IMPROVING PRODUCTIVITY OF

TUNNEL BORING MACHINES

by

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ABSTRACT

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Tunneling with tunnel boring machines (TBMs) is one of the most mechanized and sophisticated processes within the construction industry. However, there are considerable risks when venturing down several hundred feet where the conditions cannot be accurately determined in advance. Months and years of planning, engineering, profiling, researching, and scheduling go into a typical tunneling project before any ground breaking event.

This thesis discussed in detail the growing technologies of the tunneling process using tunnel boring machines (TBM). First, some background information on tunneling and the use of a TBM was provided to introduce the process and the industry being discussed. A tunnel boring machine is unique to each project based on the ground conditions that will be encountered, the diameter and length of the tunnel, as well as several other technical and dynamic factors. After the introduction, the thesis examined a case study of a tunnel project, the Jollyville Transmission Main for the Water Treatment Plant #4 in Austin, Texas. More specifically, one of the TBMs used will be studied in order to maximize production. The details of this project provide an opportunity to discuss production improvements, scheduling impacts, and project costs. Different methods and their effect on the overall project outcome were compared.

The case study information was compared with literature, as well as on-the-job information gained from discussions with the project manager, superintendents, and other on-site personnel. This research concluded that given certain circumstances, the use of a continuous conveyor, rather than the muck car/rail method, has potential for a quicker completion schedule and a greater profit for the contractor.

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LIST OF ABBREVIATIONS

TBM	Tunnel Boring Machine
EPB	Earth-Pressure Balance
JTM	Jollyville Transmission Main
WTP4	Water Treatment Plant #4
STA	Station
in.	Inch
HP	Horsepower
CTHD	Cutter Head
GBR	Geotechnical Baseline Reports
JV	Joint Venture
lbs	Pounds
psi	Pounds per Square Inch
PPS	Poltinger Precision System
kVA	Kilovolt-Amps
KV	Kilovolts
ft.	Foot (Length)
Min	Minute
Sec	Second
Mil	Million
EA	Each
DSS	Decision Support System

CHAPTER 1
INTRODUCTION & BACKGROUND

1.1 Introduction

Traditionally, contractors try to complete a project under budget and on or ahead of schedule. By accomplishing these objectives, construction firms are able to maximize profit and continue business elsewhere. The tunneling industry is no exception. The majority of tunneling contractors are compensated by the linear foot excavated, as well as by the amount of pipe laid or concrete placed. Considering the expected lost time due to mechanical failures within a typical tunnel boring machine operation throughout project duration, it is necessary to excavate more than the scheduled linear footage in order to stay on schedule. Therefore, using the most efficient tunneling method to maximize production is essential.

This thesis used a case study tunnel project, in which at the time of this writing, the tunnel stretch being studied was scheduled to be completed in April 2013. This tunnel reach was delayed two months as a result of locomotive issues, resulting in TBM downtime. The project had three tunnel reaches totaling approximately 35,000 feet. This thesis will focus on Reach #2, which totaled approximately 20,450 feet by the end of excavation. The case study investigated the critical parts of production operations which needed improvements. The means and methods of removing the excavated material from the tunnel to minimize the TBM downtime will be discussed. Reducing downtime will increase linear footage production, which will in turn, create an earlier project completion date thereby providing a greater profit.

1.2 TBM Background

There is little doubt that the use of tunnel boring machines (TBMs) highly automates the tunneling process. Tunnel boring machines are essential to the construction of tunnels. Most often the intended tunnel use is for underground transportation such as roadways or subway tunnels or for pipelines dedicated to water intake, water transmission, or wastewater transport. TBMs are highly efficient for construction of tunnels with a circular cross section that are generally greater than approximately 3.5 feet in diameter and approximately 1.33 miles in length (Girmscheid and Schexnayder 2003). The function, as well as layout of a TBM, has basically remained the same since its first days of application (Laughton 1998).

The use of a TBM varies with individual projects and the available methods for excavating these tunnels. The use of TBMs is growing as opposed to drill and blast methods, excavating with road headers or excavators, or chipping by hand for a few main reasons. First, although the upfront cost of a TBM is expensive, present day tunneling projects are growing in diameter and length. Therefore the use of a TBM has large benefits in terms of schedule due to the efficiency of the machine (Girmscheid and Schexnayder 2003). The second main benefit is the fact that when excavating rock with a TBM, it is often unnecessary to provide tunnel lining, which significantly reduces the costs of construction. The TBM will produce a tunnel with a circular cross section and a smooth tunnel wall that is often stable with only periodic rock dowels. The use of tunnel lining depends on the type of rock being excavated, as well as the groundwater conditions (Rostami 2011). When tunnel lining is required, there are several methods of providing this support, ranging from layers of concrete applications to steel circular liner plates to concrete segments.

Other methods of tunnel excavation are available and will largely depend on the size of the tunnel being excavated. It would not be practical to use an excavator to mine a 20,000-foot tunnel. This method of excavation is realistic for short lengths, such as a 150-foot tunnel under a road or highway. Many open cut projects might require a small tunnel along the stretch of excavation. Excavators and road headers are largely beneficial for this application. In fact, in special cases, some tunnels in excess of 5,000-foot lengths are excavated using a road header much like the one shown in Figure 1.1. In certain ground conditions such as hard rock, a road header can mine up to 50 feet per day. Theoretically, in the same ground conditions, the TBM excavation rate would be significantly higher due to the efficiency of TBMs. Chipping by hand with a pneumatic chipping hammer or rivet buster can be a gruesome job and would only be practical for a small amount of excavating. Situations do arise where the allotted space cannot fit a piece of equipment, therefore requiring a laborer to take action with pneumatic tools. When a particular section of tunnel needs to be opened up in the crown, it is practical for laborers to perform this action using a chipping hammer.

Figure 1.1. Typical road header used in the tunnel excavation process can be practical for short distance tunnels, as well as starter and tail tunnels (Source: Mitsui).

Many other tunneling methods, such as drilling or drill and blast, are practical for various project settings such as rock that is difficult to be bored by a TBM. However, TBMs can be used for the boring of any material, from hard rock to sand, as well as conditions below the water table, and provide little to no disturbance to the surrounding environment (Mathy and Kahl 2003). Different types of tunnel boring machines exist. Each TBM is engineered with a specific project in mind, as well as the projected ground conditions that may be encountered. The hard rock TBMs are designed for chipping away using cutting discs located on the cutter head. Hard rock TBMs can be open-shield or closed, depending on the rock support being installed in the tunnel. The soft rock TBMs can be either an earth-pressure balance (EPB), a slurry shield (SS), or an open face TBM. Again, the use of a particular soft rock TBM will vary with ground conditions. An open face TBM relies on the fact that the rock being excavated can support itself for a small time frame after excavation. Typically these machines will excavate the distance of one push, approximately 5 to 10 feet, install the necessary tunnel support, and then repeat the cycle (Girmscheid and Schexnayder 2003). A bentonite slurry machine or EPB is used for tunneling in soft water-bearing ground conditions and contains a pressurized compartment towards the front end. This function will pressurize the ground in front of the TBM cutter head to balance the water pressure (Chapman 2010). Table 1.1 presents the different tunnel excavation methods.

Table 1.1 Tunnel Excavation Methods

Excavation Method	**Applicable Situations**	**Description**
Tunnel Boring Machines	Beneficial for large diameter and lengthy tunnels. Hard rock, soft rock, water-bearing ground conditions.	Machines of a circular cross section that bore through the existing ground.
Drill and Blast	Hard rock where boring with a TBM is difficult.	Placing and detonating explosives causing rock to collapse.
Cut And Cover	Shallow tunnels.	Trench is excavated. Roof provided overhead to support future loads.
Excavators/Road Headers	Soft and hard rock. Lengths in excess of 5,000 ft may become impractical.	Chipping at rock using a chipping hammer attachment or rotating heads with various teeth.
Hand tools/Pneumatic Tools	Soft and hard rock. Small in diameter and small in length. Small changes to existing tunnels.	Chipping rock using pneumatic hand tools by laborers.

1.2.1 TBM Configuration

A tunnel boring machine consists of a cutter head pushed to the face of the tunnel. In most situations, the overall diameter of the cutter head will be equal to the diameter of the finished tunnel. In hard rock TBMs, the conical shaped cutter head will contain several large, hardened metal discs that roll and cut along the rock of the tunnel face as the cutter head rotates. These discs create a compressive stress that will chip away the rock as the machine pushes forward. In soft or water-bearing ground conditions, where the use of an EPB or slurry shield is used, the cutter head will use cutting bits and disc cutters to excavate material. The excavated rock, known as muck or spoils, is scraped and collected in cutter buckets located on the face of the TBM. The muck is then guided to the conveyor belt through a transfer chute. The conveyor system often runs along the center axis of the machine to transport spoils into the muck trains or carried out by transferring the spoils to another conveyor. Figures 1.2 and 1.3 present different designs for cutter heads and demonstrate the layout of disc cutters.

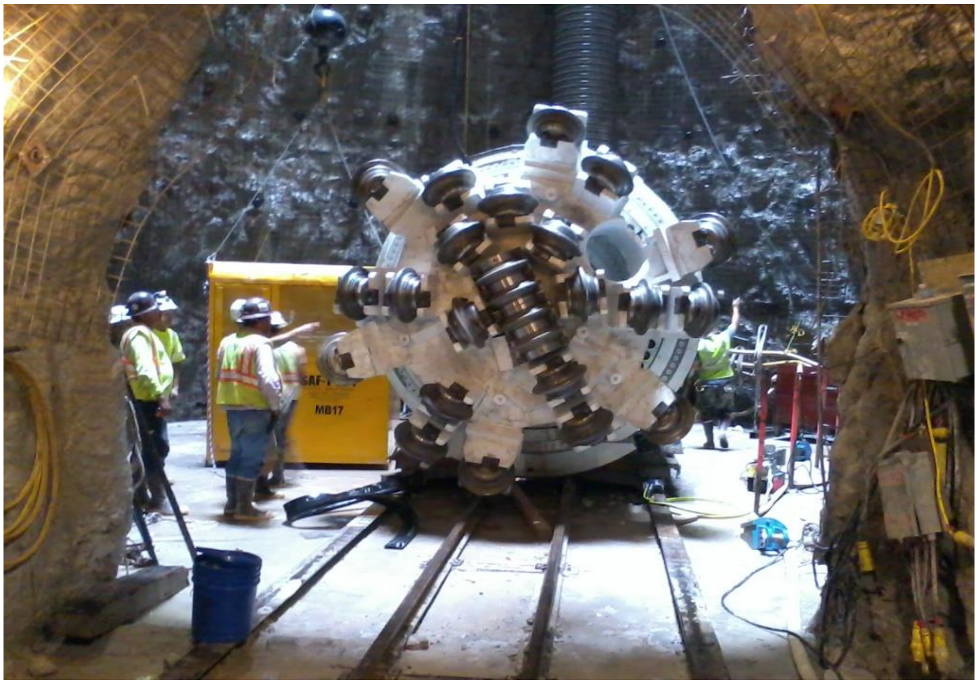


Figure 1.2. Robbins manufactured cutter head. This particular cutter head was used on Reach #2 of the Jollyville Transmission Main project in Austin, Texas.

