maximum impact on box jacking operation with a close rating average of 4.75 each and mean deviation between responses of 0.46. Drive length is indicated to have significant impact and ground water condition and friction force have moderate impact on the box jacking operation. The availability of soil investigation report and obstruction or unusual soil conditions has the maximum impact on box jacking operation. Drive length also impacts the operation significantly while ground water condition and friction force have moderate impact.

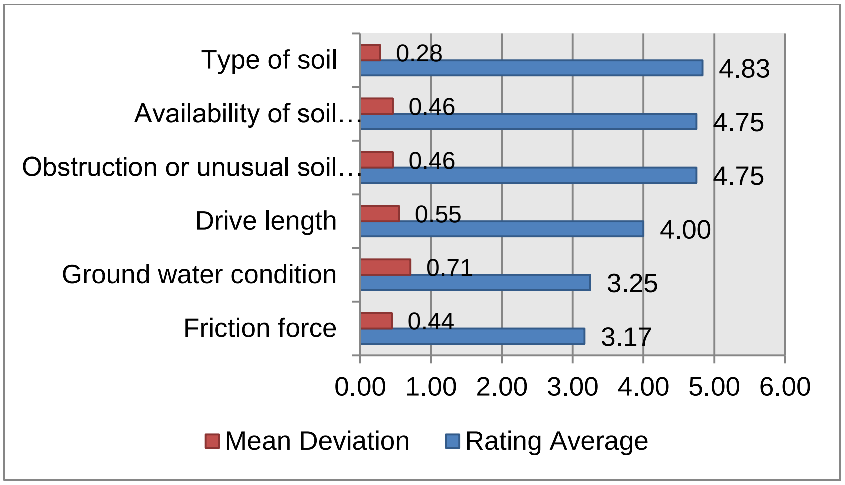


Figure 5.4: Relative Ranking of Soil Conditions Impacting Jacking Operation

(Based on Individual Responses)

5.1.4 Box Installation Factors

A total of 7 box installation related factors described below were considered for evaluating impact on productivity of box jacking operation.

1. Depth of installation
2. Type of joint between boxes
3. Straight alignment
4. Curved alignment
5. Shaft design (size, layout, structural integrity)
6. Use of intermediate jacking station
7. Use of lubrication

The survey results demonstrated that the design of shaft and the use of intermediate jacking station have the second and third highest impact on the productivity of the e/box jacking operation amongst all the considered factors with a rating average of 4.82 each and a mean deviation of 0.74. The use of lubrication with a rating average of 3.92 also significantly impacts the box jacking operation. Curved alignment impacts the process moderately and straight alignment has slightly lesser impact on the operation. The type of join between boxes had moderate impact and depth of installation has minimal impact on the productivity of box jacking operation. The Figure 5.5 illustrates the relative ranking of the box installation related factors in terms of impact on box jacking operation.

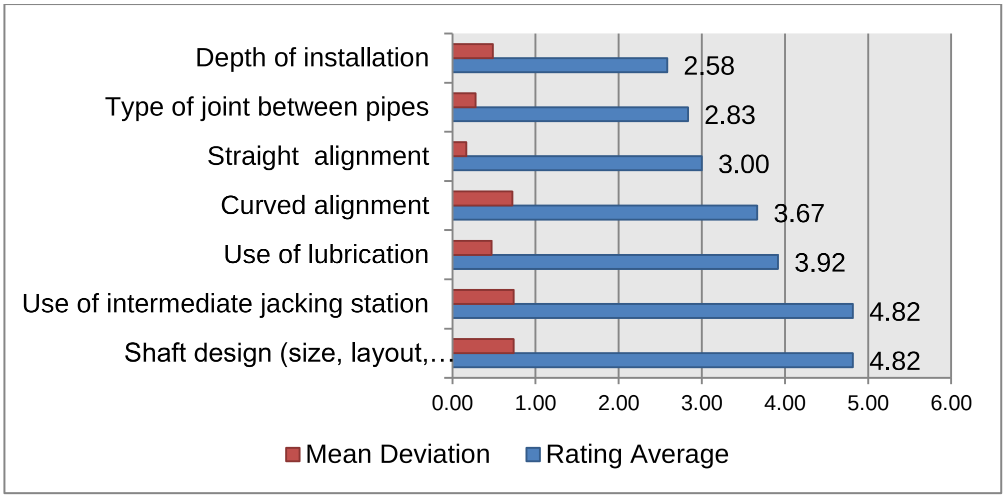


Figure 5.5: Relative Rating of Box Installation Factors In Terms Of Impact on Box Jacking