Figure 1.3. Cutter head and TBM can, which will hold the TBM operator and contains the grippers. This particular cutter head was built by Southland Contracting and used on Reach #1 of the Jollyville Transmission Main project in Austin, Texas.

Behind the cutter head is often a main bearing, which is typically followed by a shielded section containing a set of steering cylinders and/or some configuration of a thrust system, varying with each machine. The main bearing is the essential piece that allows the cutter head to rotate without rolling the machine. The steering cylinders guide the machine in the desired direction, not suddenly but over a stretch of excavation. These cylinders apply different forces to different locations of the head, depending on which direction is desired. Often the steering cylinders are located in the 1:30, 4:30, 7:30 and 10:30 clock positions or the 3, 6, 9, and 12 clock positions. The thrust system is generally a set of sidewall grippers that are forced out into the surrounding rock, or tunnel liner support, using hydraulic cylinders, to hold the TBM in place. Once the grippers are in place, another set of hydraulic cylinders will provide the force needed to push forward on the tunnel face. Once the push cylinders have completed a full stroke, the cylinders will be retracted and the cycle will be repeated. Behind the thrust system are several sections of trailing gear, which include hydraulic motors and transformers, along with electrical boxes and dust control systems. Behind those skids will be the gantries, also known as the backup systems, which hold the conveyor system along with hoses, utilities, cables, and cords. Figure 1.4 presents a view of the back-up system for a TBM in operation.

Figure 1.4. Backup system to the TBM. A series of skids will hold the conveyor system up and allow for the muck cars to fit under.

The configuration of the tunnel boring machine will vary with each project (The Robbins Company 2012). The type of machine is largely dependent on the particular geology of the project. Other variables include the length and diameter of the tunnel being excavated as well as the amount of water present in the tunnel. Specific project site conditions will contribute to the type of muck removal, tunnel support system, ventilation layout, electrical systems, and dust control methods (Girmscheid and Schexnayder 2003). Each of these variables is important to the productivity of the machine as well as the safety of the laborers.

1.2.2 Muck Removal Methods

The chosen methods to remove muck from a tunnel is based on several variables, including, but not limited to, project time constraints, budget, manpower, size, and local conditions. The main options for muck removal is the muck car/rail method, which requires filling muck cars with the excavated material and pulling these muck cars to the shaft by a locomotive on rail system, or the use of a continuous conveyor. If a tunnel is large enough, dump trucks, such as transfer dump trucks or articulated haulers, can be another option. There are also options that involve a combination of methods. It is important to know the muck removal method so that the TBM configuration can be engineered and manufactured compatibly. Figure 1.5 demonstrates the options for each stage of the muck removal process, with the first column representing the TBM, the second column representing the tunnel, and the third column representing the shaft.

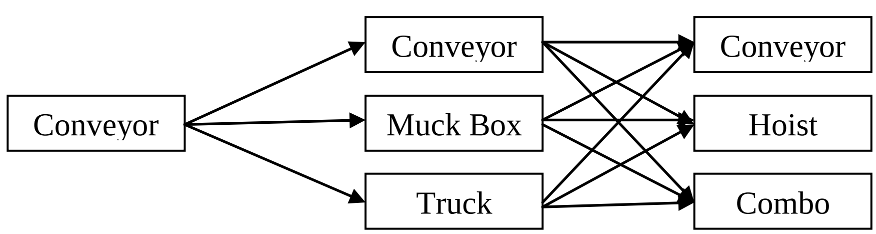


Figure 1.5 Material removal options for TBMs (Laughton 1998).

1.2.2.1 Muck Car/Rail Method

The muck car/rail method requires the TBM trailing gear to allow muck cars underneath. A locomotive will push the empty muck cars (often 3 or 4 per train) towards the machine and will then stop the train when the first muck car is under the dumping end of the conveyor system. The muck boxes are designed to accommodate the muck produced by one boring cycle of the TBM, while also taking into account the 1.5 or 2.0 bulking factor (Laughton 1998). The bulking or swelling factor is the expansion of the soil after being taken from its original setting. As the muck cars fill up, the locomotive operator will need to gradually pull forward so that the train of muck cars can be filled without stopping the TBM from excavating. Once all muck cars have been filled, the locomotive will pull the full train to the entry shaft, where the crane will remove and dump each muck car into a designated area on the surface (Girmscheid and Schexnayder 2003).

With a full train, it is clear that speed will be decreased due to the weight. Depending on the size of the muck cars, the weight of an individual muck car that has been fully loaded can reach 30,000 to 50,000 pounds, varying with the size of the muck box. It is also important that the rail be laid flat and tied together tightly. Flaws in the rail can cause derails, which delay production. The fewer issues operators encounter with rails, the quicker they can complete the excavation process. Whether the tunnel is at an uphill or downhill slope will affect the overall speed of the trains. It may be preferred and will certainly be an advantage to pull a full train downhill rather than uphill. If possible, this action will prevent issues with locomotives as the project continues, as well as prevent delays due to the decreased downtime.

If the tunnel length exceeds 8,000 feet, the installation of a switch track will help to increase production. A switch track is a scissor-like rail that mechanically guides the train from one set of rails to another, essentially forming a “Y.” In mining applications, the two sets of rails run parallel, stretching out long enough to hold the length of train, which requires an individual “Y” switch track to be placed at both ends. In the mining industry, the complete assembly is classified as a switch track. For each switch track installed, an additional train can be added. This will decrease the downtime for which trains travel the tunnel, or increase the time that the TBM can be utilized. Table 1.2 presents information on the switch track. Figure 1.6 shows the mucking process while in operation.

Table 1.2. Switch track layout and tunnel cross section.

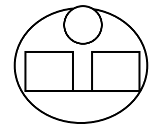
Switch Track for Single Rail	Track Layout	Tunnel Cross Section
• Conventional "Y" turnouts • Allows for two trains running parallel		

Figure 1.6. A muck car being filled during TBM operations.

1.2.2.2 Continuous Conveyor Method

The second method of muck removal is the continuous conveyor. It is essentially what the name states, a conveyor belt that runs the entire length of the tunnel, making bends and curves to match the tunnel (The Robbins Company 2012). The conveyor typically runs along rollers tied to the side of the tunnel, known as side-mounted rollers, or the conveyor can run along the crown of the tunnel, depending on location of ventilation and utilities. The continuous conveyor method requires more of an upfront cost than the muck car/rail method, but it can significantly decrease the amount of time it takes to excavate a tunnel. The continuous conveyor will allow for more TBM operating time due to the fact the TBM will not be required to wait for a train to be emptied and returned. When tunneling with the muck car/rail method, the TBM utilization rate will be approximately 40% to 60%, but with the use of a continuous conveyor, utilization is typically 80% or greater (Rostami 2011).

A belt storage cassette is used to allow for continuous operation of the TBM, typically located in the shaft or tail tunnel. As the TBM pushes forward through the tunnel, the storage cassette extends the conveyor belt while maintaining tension. The storage cassette will contain a splice stand, which is aimed at minimizing downtime. In theory, the TBM should be running continuously until the belt runs out, which requires an additional roll of belt to be installed on the splice stand so that a connection can be made to the existing belt by using a standard belt splice kit. Adding a roll of belt can take approximately 8 to 12 hours and is typically added in 500-foot, 1000-foot, or 1,500-foot increments (Willis 2012).

At the shaft, the continuous conveyor will often be dumped into a vertical conveyor running along the shaft wall leading to a radial stacker located over the designated dump area on surface (Willis 2012). The radial stacker allows for maximizing the storage area as it distributes material by moving from side to side (The Robbins Company Brochure 2012). This type of vertical conveyor can be combined with the muck car/rail method, where the muck cars would empty into an area where the conveyor system could scoop and carry the material to surface. Figures 1.7 and 1.8 portray the storage cassette and splice stand, used with continuous conveyors. Table 1.3 summarizes the different muck removal methods.

Figure 1.7. The storage cassette for a continuous conveyor system. The weaving between rollers will help to keep the belt in tension (Source: Robbins).

Figure 1.8. A splice stand that holds a roll of conveyor belt for a continuous conveyor

(Source: Robbins).

Table 1.3 Muck Removal Methods

Muck Removal Method	Description	Advantages	Limitations
Muck Car/Rail Method	Locomotives drive muck boxes to and from the TBM via rail.	Less expensive and often less experience required.	Additional TBM downtime while waiting for muck train cycle.
Continuous Conveyor	Conveyor belt runs the entire length of tunnel.	Allows for a more continuous operation of TBM.	Experience required. More time efficient but initial setup costs more.

1.3 Jollyville Transmission Main WTP4 Tunnel Project

The Jollyville Transmission Main was a tunneling project in Austin, Texas constructed by Southland Contracting and Mole Constructors in a joint venture. The overall project began in September of 2011 with the tunneling portion of the work beginning in April of 2012. The finished tunnel contains an 84-inch pipe used to transport treated water from the Water Treatment Plant #4 located on the edge of Lake Travis, where the water intake pipeline is located. The pipeline travels approximately 35,000 feet to the Jollyville Reservoir and Pump Station using gravity flow. The project consisted of four vertical shafts, excavating through the four different soil or rock formations: Edwards, Comanche Peak, Walnut, and Glenrose formations. The shafts bottomed out in the Glenrose formation, which consists of alternating horizontal layers of dolomite and limestone, essentially weak limestone. The water flow in the Glenrose formation is rather low, with the rock showing to be consistently tight or impermeable (Rostami 2011). Figure 1.9 presents the overall tunnel project. The red star shows the location of the Water Treatment Plant #4 just east of Lake Travis. The blue dots represent the former shaft locations, while the arrows represent the tunnel reach as well as the direction of excavation.

Figure 1.9. Map of the Jollyville Transmission Main WTP4 Project (Source: Google Maps).

1.3.1 Jollyville Transmission Main WTP4 Tunnel Project – Shafts

The WTP4 shaft was located at the Water Treatment Plant jobsite at a depth of nearly 210 feet. The top 30 feet was approximately 15-foot in diameter, with the remaining 180-foot depth being excavated to a diameter of 13.67 feet. The shaft was drilled by ATS drilling, a large-scale drilling company based in Fort Worth, Texas. A 210-foot steel casing was welded together on the surface, and then lowered into the shaft in two critical lifts. The diameter of the steel casing was 13 feet and the annular space was filled in with grout, pumping and placing in small lifts so as to not damage the steel casing by exceeding pressure limits. Figure 1.10 shows the drilling attachment used to drill the WTP4 shaft. Figure 1.11 portrays the finished shaft, while Figure 1.12 demonstrates the difficult task of lowering the steel casing into the hole.

Figure 1.10. ATS Drilling beginning the drilling process at the WTP4 shaft location.


Figure 1.11. Drilled shaft at WTP4 shaft location.

Figure 1.12. The steel casing being lowered into the shaft at the WTP4 shaft site.

The next shaft along the tunnel, the Four Points Shaft, was a working shaft site with a depth of 270 feet and a 36-foot diameter. The Four Points Shaft was supported by a 10-gauge steel liner plate to a depth of 190 feet, with about 8 to 10 inches of grout between the rock and liner plate for additional support. The remaining 80 feet had wire mesh and rock dowels for support. The Four Points Shaft was the location of the launch point for the Reach #1 and Reach #2 TBMs, and, therefore, was the location at which the excavated material was removed. It was also the location of stored materials and equipment, due to the fact it was the largest of the jobsites.

The next shaft in line was the Spicewood Springs Shaft (PARD Shaft), which was approximately 130 feet in depth and 31 feet in diameter. The top 20 feet required double layered 10-gauge steel liner plate, with a ring beam placed every five feet after the second layer. This was due to the fact that the Edwards Formation at this location was shown to have excessive fill rock. The procedure was as follows:

- Dig 6 to 8 feet; place first layer of liner plate in 6-foot to 8-foot lifts.

- Pump grout behind liner plate.
- Place second layer of liner plate.
- Pump grout behind second layer of liner plate.
- Hang steel ring beam in 5-foot lifts.

The following 50 feet required a single layer of 10-gauge steel liner plate with grout providing additional support. The remaining 60 feet was supported with wire mesh and rock dowels. This shaft was used mainly as a retrieval shaft for the Reach #2 and Reach #3 TBMs.

The final stop for the transmission pipe and location of the pumps was the Jollyville Shaft. This shaft was the deepest of the project, reaching a depth of just over 350 feet. It was 36 feet in diameter and was used as the second working shaft, due to its location where the Reach #3 excavated material was removed, dumped, and then hauled. This shaft required approximately 160 feet of the 10-gauge steel liner plate with a grout filled annulus, with the remaining 190 feet containing wire mesh and rock dowels, with a flash coat of shotcrete.

1.3.2 Jollyville Transmission Main WTP4 Tunnel Project – Tunnel Reaches

Reach #1 was excavated slightly uphill from Four Points Shaft to the WTP4 shaft site located on the Water Treatment Plant jobsite. Reach #1 was approximately 118 inches in diameter. It was excavated using a Southland TBM and was just under 4,500 feet in length. Reach #1 began in April of 2012 and was completed in July of 2012.

Reach #2 ran downhill from the Four Points Shaft to the Spicewood Springs Shaft. Reach #2 was a slightly larger diameter tunnel at 128 inches and was approximately 20,500 feet in length. This tunnel reach was being excavated by a brand new Robbins made tunnel boring machine and contained at least 3 California Switches, each allowing for the addition of another mining train. A California Switch, which is a switch track that is placed on top of an existing rail and can be easily moved by riding the existing rail, has been installed approximately every 4000 to 5000 feet. As the TBM treks farther and farther away from the launch shaft, the additional train helps to maintain production. Reach #2 began mining in late August of 2012, and it was initially scheduled to be completed in April of 2013, but was completed in July of 2013.

Reach #3 was excavated uphill from the Jollyville Reservoir Shaft and met Reach #2 at the Spicewood Springs Shaft. The TBM was 118 inches in diameter and was a Southland Contracting refurbished machine containing a new Robbins made cutter head. Reach #3 had a finished length of approximately 9,700 feet and contained one switch track that allowed for the additional mining train. Table 1.4 provides a brief summary of the tunnel, while dividing it into the three tunnel reaches.

Table 1.4 Summary of Case Study Project

Tunnel Reach	Direction of Excavation	Start STA	Finish STA	Distance	TBM
Reach #1	FP to WTP4	44+51	0+00	4,451 ft	Southland TBM 118 in – 450 HP
Reach #2	FP to Spicewood	44+51	248+85	20,434 ft	Robbins TBM 128 in – 900 HP
Reach #3	JR to Spicewood	345+65	248+85	9,680 ft	Southland Refurbished/Robbins CTHD 118 in – 750 HP

1.4 Objectives and Scope

The objective of this thesis was to understand the difference in muck removal methods and the effects on TBM performance. The muck removal process seems to be a major limiting factor in tunneling production and TBM utilization. Therefore, this thesis studied an ongoing project, observed and recorded data for the muck removal process, researched alternative muck removal processes, and conducted an analysis of the options.

The topic of this thesis presents a common problem among the majority of global tunneling projects. The production methods must be consistent with budget and schedule, and therefore, it is necessary to utilize the most effective means of tunneling and muck removal.

1.5 Research Needs and Expected Outcome

Currently, there is little research and academic literature regarding TBM production, and even less research regarding muck removal methods. In the literature, results of tunnel boring machines for different projects were available, such as TBM utilization, daily production numbers, and muck removal methods utilized. One main issue is that available data varies with each individual project according to the specific conditions of the work site where the TBM was used. These conditions include the crews and personnel, the ground conditions, tunnel length and diameter, and tunnel support. For example, a tunnel with no tunnel liner being excavated using a Robbins Hard Rock TBM might average 40 feet/shift, whereas a tunnel with concrete segments being excavated with a refurbished TBM might average 20 feet/shift. This thesis is unique in the fact that the author had full capability to witness all tunneling operations. The setback is that the author did not have access to data for the continuous conveyor methods of muck removal, and therefore, had to use the past literature and in-depth discussions with tunneling professionals to conduct the study.

The results of this thesis will show an advantage in using a continuous conveyor, in particular on this case study project. It would be difficult to predict this at the beginning of the project being considered, due to the fact that the many mechanical issues are hard to foresee. If the locomotives and TBM were continuously running at full speed, the outcome of this analysis would have been different. Also, the experience of the company and personnel play a large part in deciding on the method of muck removal. It is necessary to have knowledge on the maintenance processes of a continuous conveyor. The many unknowns encountered in the tunneling industry are the intriguing factors for the chosen topic of this research.

1.6 Methodology

The techniques that were used to investigate the effects of different TBM production methods included literature reviews, speaking with contractor team members, and other professionals in the industry, and practical applications within a real-life construction project.

To perform this study, the production methods and processes available to the tunneling industry needed to be understood. The observation of three different tunnel reaches, as well as validation of results through speaking with professionals in the field, provided the knowledge needed to understand the process. Observing how the TBM works, as well as the production process, clarified the impact of these parameters on overall tunneling productivity. Different tunneling magazines and journals, such as Tunneling Journal and TBM: Tunnel Business Magazine, as well as databases such as ASCE, ProQuest, and Engineering Village were used in order to view different applications and tunneling methods. The literature search was critical to the completion of this thesis.

There were several different types of literature that were reviewed in order to complete the research that was conducted. The references cited were reports that have been read and studied prior to the start of this research, as well as other reports and articles written to continue the growth of knowledge in the tunneling industry. The literature guided the author to determine where improvements could have been made in information gathering and provided the information needed to conduct a thorough and useful study.

The author was fortunate to speak with professionals working in the industry. This was largely beneficial to gain knowledge and understanding of the factors being considered when making decisions, not only for this thesis, but career wise as well. It was important to specifically use information gathered from the tunneling contractor performing the work of the project, which this thesis reviewed as supporting research. The Project Manager, Superintendents, Project Engineers, and Foremen were also available for performing interviews and responding to questions.

This thesis included a study on the time it takes to complete a push (or fill up a muck train), pull the muck train to the shaft (or tunnel entry), and empty the muck train. While this process was occurring, there was often downtime while waiting for an empty train to arrive. This downtime needed to be minimized in order to maximize production. This cycle is the muck removal process.

It was important to note that the author’s job offered the privilege of observing and overseeing portions of the construction process at four separate shaft sites, as well as three tunnel reaches between the shaft sites. Firsthand observations of the tunnel boring machines, as well as the muck removal processes, were very helpful to the research. Onsite, opportunities arose to speak with various levels of the tunneling industry to get a direct response.

1.7 Chapter Summary

Chapter one provided background information on the tunneling industry, as well as the basics about tunnel boring machines, including methods of tunneling, TBM configuration, and muck removal methods. This chapter also introduced the case study project used in this thesis. This information will be critical as the thesis continues, and in particular to understand the analysis performed. Chapter one explained the scope of this thesis, as well as the methodology and expected outcomes of the research. The methods and processes involved in excavating a tunnel were described.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This thesis has progressed with a slightly different approach. Several sources of literature were used to provide background information and to expand knowledge of TBMs and tunneling. As mentioned previously, much of the data and research were done by observing a real-life tunneling project, as well as consulting with professionals in the tunneling industry. Project documents played a large role in gathering information for this thesis.

2.1.1 Mexico's Mega Tunnel

The journal article on Mexico's Mega Tunnel was found in the April 2012 issue of TBM: Tunnel Business Magazine (Willis 2012). This article was interesting due to the fact it discusses the immense scale of the project as well as its importance. The project was known as the Emisor Oriente Wastewater tunnel and is a total of 62-kilometers (38-miles) in length located in Mexico City. Over the years, the gravity canal known as the Gran Canal had lost it slope, causing excessive floods of untreated, or what is commonly known as black water. The idea behind the large project was to install pipelines that would take the black water and distribute it to several water treatment plants that were currently under construction.

The project had approximately 20 shafts placed periodically throughout the tunnel, roughly every 2 miles. The majority of the periodic shafts were small and used for inspecting the cutter and head conditions as well as serving as ventilation shafts. The TBMs, three of which are EPBs, were built for complex ground conditions which included lake clays, volcanic rock, and boulders. The water pressure was in the range of 60 to 90 psi, making it some of the highest pressures any EPB has ever worked under. Due to the fast-track tunneling project, the machines used a continuous conveyor to expedite muck removal.