(Based on Individual Responses)

5.1.5 Box Dimensions

The box dimension factors namely size, shape, and weight of box, box section length, and box material were considered for the purpose of this survey. The expert judgments demonstrated that amongst the box dimensions the shape of box has the highest impact on the productivity of the box jacking operation with an average rating of 4.58 and mean deviation of 0.63. Material of box and size of box have equal and significant impact with average rating of 4.0. The box section length has lightly lower but moderate impact and the weight of box has overall second lowest impact on the box jacking operation with an average rating of 2.18. The Figure 5.6 below illustrates the relative ranking of the box dimensions with respect to their impact on box jacking operation.

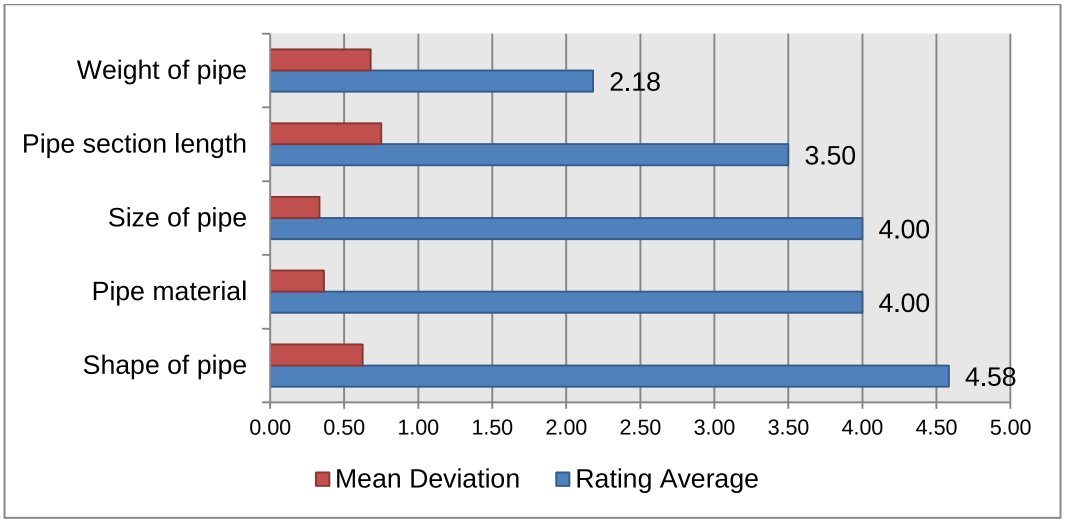


Figure 5.6: Relative Rating of Box Installation Factors in terms of impact on box jacking (Based on Individual Responses)

5.1.6 Response Analysis using Pairwise Comparisons

Pairwise computations were applied to process the received responses as shown in Table 4.2 and Table 4.3. The tables also list weights of each factor in the AHP in the terms of the global weighting methodology and local weighting methodology. The Global Weight represents opinions for weights of 27 factors while the local weight only focuses on the weight amongst those sub-criteria factors, which was achieved by simply setting the weight of each sub-criteria to 100% for the calculations.

5.1.7 Favourable Soil Conditions

Each types of soil ha a positive or negative effect with respect to productivity. The survey participants were asked to rank the types of soil from 1 to 5 in terms of their favourability for box jacking operation with 1 being least favourable and 5 being most favourable in order to determine the overall favourable condition. The survey results concluded that the Non-cohesive soils are the most favorable for box jacking operation, and cohesive soils are the second best. Solid rock, and Boulders & cobbles are the least favorable for box jacking operation. The average rating of the soil types from the survey results is demonstrated in the Table 5.3 and Figure 5.7 based on individual responses.