This project was intriguing because of the constant solutions to the many issues the tunneling contractors encountered. Mexico had not used a TBM in nearly 20 years prior to the start of this project in 2009. Now tunnel boring machines in Mexico are becoming the new technology for a much needed new infrastructure.

2.1.2 Jollyville Water Transmission Main WTP4 Tunnel Project

This report was a TBM performance study done by TBM consultant and Pennsylvania State University professor, Dr. Jamal Rostami (2011). He performed this study prior to the start and during the bidding of the Jollyville Water Transmission Main WTP4 tunnel project. Dr. Rostami studied in depth the options of using a new Robbins TBM versus using a refurbished TBM. The report involved looking at the utilization rates of both options as well as the maximum daily rate of excavation.

Dr. Rostami discussed the overall project as well as the tunnel reaches. The ground conditions for the Jollyville Transmission Main WTP4 project were identified, and he used that information to perform a study on the TBM performance options. He analyzed both options and estimated the rates of production. After performing his study, he gave options for improving productivity, such as the use of a continuous conveyor or monitoring ground conditions of the tunnel closely to avoid delays. One of his additional comments recommends the purchase and use of the new TBM, stating that this purchase would be an investment in which the TBM can be used for future projects. This report was useful because it was focused on the same project which this thesis uses as a case study.

2.1.3 Tunnel Boring Machines

This journal article was cited at the ASCE database and was written by G. Girmscheid and C. Schnexnayder (2003). This report presented a background of TBMs. It provided a look at different TBM configuration options as well as the reasons for choosing a particular configuration. It discussed the factors affecting the selection of different tunnel boring machines. The report gave a description of the importance and functionality of the components of a TBM, including the cutter head, gripper system, thrust components, and the back-up system. Furthermore, it provided information on mucking and the conveyor system. It focused on the muck car-rail method. This informational article did not perform an analysis or study. Therefore, it did not provide results or conclusions.

2.1.4 Project Documents – Jollyville Transmission Main WTP4

Much of the information used for this thesis was extracted from the Jollyville Transmission Main WTP4 tunnel project contract documents. The plans, specifications, and Geotechnical Baseline Report (GBR) were beneficial to the completion of this research. The project submittals provided by Southland Contracting/Mole Constructors Joint Venture contained information on the methods of production as well as details regarding the equipment used on the project. It was necessary to thoroughly read and understand these documents.

Consulting with the management, superintendents, and professionals in the tunneling industry was largely beneficial with the costs and time restraints associated with various options. These individuals were able to help the author understand the different mucking methods. It was important to have access to vendor quotes, subcontracts, and purchase orders for the project.

2.1.5 Evaluation and Prediction of Tunnel Boring Machine Performance in Variable Rock Masses

This study was a dissertation found on the ProQuest database and describes the basic operating features of tunnel boring machines and recognizes factors that impacted their performance (Laughton 1998). It used a database to perform prediction of excavation rates based on performance, machine, and rock masses. This dissertation studied other areas involved in tunneling such as rock mass behavior and cutter head penetration, but the main focus was on TBMs.

Although this reference did not emphasize muck removal methods, it did discuss various muck removal options. It also recognized issues regarding the lack of data for TBM penetration rates and productivity. That issue was evident when searching for valuable references. The dissertation aimed at providing a method for quantifying the risks involved with tunnel excavation based on the context of the project plan.

2.1.6 Simulation Based Productivity Modeling for Tunnel Construction Operations

The focus of this dissertation was the simulation of tunneling projects to assist with the planning of the project (Chung 2007). Due to the obvious risks involved with excavating a tunnel, the simulation allowed prediction of problems prior to the costly effects of approaching the issues in the field. Schedule and budget largely benefited from the use of productivity simulation.

Chung (2007) presented the simulation-based productivity model while focusing on three major areas of research. First, he used a Bayesian updating application, the original schedule and budget was updated based on the actual construction data combined with subjective construction data. This increased the accuracy of future simulation outcomes. Second, the author developed a productivity model to portray the effects of factors of uncertainty. The accuracy of estimating excavation rates, TBM downtime, and mechanical issues were initially based on past experiences and, therefore, could be incorrect. The third area of research involved planning for future transitions in soil conditions using the simulation-based productivity model. This research concluded that simulation of the tunneling project can increase productivity.

2.1.7 A Risk-Based Dynamic Decision Support System for Tunnel Construction

This dissertation was focused on developing a computerized decision support system (DSS) to allow for contractors to plan for optimal sequencing of tunneling operations (Likhitruangsilp 2003). It discussed the important factors of uncertainty involved with tunneling and used available information to directly address these issues.

The dissertation recognized the difficulty in predicting ground conditions as well as the performance of a TBM. This report was significant to the industry by providing a DSS that was sensitive to risks while combining that with the contractor's work breakdown structure. The risk-based dynamic support system was capable of examining the associated risks of a project, investigating the contractor's risk relative to the chosen tunneling method, and providing results for a more accurate time and cost estimate.

2.1.8 Intelligent Decision Support System of Type Selection for Tunnel Boring Machine

This journal article emphasized the need to select and design the proper TBM for the desired project (He and Wu 2007). The authors studied important features and parameters of rock TBMs, as well as engineering data of completed tunnels. They analyzed the economic efficiency and overall productivity of the TBM by predicting and evaluating the time and cost associated. They then created a computer-based decision support system. This DSS was beneficial to the designer of TBMs by fulfilling the TBM type selection during the conceptual stages of design and allowed for the selection of the TBM to be compatible and appropriate for the associated tunnel construction.

2.1.9 Computer-Based Hybrid Model for Estimating Tunneling Excavation Productivity

The author of this thesis focused on simplifying the process of predicting tunnel excavation productivity (Baeza-Pereyra 1998). He used a model for enhancing the computational process by combining Artificial Neural Networks, Knowledge-Based Expert Systems, and Discrete Event Simulations. He was able to compare the tunnel excavation rates of the model to historical data from completed tunnel projects that were excavated using drill and blast method and TBMs. His model provided an advantage by speeding up the process of predicting excavation rates, being implemented using commercial software available to the market, and discovering trends and behaviors from databases regarding tunnel excavation.

2.1.10 Analysis of Performance of Tunnel Boring Machine-Based Systems

This thesis focused on maximizing the performance of TBMs and accurately predicting the performance prior to the tunnel project (Abd Al-Jalil 1998). He completed a breakdown of the components of a tunnel boring machine, as well as the production process of typical tunnel excavation projects. He aimed to completely comprehend the variability in the time and cost to complete a tunnel by considering three main factors: reliability and characteristics of the TBM and back-up system, geologic conditions and variations along the tunnel, and the comprehensive quality of management. One main contribution of this study was the compilation of approximately twelve tunneling projects and forming a database so that construction simulation programs could be developed and validated. He concluded that overall TBM performance relies directly on the machine failures and the time required making the necessary repairs.

2.1.11 Simple and Practical TBM Performance Prediction

This journal article presented the factors involved in maintaining performance of tunnel boring machines (Tarkoy 2009). He discussed the methods for predicting TBM excavation rates and utilization rates. He mentioned that the predicted utilization rate was often overlooked and could be a large variable with the greatest impact. He further discussed the other variables involved in TBM performance, such as project conditions, TBM downtime, management, site limitations, and the labor work force. He mentioned that many of the factors are based on human elements, and therefore can be difficult to predict. This article concluded the excavation rates will typically vary from predicted rates by +/- 5%, and utilization rates will vary +/- 20% from those predicted based on experience, calculated cycle times, and professional judgment. Therefore, the utilization rate will have a greater impact on the daily advance rates of a TBM.

2.1.12 Advancement Simulation of Tunnel Boring Machines

The authors of this article aimed at foreseeing the disturbances in tunnel excavation production involved with TBMs (Rahm, et al. 2012). It has been studied and reported that a significant amount of time is lost due to unknown geological conditions, machine component failures, and inefficient production methods. This paper presented two combined simulation techniques involving the advancement rates of TBMS and allowing for disturbances to be easily noticed: discrete simulation and continuous simulation. They implemented a case study using the simulation technique to demonstrate the functionality of the process. The case study comparisons demonstrate the significant influence of technical failures on TBM performance.

2.2 Chapter Summary

This chapter provided examples of past research on tunneling productivity. The sources presented were beneficial to the completion of this thesis by expanding the author's knowledge of the tunneling industry. These sources demonstrated the uniqueness of each tunnel and how project and site factors can determine means and methods. The Southland Contracting project documents were critical to the data collection portion of the case study.

CHAPTER 3

CASE STUDY DATA COLLECTION

3.1 Introduction

As mentioned earlier, this thesis used the Jollyville Transmission Main – Reach #2 for the Water Treatment Plant #4 near Lake Travis in Austin, Texas. Data was collected as a result of many hours of observation and based on personal involvement with the project, which enabled the author to record the times used for the muck removal method.

3.2 Jollyville Transmission Main WTP4 – Reach #2

Reach #2 of the Jollyville Transmission Main WTP4 tunneling project stretched a total of 20,434 feet, and was more than twice as long as Reach #3, the second longest reach. It was excavated using a manned 128-inch new High Performance Open Gripper Hard Rock Tunnel Boring Machine and Back-up System, a TBM that was specifically designed and manufactured by Robbins for the Jollyville Transmission Main WTP4 Project.

The tunnel reach did not require the construction of a starter tunnel and a tail tunnel due to the fact it was extending on from a completed Reach #1. A starter tunnel and tail tunnel are mined to provide working room in the shaft. For example, a muck train can pull into the tail tunnel in order to provide space for raising and lowering individual muck cars. The Reach #1 tail tunnel became the Reach #2 starter tunnel, and the existing Reach #1 tunnel became the Reach #2 tail tunnel. The starter tunnel was a 12-foot horseshoe shape supported with split set bolts over wire mesh.

3.2.1 Robbins Tunnel Boring Machine

The TBM cutter head consisted of twenty-five (25) 17-inch cutters mounted with propel pressure coming from the two (2) 14-inch diameter main thrust cylinders capable of a 60-inch stroke. The Reach #2 cutter head is shown in Figure 1.2. The completion of one 60-inch stroke was considered one cycle. The TBM used 900 horsepower with a maximum thrust of 1,400,000 lbs @ 5,000 psi and used the Poltinger

Precision System (PPS), a TBM-type guidance system which monitors real-life line, grade, and location. The PPS used a survey total station and set of prisms to continuously locate the TBM coordinates. The TBM's gripper system contacted rock from 45-degrees above spring-line to 45-degrees below spring-line. Once in place, the TBM pushed off the cylinders and inched forward. The grippers remained in place for a maximum of 60 inches, and were the only part of the machine that remained in place. Once the stroke was completed, the grippers were retracted, pulled forward along the gripper carrier and once again forced out making contact with the rock. The gripper carrier was located on the main beam, a large beam that ran from the main bearing to the back of the operator's cab. The main beam was essential for the configuration of the open gripper system. Figure 3.1 presents the open gripper system.

Figure 3.1. The Robbins TBM gripper system.

Ventilation ducts were 38 inches in diameter made from 20-gauge steel with negative air pressure to remove dust and contaminated air. Electrical equipment consisted of a 1,200 kVA ventilated dry-type transformer on the TBM and a 15 KV 4/0 3-phase power cable in the tunnel. The TBM power cable ran along the tunnel wall. There were utilities running along the opposite wall, including a 6-inch PVC water discharge, a 2-inch PVC water supply, and a 2-inch black steel air supply.

3.2.2 Muck Removal Procedure

The back-up system was designed for the use of the muck car/rail method of muck removal. Spoil material generated by the TBM cutter head was transported out of the head by a 22-inch belt conveyor running through the main beam of the TBM. It dropped the material through a transfer chute located just behind the operator's cab, onto a connecting conveyor belt that inclined upward and passed over the equipment sleds to discharge the cuttings into muck cars. The material was placed into three eight (8) cubic yard lift-off muck boxes. They were pulled by one 10-ton locomotive used to transport muck, via rail, to the shaft for removal. The boxes were then raised to the surface, dumped in the designated area, and lowered back onto the rail.

While the muck cars in the heading were filled during one cutting stroke of the machine, another muck train was unloaded in the shaft area. Once the train was unloaded, it was parked on one side of the switch that was located in the starter tunnel. This allowed the full train to return to the shaft and pass the empty train. A California Switch, a raised switch that is capable of being pulled throughout the tunnel along the rail, was installed approximately every 4,500-foot in order to allow for an additional muck train to maintain production.

3.3 Conceptual Hierarchy Flowchart

To determine which muck removal method to utilize, a hierarchy process, or decision flowchart, can help to guide a contractor through factors that needed consideration.

It was necessary to understand that the continuous conveyor method would involve additional capital costs for the contractor, compared with the muck car/rail method. For rough order of magnitude estimating purposes, the continuous conveyor method can be considered to double the price of a TBM configured for the muck car/rail method. For the given case study, the TBM was purchased at $4.8 million, whereas the TBM configured for a continuous conveyor would have cost $9.8 million. All the factors shown in Figure 3.2 were considered and had an impact on the project costs and savings.

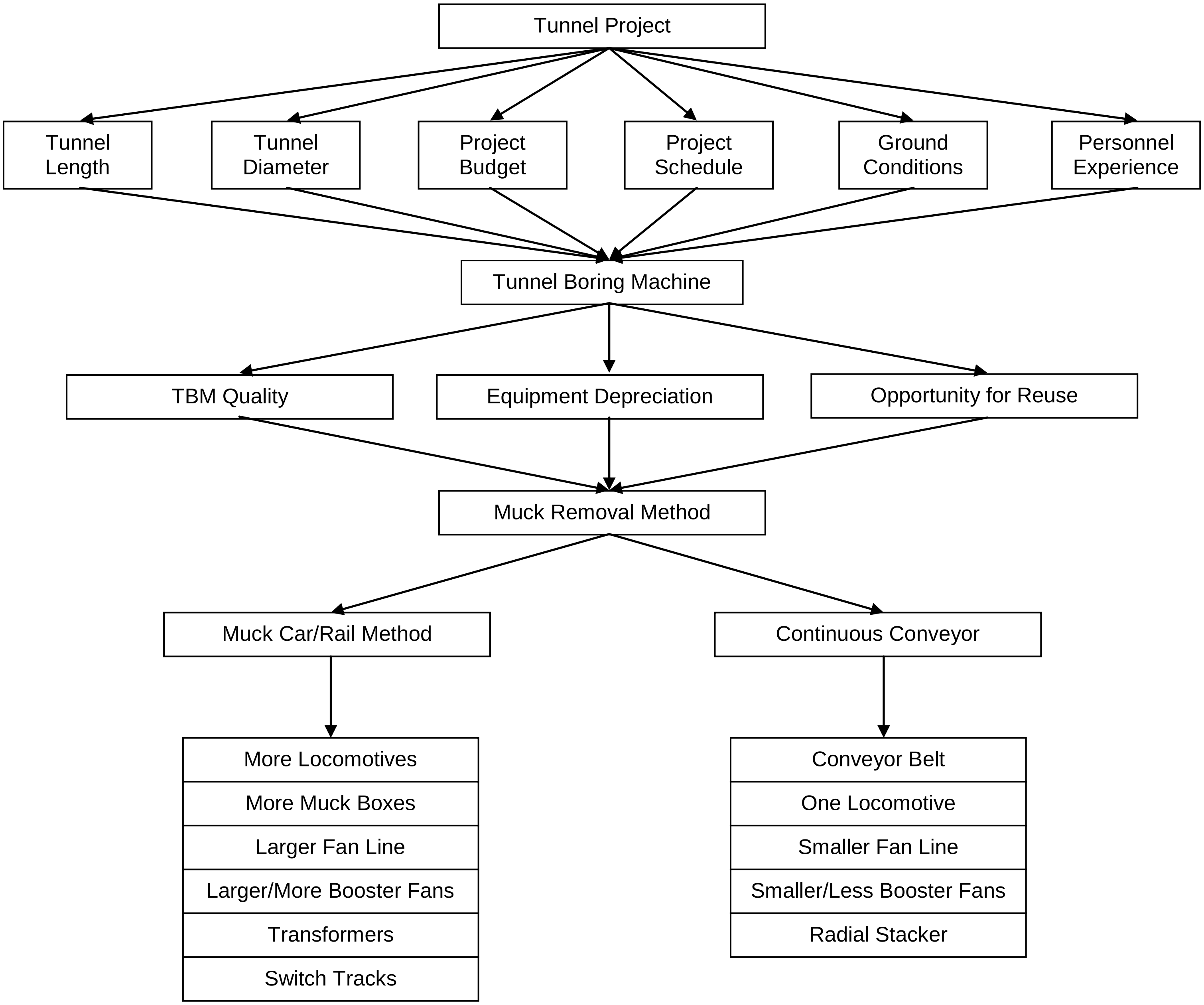


Figure 3.2. Conceptual Hierarchy Flowchart for Tunneling Projects.

As shown in the Figure 3.2, during the first stages of decision making for a tunneling project, the major factors are the tunnel length, tunnel diameter, project budget, project schedule, ground conditions, and personnel experience. These factors not only influence the muck removal method, but significantly influence the means and methods for shaft excavation, the use of a TBM, and tunnel lining. Table 3.1 demonstrates the main factors when considering the use of a TBM.

Table 3.1 Factors to Consider for Use of TBM

Factor	Description
Tunnel Length	Practicality of using a TBM.
Tunnel Diameter	Determine constructability of tunnel using TBM.
Project Budget	Quantity, size, quality of TBM.
Project Schedule	Determine the necessary excavation rate.
Ground Conditions	Determine type of TBM to be used.
Personnel Experience	Experience working with TBM and desired muck removal method.

Once the decision to use a TBM is made, the contractor must then consider secondary factors. First, it is necessary to weigh the different TBM options. A refurbished TBM might be more problematic then the new TBM. So TBM quality needs to be considered. Often a refurbished TBM is utilized for shorter reaches where managing the problems is more practical. Second, the contractor must determine the depreciation of the TBM over the project duration. If the TBM will be paid in full for the intended project, it allows for savings on future projects. Third, what options for reuse will be available at the end of the project. Often the TBM will need to be refurbished for the use on the next project due to the uniqueness of a tunneling project. Muck removal equipment, such as the locomotives and muck cars can often be reused as well. The small costs associated with repairs and services of the used equipment rather than purchase of new equipment, increases the savings on future projects.

After the TBM type and size is determined, the options for muck removal must be weighed. Once this decision is made, the TBM can be engineered to the specifications desired by the contractor. The two options are muck car/rail method and continuous conveyor. The major costs associated with each method will also influence a decision as well as help to estimate an overall budget and schedule. A time and cost analysis must be performed to determine the muck removal method. It would benefit the contractor to estimate the utilization rate, and then estimate the excavation rate with each different type of muck removal method. Table 3.2 presents the use of an estimated utilization rate. Table 3.3 presents the formula and example for predicting excavation rate. Table 3.4 shows the factors related to the individual muck removal methods.

Table 3.2 Example for Calculating Utilization

	Muck Car/Rail Method	**Continuous Conveyor**
TBM Utilization = U	40%	75%
Hours/Shift = S	12 hrs	12 hrs
Hours of TBM Operation = U*S = X	(12) * (0.40) = 4.8 hrs	(12) * (0.75) = 9

Table 3.3 Example for Calculating Excavation Rate

	Muck Car/Rail Method	**Continuous Conveyor**
Feet of Excavation = F	50 ft	180 ft
Hours of TBM Operation = H	4.8 hrs	9 hrs
Excavation Rate = F/H = Y	50/4.8 = 10.42 ft/hr	180/9 = 20 ft/hr

Table 3.4 Considerations for Muck Removal Methods

Factor	**Muck Car/Rail Method**	**Continuous Conveyor**
Cost	Lower upfront cost	Higher upfront cost
Schedule	Lower TBM utilization	Higher TBM utilization
Locomotives	Additional locomotives for each switch track.	Only one locomotive required
Transport	Three muck cars for each locomotive	Conveyor belt double the length of the tunnel
Ventilation	Larger fan line and more booster fans.	Smaller fan line and less booster fans.
Other Equipment	Switch tracks, Transformers	Radial stacker

3.4 Muck Removal Time Study

On Reach #2 of the Jollyville Transmission Main WTP4 project, one month of the tunneling process was taken to observe and record the push times and downtimes for approximately twenty (20) 12-hour shifts. By recording the start and finish of a push, one objective was to track how long it took to fill up a muck train and how long between pushes. This was essentially the time it takes for one train to get to the shaft and one train to return to the machine. Due to large data size of train cycle times (travel of trains to and from shaft), it is provided in Appendix A, Push Time/Downtime – Time Study.