Table 5.3: Favorable Soil Type With Respect To Box Jacking Operation

Soil Type	Rating Average	Mean Deviation
Non-cohesive soil	4.4	0.78
Cohesive soil	3.9	0.31
Mixed soils	3	0.45
Fill material	2.3	0.33
Solid rock	1.2	0.28
Boulders & cobbles	1.2	0.28

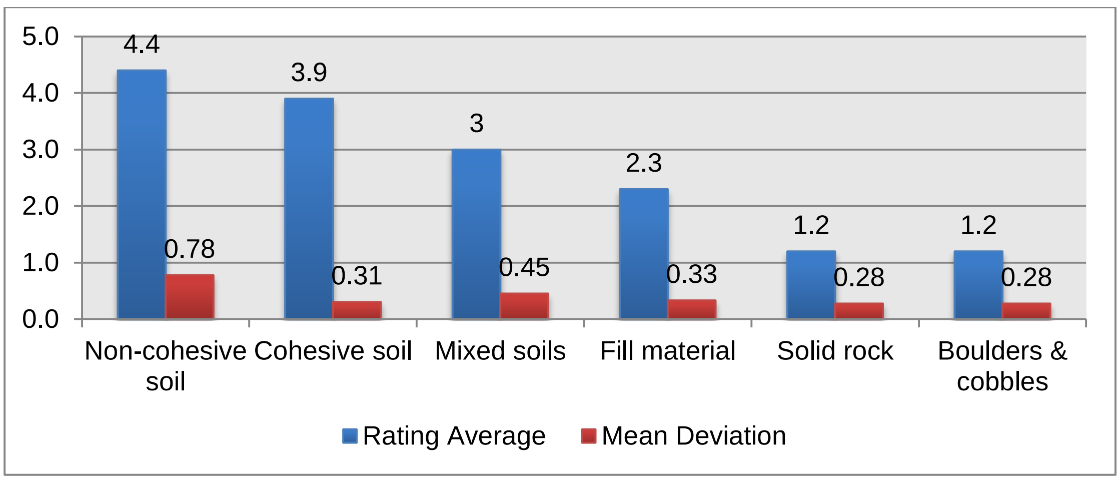


Figure 5.7: Questionnaire Responses of Favorable Soil Type for box jacking.

5.2 Chapter Summary

This chapter presented the results of the research undertaken for this thesis. These results have been categorized in two areas: (1) the results obtained from case studies, and (2) the results obtained from the survey responses to identify issues affecting productivity of box jacking projects.

CHAPTER 6

CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

This chapter includes the conclusions drawn from the research conducted on identifying issues impacting box jacking productivity. It also includes the limitations and recommendations for the same subject area.

6.1 Conclusions

The following conclusions can be derived from this thesis:

1. Six important issues to be considered while modeling and determining the box jacking productivity were identified.
2. Soil related factors with a local weight of 42.61 % in level 2 were identified as the rated more influencing factors.
3. Type of soil got the highest rating average value of 4.83/5 with a mean deviation of 0.28. Its AHP local weight in level 3 was 29.76%
4. Types of soil, spoil removal system, crew operator experience, use of intermediate jacks were identified as the most influencing which affect box jacking productivity.
5. Friction force and type of joint system received the lowest AHP level 3 local weight value at 2.34%.

Interestingly, in the overall ranking of factors impacting box jacking productivity friction force and type of joint system were not the lowest ranked factors. This shows some issues might not have affect on productivity when looked individual, but when grouped they play an influencing role in calculating box jacking productivity.

6.2 Limitations

1. Very few industry leaders involved in pipe/box jacking operation wanted to give their opinion.
2. Substantial research was not available on the factors to be considered in determining jacking productivity.
3. More extensive survey should be conducted involving box jacking leaders from around the world on this issue.