It must be noted that throughout the recording and observing of the muck removal process, mechanical issues with the tunnel boring machine as well as the locomotives caused further downtime. Mechanical issues, as well as routine maintenance were inevitable for ongoing operations, such as replacing hoses, changing filters, repairing the conveyor system, as well as fine tuning the tunneling process and increasing teamwork amongst the crews. These tasks are necessary to maintain good production.

There was a change in downtimes towards the end of August 2012, in which downtime decreased. This was because within the first 500 – 600 feet of excavation, only one train was used. After that, a switch was installed in the starter tunnel, and a second train was added resulting in an increase in production. As the distance to travel from the machine to the shaft increased, so did the amount time it took to complete one cycle.

According to this case study, the TBM average push time was 18 minutes. The average wait time for another train to arrive at the machine was 20 minutes, with a total 38-minute average cycle time. If the TBM and crew were able to operate the machine for 10 hours without delays, theoretically, that would allow for 15 cycles. If time was deducted for lunch, maintaining rail, fan line, utilities, and other maintenance, it would allow for only 13 cycles. It also must be noted that for the range at which the observations were made, the train was traveling anywhere from 200 feet to 2,000 feet based on the distance from the shaft to the TBM. The periodic recordings of this study, shown in Table 3.5, proved that the locomotives on average pulled a full train at a rate of approximately 350 feet per minute.

Table 3.5 Rate of Speed to Pull Muck-Filled Train

Date	**TBM Station**	**Shaft Station**	**Distance (ft)**	**Time (min:sec)**	**Speed (ft/min)**
8/27/12	50+83	44+51	632	1:48	351.1
9/24/12	67+77	44+51	2326	6:54	337.1
10/5/12	81+33	44+51	3682	10:25	353.5
11/16/12	113+57	44+51	6906	19:29	354.5
12/1/12	123+25	44+51	7874	23:11	339.6
12/12/12	133+96	44+51	8945	26:01	343.8
				Avg.	**347 ft/min**

The above recordings were taken before the installation of the California Switch. The installation of the California Switch allowed for an additional train. Traditionally, with the use of a California Switch, there is a train being loaded with muck at the machine, an empty train waiting at the switch, and a full train with individual muck cars being raised to the surface for dumping. These California Switches were installed approximately every 4,500 feet. This addition to the muck removal process changed the time it took to pull a muck train to the shaft, although it slightly increased or maintained productivity.

One recurring issue that was encountered on this tunnel reach was the wheels of the locomotive slipping on the rail. This was caused by the fact that fully loaded muck trains were being pulled slightly uphill to the shaft, combined with the water along the tunnel invert, reducing the frictional force between wheels and rail. Attempts were made to overcome the issue: new, larger engines were installed in the locomotives, sandboxes were attached to the locomotives to provide traction, and locomotives pulled only two muck cars per train in order to reduce weight. All of the above solutions could not completely fix the problem, and these efforts took time away from production. Therefore, the tunnel boring machine was not running at its full potential capacity.

One main improvement could have certainly maintained production. An increased size of locomotives would have been largely beneficial, although that required many extreme changes to the overall project: larger diameter TBM due to increased tunnel diameter, larger ventilation, and larger switch tracks. This decision would have needed to be made in the planning stages of the project. Therefore, the requirements for maintaining the locomotives included proper training to the locomotive operators as well as continuously fulfilling the necessary routine services. Using simulation techniques to foresee the challenges faced with the locomotives could have allowed for a more efficient muck removal process.

3.5 Continuous Conveyor

All these downtimes and loss of overall production brought up the question of how to improve overall production of a tunnel boring machine and decrease the amount of downtime. One solution, and most likely, the only solution, would be to use a continuous conveyor. This decision is not one that can be made in mid-operation. It needs to be planned when the TBM configuration is being designed, as well as when the budgeting and scheduling portions of the preconstruction process are occurring. This option was weighed on this particular project, although there is difficulty in anticipating future issues and the late start of tunnel excavation, even with the use of simulation.

3.5.1 Continuous Conveyor – Cost Analysis

The use of a continuous conveyor would cost the tunneling contractor significantly more money on the front end of the project. Using the Jollyville Transmission Main WTP4 Project, it was necessary to consider the additional costs, as well as the costs for items not needed with the use of a continuous conveyor. Clearly, one of the most important changes would have been schedule. It would have taken Southland/Mole Joint Venture an additional one month for initial setup for using the continuous conveyor. Whereas the Reach #2 was scheduled to excavate approximately 85 feet per day with utilization rate of 35%. The use of a continuous conveyor would have allowed for a rate of 190 feet per day with a utilization rate of 75%. These rates (daily linear footage) were a result of in-depth discussions with upper management at Southland Contracting and The Robbins Company. This would have cut the scheduled time for excavation in half, which cuts the daily job costs in half, including wages, fuel, and the overall haul-off costs. Table 3.6 shows the major front-end cost differences between using the muck car/rail method and the continuous conveyor method.

Table 3.6 Up front costs for muck removal methods (2012 dollars)

Item	**Muck Car Rail Method ($)**	**Continuous Conveyor ($)**	**Continuous Conveyor Explanation**
Locomotives $200,000	6 Needed $1.2 mil	2 Needed $400,000	Needed only to bring in utilities and personnel
Muck Cars $25,000	16 Needed $400,000	0 Needed	Not needed
California Switch $150,000	4 needed $600,000	0 Needed	Not needed
TBM	$4.8 mil	$9.8 mil Including cassette, belt	Additional 1-2 months for initial setup
Ventilation $19/ft plus fans	$500,000 Including fans	$150,000 Including fans	More locomotives require more ventilation
TOTAL	**$7.5 mil**	**$10.35 mil**	**Net difference = $2.85 mil**

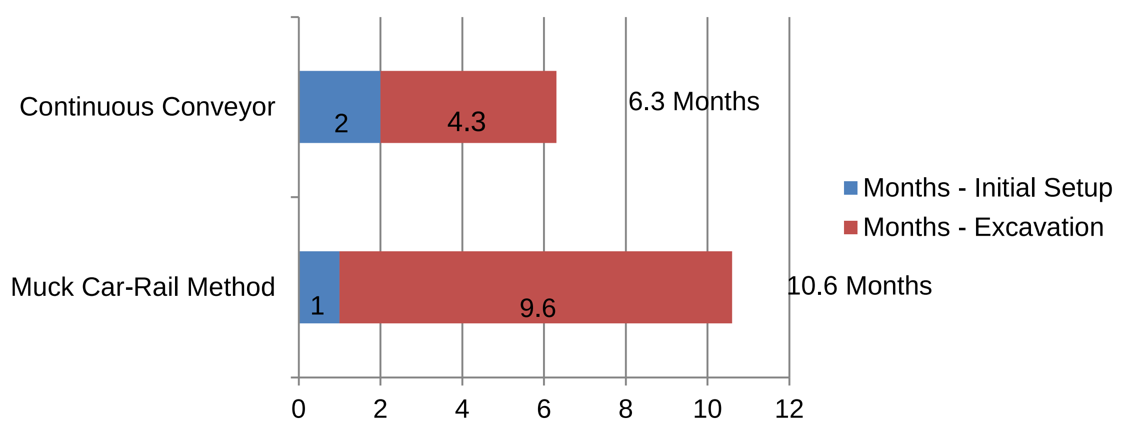
The net difference in the up-front costs was approximately $2.85 million. That is a large amount of money on the front-end of the project, but simultaneously, could be viewed as a wise investment when

TBM utilization is considered. According to project personnel, the daily rate for operations was approximately $18,000 for Reach #2. Using that number, Table 3.7 shows an analysis of the costs representing work completed based on schedule. Figure 3.3 presents the excavation schedule for each muck removal method.

Table 3.7 Cost analysis of muck removal methods (2012 dollars)

	Daily Rate of Operations for Reach #2 (Wages, fuel, misc.)	**Number of Days in Operation (25 Working Days/Month)**	**Total Costs**
Muck Car/Rail Method	$18,000	10.6 months = 265	$4.77 mil
Continuous Conveyor	$18,000	6.3 months = 158	$2.844 mil
Net Difference		**107**	**$1,926,000**

Figure 3.3 TBM Excavation Schedule



The use of a continuous conveyor would have resulted in the contractor accumulating an extra $924,000 in upfront costs ($2.85 mil - $1.926 mil). If the contractor was being paid $800 per foot for horizontal excavation, Reach #2 would generate approximately $16.35 million in revenue. That revenue would be generated in 6.3 months (158 days), rather than the 10.6 months (265 days) it would have taken using the muck car/rail method. There was a total of 4.3 months after the completion of the tunnel reach that would have allowed for the installation of pipe, which would typically generate its own revenue based on footage installed. Given that Reach #2 was on the critical path, this allowed for an estimated 2- to 3-month completion ahead of the scheduled project. That quicker completion would have saved money on project costs, project wages, and overhead, as well as the depreciation and quality of equipment and assets.

Table 3.8 shows what items would have been necessary and what items could have been avoided by completing the project two months ahead of the overall project schedule. The numbers are based on the fact that Reach #2 was on the critical path and the other legs of the tunnel were completed prior to or simultaneously. Therefore, the pipe installation could have been simultaneously occurring on Reach #2 and Reach #3. Additional pipe carrier and additional crew might have not been necessary, but the overall difference exceeds the $924,000 spent on the front end. Table 3.8 only includes the major items.

Table 3.8 Overall Project Cost Savings

Description	**Additional**	**Unit Price (2012 Dollars)**	**Overall Project Total Costs (2012 Dollars)**
Daily Costs of Overall Project	2 months = 50 days	$40,000/day	$2.0 mil
Project Overhead	2 months	$25,000/month	$50,000
Additional Pipe Carrier	1 EA	$100,000	($100,000)
Additional Labor	1.8 months = 45 days	$300,000	($300,000)
		TOTAL	**$1,650,000**

3.6 Chapter Summary

Chapter three provided key information regarding the case study project. This chapter also provided a flowchart for the decision making process involved on a tunnel project. The case study was used to perform a time based measurement which resulted in the average push times and downtimes for the production process. The study compared the existing muck removal method with the continuous conveyor method, which further allowed for a cost comparison and the resulting possible amount of time and money saved on the Jollyville Transmission Main WTP4 project. It is important to note that this study involved the major costs which can vary with other factors and unknowns involved in all tunneling projects. With each individual tunneling project being unique, it was essential to include various costs associated with each muck removal method. This study provided contractors with an example of theoretical analysis of the options available to them. The study showed that the contractor would have saved at least $726,000 ($1,650,000 - $924,000) by using the continuous conveyor, not including several other factors involved in the project, such as mechanics fees, locomotive repairs, miscellaneous tools and parts. This savings included an estimated expense for project overhead.

CHAPTER 4

DISCUSSION OF RESULTS

4.1 Discussion of Results

Based on the data collected in this thesis, the decision to use a continuous conveyor would have had a beneficial impact on project costs and project schedule. Other issues that can impact the decision are contractor's experience with the muck car/rail method or continuous conveyor. There are other justifications for such a decision. In fact, Southland Contracting considered use of a continuous conveyor, particularly for Reach #2. When the project was initially scheduled, Reach #2 was not the tunnel reach in which they were concerned about delays, resulting in the decision to use the muck car/rail method. This case shows the difficulty in anticipating the delays of a tunneling project.

The contractor must take certain steps and consider factors when selecting a method to excavate a tunnel. First, the following parameters must be considered in order to decide if a TBM is practical and is the most efficient method.

- Tunnel Length
- Tunnel Diameter
- Project Budget
- Project Schedule
- Ground Conditions
- Personnel Experience

Once the decision is made to use a TBM, the factors of depreciation, TBM quality, and the availability of the TBM for reuse on future projects must be taken into account. The contractor can then decide on the muck removal method: muck car/rail method or continuous conveyor, and begin the engineering and manufacturing of the TBM. Table 4.1 summarizes the factors to be considered when selecting a method.

Table 4.1 Factors Affecting Muck Removal

Muck Car/Rail Method	**Continuous Conveyor**
Lower Upfront Cost	Higher Upfront Cost
Lower TBM Utilization Rate	Higher TBM Utilization Rate
Less Experience/Maintenance Required	More Experience/Maintenance Required
More Locomotives	One Locomotive
Muck Boxes	More Conveyor Belt
Larger Ventilation	Smaller Ventilation
Larger/More Booster Fans	Smaller/Less Booster Fans
More Transformers	Radial Stacker
Switch Tracks	

If this project were to be duplicated, the decision to use a continuous conveyor would be wise. This would prevent the many stresses caused by mechanical issues encountered with locomotives, as well as the issues with muck boxes derailing thereby causing further delays. The use of a side-mounted continuous conveyor allows for maximizing TBM utilization that would have provided the contractor with a chance to maximize profit.

As mentioned previously, in the existing literature, there is lack of data regarding the TBM productivity and excavation rates. The excavation rates are directly proportional to the muck removal process. There are so many variables that affect the daily average or shift average rates (e.g., length of tunnel, diameter of tunnel, tunnel support, ground conditions, condition and type of TBM, muck removal methods, crew experience, utilization rates, and shift lengths). Considering the three tunnel reaches of the Jollyville Transmission Main (with similar ground conditions) the following excavation coverage data was recorded:

- Reach #1 excavated 4,451 feet of tunnel with an average of 34 feet/shift.
- Reach #2 excavated 15,142 feet of tunnel with an average of 44 feet/shift. This mining process was ongoing.
- Reach #3 excavated 9,680 feet of tunnel and averaged 33 feet/shift.

Reach #1 and Reach #3 were excavated using refurbished TBMs. All tunnel reaches were running 24-hour operations (two 12-hour shifts). These average shift rates include all downtime for various mechanical failures as well as installation of switch tracks and other necessary equipment. In another example, the Onion Creek tunnel, a similar project completed by Southland Contracting in Austin, Texas, excavated 4,600 feet of tunnel while averaging only 15.5 feet/shift. That tunnel was 88-inches in diameter, required no tunnel support, and was mined using a refurbished TBM. This example proves that many variables play a role in the overall production rate of a tunnel boring machine.

To validate the results of this research, they were discussed with the General Superintendent and Project Manager of the case study project. Both approved the data used to conduct the analysis, as well as the findings, and admitted that Southland Contracting did consider the use of a continuous conveyor for the Jollyville Transmission Main Tunnel Project. They performed a cost analysis, similar to the one provided in this thesis, which resulted in an overall savings. They calculated $2.6 million in up-front cost for the continuous conveyor, but expected a greater savings, especially when considering an early overall project completion. The overall savings and profit was difficult to accurately calculate due to the unknowns involved with the remainder of the project. One primary reason for the decision to use the muck car/rail method was the personnel inexperience with continuous conveyors, or even more-so the combined knowledge using the muck car/rail method. Also, Reach #1 and Reach #3 were using the muck car/rail method, which allowed for an overlap of equipment, parts, and rail. With the purchase and use of the brand new Robbins TBM, production and utilization rates of the TBM was not considered an issue.

4.2 Chapter Summary

This chapter provided a discussion of the case study results. A summary of the factors to be considered by the contractor for determining not only the use of a TBM, but the configuration and muck removal method of a TBM and the production process was presented. The results were validated by discussions and comparisons with the project contractor and personnel.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusions

The tunneling industry is no different than any industry within the construction business. Options must be weighed and measured in order to visualize how the project will progress. Sometimes, the decisions must be made months and even years in advance of the actual date of excavation, and therefore, studies such as this one need to be conducted and utilized for all areas of construction that are critical to project completion. Simultaneously, it is difficult to envision what the future holds for a construction project, especially a tunneling project. Rarely will operations occur exactly as they were envisioned and planned.

The overall goal of the tunneling contractor is to minimize project downtime and maximize production. Efficient project production is the key factor to maximizing profits. It was concluded that the use of a continuous conveyor for the Jollyville Transmission Main WTP4 Reach #2 Tunnel would have maximized productivity of the TBM. The TBM was capable of a greater utilization rate than the muck car/rail method, and the use of a continuous conveyor would have resulted in a faster completion and greater profit for the contractor.

The conclusions of this thesis can be summarized as follows:

- All tunneling projects are unique and it can be difficult to compare TBM production.
- Many factors need to be considered before selecting a tunnel excavation method for a project. Decision support systems and simulation techniques can assist with the investigation process.
- The chosen muck removal method can largely impact production, utilization, budget, profitability, and schedule.
- The JTM – Reach #2 would have largely benefited from the use of a continuous conveyor.
- The tunneling industry needs a common database and more research on historical productivity. It is difficult to gain access to the individual tunneling projects and associated production numbers.

5.2 Recommendations for Future Research

To individuals looking to conduct a study such as this, the assistance of professionals in the tunneling industry as well as the ability to view project documents could greatly facilitate the process.

For students searching for research topics, this thesis would be beneficial to the following topics:

- Research possibility of switching muck removal methods mid-operations. It is assumed that this option is not practical due to the TBM design and financial loss suffered by the contractor. Contrary to this, it has not been researched and could provide valuable information to the industry.
- Create a decision support system (DSS) for TBM productivity and muck removal methods that include risk factors. The DSS would certainly be beneficial to the tunneling industry and will provide contractors with the necessary information to make major decisions. It would allow a contractor or engineer to enter the specific tunnel information to the spreadsheet, and results would provide essential information for choosing the most compatible TBM type and the preferred method for muck removal.
- Use the accurate data provided in this thesis to compare to a real-life tunneling project utilizing a continuous conveyor. This thesis did not have access to observe and record data for a continuous conveyor. The ability to study a continuous conveyor and make comparisons between results would be interesting and beneficial.
- Further analyze other muck removal methods and TBM downtimes. The observation and recording of muck removal methods and TBM utilization rates for several case study projects would supply contractors with results to which preliminary estimating and scheduling can be based.

APPENDIX A

PUSH TIME/DOWNTIME
TIME STUDY

APPENDIX A – Push Time/Downtime – Time Study

Push Time/Downtime – Time Study

Date	Line	Grade	Time Start	Time Finish	Station	Time of Push	Downtime
8/20/2012	-0.30	3.60	9:06	9:47	4716	0:41	
	-0.30	3.66			4720	0:00	
	-0.26	3.67	10:02	10:48	4724	0:46	0:20
	-0.24	3.62	11:08	12:26	4729	1:18	0:28
	-0.23	3.59	12:54	1:54	4733	1:00	0:21
	-0.22	3.55	2:15	3:14	4738	0:59	3:26
	-0.21	3.53	6:40	6:51	4739	0:11	
8/22/2012	0.14	3.40			4759		
	0.13	3.37	10:07	10:37	4763	0:30	0:27
	0.10	3.34	11:04	11:23	4767	0:19	0:25
	0.08	3.31	11:48	12:04	4772	0:16	0:24
	0.07	3.29	12:28	12:54	4776	0:26	0:26
	0.05	3.29	1:20	1:30	4780	0:10	0:28
	0.03	3.29	1:58	2:08	4785	0:10	0:32
	0.01	3.26	2:40	2:50	4789	0:10	0:27
	0.00	3.24	3:17	3:29	4794	0:12	0:27
	0.02	3.23	3:56	4:09	4798	0:13	0:24
	0.03	3.20	4:33	4:43	4803	0:10	0:29
	0.04	3.20	5:12	5:23	4807	0:11	0:26
	0.06	3.20	5:49	6:00	4812	0:11	0:30
	0.06	3.18	6:30	6:39	4810	0:09	
8/23/2012	0.23	2.86			4871		
	0.25	2.80	7:50	8:01	4875	0:11	0:23
	0.26	2.83	8:24	8:40	4879	0:16	0:25
	0.28	2.84	9:05	9:18	4884	0:13	0:27
	0.32	2.81	9:45	9:58	4888	0:13	0:44
	0.33	2.79	10:42	10:50	4892	0:08	0:26
	0.35	2.78	11:16	11:27	4897	0:11	0:28
	0.35	2.77	11:55	12:08	4901	0:13	0:26
	0.35	2.74	12:34	12:54	4905	0:20	0:24
	0.36	2.72	1:18	1:37	4910	0:19	0:23
	0.36	2.71	2:00	2:26	4915	0:26	
8/24/2012	0.35	2.66			4928		
	0.32	2.66	7:53	8:04	4932	0:11	0:26
	0.29	2.64	8:30	8:41	4936	0:11	0:23