6.3 Recommendations for Future Research

The following topics are recommended for future research on the subject of identifying issues impacting box jacking productivity

- The identified issues can be used to model a box jacking operations which will help in predicting the productivity of box jacking crew and machines under different types of soil conditions.
- Individual costs influence by these issues should be studied separately by box jacking industry professionals in-order to determine profitability.
- The identified issues could be used in order to develop a risk vs. cost analysis matrix to determine the effectiveness on the bidding prices for box jacking projects which are usually kept on a higher side due to these uncertainties.
- A research can be done in providing curved surface to the top flange of the box culvert to increase box jacking productivity.

APPENDIX A

SURVEY QUESTIONNAIRE

Exit this survey

The University of Texas at Arlington

Center for Underground Infrastructure Research and Education (CUIRE)

Phone: 817-272-0507 Fax: 817-272-2630
E-mail: najafi@uta.edu
www.cuire.org

Issues Impacting Pipe Jacking Productivity

1. General Information

11%

Thank you for your participation in this survey. Your valuable experience in Pipe Jacking Operations is greatly appreciated. This questionnaire is conducted for the purpose of a M.S. research to identify and quantify issues impacting productivity in pipe jacking trenchless construction. Your expert opinion would help us rank these factors and this would be the basis to develop a model that aims at improving productivity of pipe jacking process through planning and execution in a more efficient manner. All the information provided will be kept confidential.

If you have any question regarding this questionnaire, please do not hesitate to contact Bhaumi Chaurasia, Research Student at bhaumi.chaurasia@mavs.uta.edu or (740) 707-1991. You can as well contact my advisor Dr. Mohammad Najafi, P.E., F. ASCE at najafi@uta.edu or (817) 272 - 0507.

Please fill in your contact information below before proceeding to the questionnaire:

Contact Information

Name:

Company:

Title:

Address:

City/Town:

State: -- select state --

ZIP:

Country:

Email Address:

Phone Number:

Please select whichever is most applicable to you.

- Contractor
- Subcontractor
- Owner
- Engineer
- Professional Consultant

For how many years have you been dealing with Pipe Jacking Operations?

Next

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Issues Impacting Pipe Jacking Productivity

2. Definitions

22%

- **Ground Movement:** During pipe jacking operation ground movement such as settlement, heaving, or collapse of surface may occur, which may or may not be significant.
- **Grade & Line Control System:** A device such as laser guided system, which helps in maintaining the proposed Grade and Line of pipe installation. Grade is the vertical slope of the pipe and the line of the pipe is the horizontal direction of the pipe. In order for pipe line to function as designed, it is important to install the pipe to the proper line and grade.
  Intermediate jacking station: This is a fabricated steel box or cylinder fitted with hydraulic jacks that are installed temporarily between two pipes. These stations reduce the forces exerted by the main jacks. They are commonly used where jacking forces exceeds the maximum limit that the pipes or main jacks are capable off.
- **Lubrication:** In pipe jacking operation lubrication is performed to reduce frictional force between the pipe and the adjacent soil and to stabilize the tunnel.
- **Productivity:** For pipe jacking operations productivity is the rate at which "x" linear feet of pipe is jacked per shift, i.e., X lf/shift.
- **Sub-soil investigation report:** A detailed sub-soil investigation report indicates the ground water condition, nature and characteristics of soil, other structures in the ground below the proposed site and also presents expert statements and recommendations on design.

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Issues Impacting Pipe Jacking Productivity

3. Pipe Jacking Operations

33%

1. How much of your total pipe jacking operation involves hand vs. mechanical excavation?

Hand Excavation (%)

Mechanical Excavation (%)

2. Please provide the pipe installation productivity for your operation in Linear feet per day for each of the excavation methods?

Hand Excavation (Linear ft/ day)

Mechanical Excavation (Linear ft/ day)

3. What percentage of your pipe installation operation is circular vs. box?

Circular pipe (%)

Box pipe (%)

4. In your opinion, which of the pipe installation is more productive? Please state why?

○ Circular Pipe ○ Box pipe

Comments to support answer

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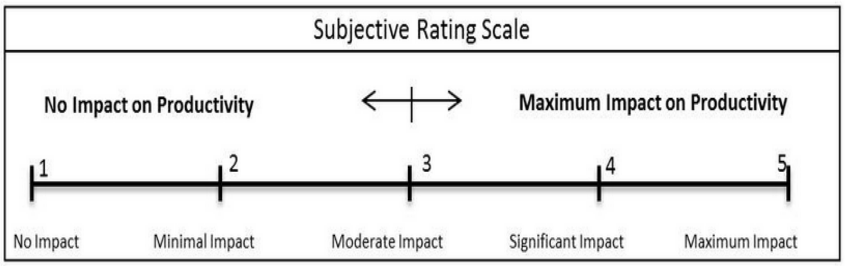
Issues Impacting Pipe Jacking Productivity

4. Surface Establishment

44%

Subjective Rating Scale



5. Rank the following surface establishment factors impacting the productivity of pipe jacking operations according to the above scale.

	1	2	3	4	5
Traffic Control	○	○	○	○	○
Safety and Security	○	○	○	○	○
Availability of Pipe Storage & Handling	○	○	○	○	○
Type of Spoil Removal System	○	○	○	○	○
Availability of Grade & Line Control System	○	○	○	○	○
Availability of Pipe Jacking Load Control Equipment	○	○	○	○	○

6. Rank the following general factors from productivity point of view according to the scale above.

	1	2	3	4	5
Crew/ operator experience	○	○	○	○	○
Restrictions to working hours	○	○	○	○	○
Technical Support	○	○	○	○	○

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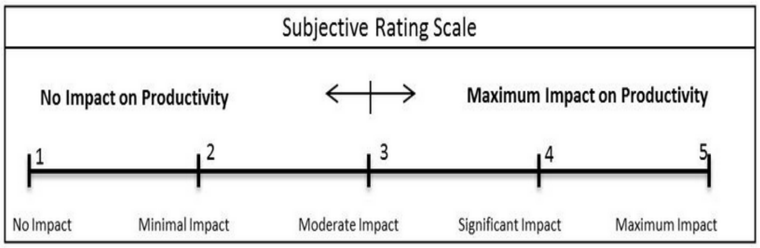
Issues Impacting Pipe Jacking Productivity

5. Soil Condition

56%

Subjective Rating Scale



7. Rank the following soil related factors impacting the productivity of pipe jacking operations according to the above scale.

	1	2	3	4	5
Ground water condition					
Obstruction or unusual soil conditions					
Friction Force					
Availability of Sub-soil investigation report					
Drive Length					

8. Rank the following soil types from productivity point of view on a scale of 1 to 5. Please rank 1 as least favorable and 5 as the most favorable type.

	1 (Least)	2	3	4	5 (Most)
Non-cohesive soil					
Cohesive soil					
Mixed soils					
Fill material					
Rock					

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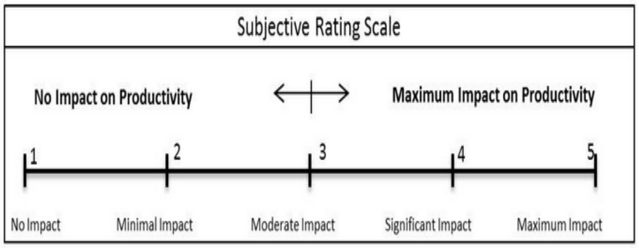
Issues Impacting Pipe Jacking Productivity

6. Pipe Jacking Pipes

67%

Subjective Rating Scale



9. Rank the following pipe installation factors impacting the productivity of pipe jacking operations according to the above scale.

	1	2	3	4	5
Depth of Installation					
Pipe Material					
Shape of Pipe					
Size of Pipe					
Weight of Pipe					
Pipe Section Length					
Type of Joint between Pipes					
Straight vs Curved alignment					
Shaft design (size, layout, structural integrity)					
Use of intermediate jacking station					
Use of lubrication					

10. Please specify any other factors you may think are of importance that impact the productivity of pipe jacking installation.

1

2

3

4

5

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Issues Impacting Pipe Jacking Productivity

8. Dependency Between Factors

88%

15. Please indicate if there is a dependency between Soil Related Factors and General Factors. If any of the Geneal Factors listed below depend on the soil related factors, please tick the applicable box (multiple answers are acceptable).

	Ground water condition	Obstruction or unusual soil conditions	Friction Force	Availability of Sub-soil investigation report	Drive Length
Crew/ operator experience	☐	☐	☐	☐	☐
Restrictions to working hours	☐	☐	☐	☐	☐
Technical Support	☐	☐	☐	☐	☐

16. Please indicate if there is a dependency between Soil Related Factors and Surface Establishment Factors. If any of the Surface Establishment Factors listed below depend on the soil related factors, please tick the applicable box (multiple answers are acceptable).

	Ground water condition	Obstruction or unusual soil conditions	Friction Force	Availability of Sub-soil investigation report	Drive Length
Traffic Control	☐	☐	☐	☐	☐
Safety and Security	☐	☐	☐	☐	☐
Availability of Pipe Storage & Handling	☐	☐	☐	☐	☐
Type of Spoil Removal System	☐	☐	☐	☐	☐
Availability of Grade & Line Control System	☐	☐	☐	☐	☐
Availability of Pipe Jacking Load Control Equipment	☐	☐	☐	☐	☐

17. Please indicate if there is a dependency between Soil Related Factors and Pipe Installation Factors. If any of the Pipe Installation Factors listed below depend on the soil related factors, please tick the applicable box (multiple answers are acceptable).

	Ground water condition	Obstruction or unusual soil conditions	Friction Force	Availability of Sub-soil investigation report	Drive Length
Depth of Installation	☐	☐	☐	☐	☐
Pipe Material	☐	☐	☐	☐	☐
Shape of Pipe	☐	☐	☐	☐	☐
Size of Pipe	☐	☐	☐	☐	☐
Weight of Pipe	☐	☐	☐	☐	☐
Pipe Section Length	☐	☐	☐	☐	☐
Type of Joint between Pipes	☐	☐	☐	☐	☐
Straight vs Curved alignment	☐	☐	☐	☐	☐
Shaft design (size, layout, structural integrity)	☐	☐	☐	☐	☐
Use of intermediate jacking station	☐	☐	☐	☐	☐
Use of lubrication	☐	☐	☐	☐	☐

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Issues Impacting Pipe Jacking Productivity

9. Dependency Between Factors

100%

18. Please indicate if there is a dependency between Pipe Installation Factors and General Factors . If any of the General Factors listed below depend on the Pipe Installation Factors, please tick the applicable box (multiple answers are acceptable).

	Depth of Installation	Pipe Material	Pipe Shape	Pipe Size	Pipe Weight	Pipe Section Length	Type of Joint between Pipes	Straight vs Curved alignment	Shaft design	Use of intermediate jacking station	Use of lubrication
Crew/ operator experience	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Restrictions to working hours	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Technical Support	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

19. Please indicate if there is a dependency between Pipe Installation Factors and Surface Establishment Factors . If any of the Surface Establishment Factors listed below depend on the Pipe Installation Factors, please tick the applicable box (multiple answers are acceptable).

	Depth of Installation	Pipe Material	Pipe Shape	Pipe Size	Pipe Weight	Pipe Section Length	Type of Joint between Pipes	Straight vs Curved alignment	Shaft design	Use of intermediate jacking station	Use of lubrication
Traffic Control	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Safety and Security	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Availability of Pipe Storage & Handling	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Type of Spoil Removal System	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Availability of Grade & Line Control System	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Availability of Pipe Jacking Load Control Equipment	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

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BIOGRAPHICAL INFORMATION

Bhaumi Bhavan Chaurasia was born in February, 1986, in Kanpur, India. He received his bachelor degree in Architecture from R.V. College of Engineering, Bangalore, India in 2007, after which he worked as a Jr. Engineer for Gayatri Project. He coordinated closely with the sub-contractors and helped them build several commercial projects in Hyderabad, India. He then joined Alpha Testing a construction material testing company as an Estimator Intern. He estimated several federal and private projects for various clients in Texas, USA.

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.