APPENDIX A – Push Time/Downtime – Time Study

	0.26	2.64	9:04	9:24	4941	0:20	0:35
	0.23	2.63	9:59	10:11	4945	0:12	0:40
	0.21	2.62	10:51	11:02	4949	0:11	0:29
	0.20	2.59	11:31	11:51	4954	0:20	0:45
	0.19	2.56	12:36	12:52	4959	0:16	0:31
	0.17	2.53	1:23	3:10	4964	1:47	0:04
	0.18	2.55	3:14	3:19	4965	0:05	0:29
	0.19	2.51	3:48	3:55	4968	0:07	
	0.18	2.51	3:55	4:05	4969	0:10	0:25
	0.18	2.50	4:30	4:42	4973	0:12	0:30
	0.20	2.47	5:12	5:23	4978	0:11	0:32
	0.20	2.45	5:55	6:05	4982	0:10	
8/25/2012	0.26	2.28			5012		
	0.20	2.26	3:30	3:42	5016	0:12	0:32
	0.21	2.24	4:14	4:27	5021	0:13	0:40
	0.21	2.23	5:07	5:25	5025	0:18	0:25
	0.22	2.20	5:50	5:57	5027	0:07	0:23
	0.21	2.19	6:20	6:30	5030	0:10	0:15
	0.22	2.17	6:45	6:52	5033	0:07	0:19
	0.22	2.11	7:11	7:18	5035	0:07	0:18
	0.23	2.13	7:36	7:43	5038	0:07	0:23
	0.23	2.10	8:06	8:14	5041	0:08	0:22
	0.23	2.09	8:36	8:44	5044	0:08	0:18
	0.22	2.07	9:02	9:10	5047	0:08	
8/27/2012	0.17	1.93			5074		
	0.17	1.87	8:20	8:30	5077	0:10	0:30
	0.17	1.85	9:00	9:11	5082	0:11	0:29
	0.16	1.83	9:40	9:51	5086	0:11	0:24
	0.15	1.81	10:15	10:25	5090	0:10	0:27
	0.14	1.80	10:52	11:05	5094	0:13	0:26
	0.12	1.78	11:31	11:42	5098	0:11	0:27
	0.11	1.76	12:09	12:21	5102	0:12	0:29
	0.11	1.76	12:50	1:02	5107	0:12	0:26
	0.11	1.75	1:28	1:41	5111	0:13	0:39
	0.08	1.73	2:20	2:32	5115	0:12	0:31
	0.09	1.72	3:03	3:14	5119	0:11	0:27
	0.09	1.69	3:41	3:53	5123	0:12	0:29
	0.09	1.68	4:22	4:33	5127	0:11	0:28

	0.09	1.68	5:01	5:13	5131	0:12	0:26
	0.09	1.67	5:39	5:50	5135	0:11	0:26
	0.09	1.65	6:16	6:28	5140	0:12	
8/29/2012	0.08	1.38	7:53	9:20	5183	1:27	0:07
	0.09	1.36	9:27	9:53	5187	0:26	0:16
	0.10	1.36	10:09	12:15	5192	2:06	0:03
	0.06	1.35	12:18	12:30	5194	0:12	0:07
	0.04	1.34	12:37	12:55	5198	0:18	0:06
	0.05	1.34	1:01	1:15	5203	0:14	0:10
	0.03	1.31	1:25	1:40	5208	0:15	0:08
	0.03	1.30	1:48	3:00	5209	1:12	0:02
	0.02	1.29	3:02	3:14	5212	0:12	0:09
	0.02	1.27	3:23	3:45	5217	0:22	0:06
	0.03	1.26	3:51	4:10	5221	0:19	0:10
	0.04	1.26	4:20		5227		
8/30/2012	0.09	1.12			5250		
	0.10	1.08	11:20	11:35	5255	0:15	0:07
	0.12	1.06	11:42	11:57	5259	0:15	0:12
	0.17	1.04	12:09	12:24	5263	0:15	0:10
	0.19	1.04	12:34	12:50	5268	0:16	0:07
	0.28	1.03	12:57	1:17	5275	0:20	0:08
	0.38	1.02	1:25	1:40	5276	0:15	0:21
	0.47	1.01	2:01	2:17	5281	0:16	0:15
	0.58	0.99	2:32	2:50	5285	0:18	0:05
	0.64	0.98	2:55	3:16	5289	0:21	0:12
	0.83	0.94	3:28	3:52	5293	0:24	0:10
	0.89	0.90	4:02	4:27	5297	0:25	
9/4/2012	1.07	0.84	8:44	9:00	5325	0:16	
	1.07	0.81	12:43	1:00	5329	0:17	0:10
	1.04	0.80	1:10	1:29	5333	0:19	0:08
	1.03	0.81	1:37	1:53	5337	0:16	0:10
	1.05	0.75	2:03	2:16	5341	0:13	0:08
	1.06	0.78	2:24	2:45	5345	0:21	0:20
	1.02	0.80	3:05	3:30	5350	0:25	0:10
	1.00	0.78	3:40	4:05	5354	0:25	0:16
	0.97	0.81	4:21	4:45	5358	0:24	0:11
	0.97	0.80	4:56	5:18	5362	0:22	0:54
	0.96	0.79	6:12	6:30	5366	0:18	

APPENDIX A – Push Time/Downtime – Time Study

9/5/2012	0.93	0.81			5378		
	0.95	0.78	7:37	7:59	5383	0:22	0:17
	0.92	0.77	8:16	8:33	5387	0:17	0:07
	0.92	0.78	8:40	8:56	5392	0:16	0:09
	0.92	0.77	9:05	9:25	5396	0:20	0:08
	0.95	0.78	9:33	9:55	5400	0:22	0:22
	0.97	0.78	10:17	10:39	5405	0:22	0:08
	0.98	0.77	10:47	11:07	5409	0:20	0:19
	0.99	0.76	11:26	11:46	5413	0:20	0:09
	0.96	0.79	11:55	12:22	5418	0:27	0:08
	0.98	0.80	12:30	1:00	5422	0:30	1:47
	0.98	0.79	2:47	3:14	5426	0:27	0:08
	0.98	0.79	3:22	3:50	5430	0:28	0:07
	0.99	0.79	3:57	4:27	5435	0:30	0:06
	0.99	0.79	4:33	5:00	5439	0:27	0:22
	0.98	0.79	5:22	5:54	5443	0:32	0:09
	0.98	0.76	6:03	6:32	5447	0:29	
9/6/2012	0.90	0.73			5494		
	0.69	0.70	9:25	9:45	5499	0:20	0:09
	0.85	0.71	9:54	10:17	5504	0:23	0:11
	0.85	0.70	10:28	10:52	5508	0:24	0:10
	0.85	0.69	11:02	11:28	5512	0:26	0:10
	0.84	0.69	11:38	12:10	5517	0:32	0:13
	0.83	0.68	12:23	12:40	5520	0:17	1:00
	0.83	0.67	1:40	2:08	5525	0:28	0:12
	0.83	0.68	2:20	2:41	5529	0:21	0:11
	0.83	0.65	2:52	3:21	5534	0:29	0:07
	0.82	0.64	3:28	3:54	5538	0:26	
9/7/2012	1.09	0.52			5620		
	1.11	0.52	7:42	7:57	5624	0:15	0:14
	1.13	0.50	8:11	8:24	5629	0:13	0:09
	1.21	0.48	8:33	8:48	5633	0:15	0:14
	1.27	0.47	9:02	9:20	5638	0:18	0:17
	1.35	0.47	9:37	9:56	5642	0:19	0:11
	1.41	0.46	10:07	10:24	5646	0:17	0:19
	1.49	0.44	10:43	11:01	5651	0:18	0:13
	1.55	0.46	11:14	11:32	5655	0:18	0:07
	1.58	0.46	11:39	11:59	5659	0:20	0:10

	1.64	0.47	12:09	12:32	5664	0:23	0:18
	1.65	0.45	12:50	1:12	5668	0:22	0:15
	1.69	0.46	1:27	1:41	5673	0:14	0:15
	1.70	0.45	1:56	2:13	5677	0:17	0:18
	1.73	0.43	2:31	2:47	5682	0:16	0:53
	1.73	0.42	3:40	3:57	5686	0:17	0:11
	1.75	0.41	4:08	4:24	5691	0:16	0:11
	1.75	0.39	4:35	4:49	5695	0:14	0:16
	1.76	0.42	5:05	5:20	5699	0:15	0:14
	1.75	0.40	5:34	5:50	5703	0:16	0:15
	1.75	0.39	6:05	6:20	5708	0:15	0:10
	0.17	0.40	6:30	6:46	5712	0:16	
9/8/2012	1.70	0.36			5720		
	1.71	0.36	3:32	3:49	5725	0:17	0:09
	1.69	0.34	3:58	4:14	5729	0:16	0:09
	1.67	0.33	4:23	5:25	5733	1:02	1:09
	1.66	0.33	6:34	7:05	5738	0:31	0:16
	1.66	0.32	7:21	7:34	5742	0:13	0:30
	1.65	0.33	8:04	8:14	5745	0:10	0:08
	1.64	0.32	8:22	8:39	5749	0:17	0:09
	1.63	0.33	8:48	8:55	5752	0:07	
9/10/2012	1.46	0.30			5817		
	1.42	0.31	7:40	7:55	5821	0:15	0:28
	1.46	0.28	8:23	8:37	5825	0:14	0:14
	1.44	0.28	8:51	9:06	5829	0:15	0:54
	1.45	0.29	10:00	10:11	5832	0:11	0:08
	1.43	0.30	10:19	10:33	5836	0:14	0:11
	1.41	0.28	10:44	10:55	5839	0:11	0:20
	1.40	0.31	11:15	11:32	5844	0:17	0:18
	1.39	0.31	11:50	12:02	5847	0:12	0:07
	1.38	0.28	12:09	12:27	5851	0:18	0:26
	1.36	0.28	12:53	1:05	5855	0:12	0:07
	1.35	0.26	1:12	1:26	5859	0:14	0:20
	1.35	0.26	1:46	1:55	5863	0:09	0:08
	1.34	0.25	2:03	2:18	5867	0:15	0:19
	1.32	0.24	2:37	2:47	5870	0:10	0:15
	1.31	0.22	3:02	3:18	5875	0:16	0:10
	1.33	0.24	3:28	3:38	5878	0:10	0:15

APPENDIX A – Push Time/Downtime – Time Study

	1.31	0.23	3:53	4:07	5881	0:14	0:17
	1.32	0.20	4:24	4:40	5886	0:16	0:10
	1.32	0.19	4:50	5:02	5889	0:12	0:21
	1.32	0.15	5:23	5:40	5894	0:17	0:08
	1.33	0.18	5:48	6:00	5897	0:12	0:20
	1.33	0.15	6:20	6:35	5902	0:15	
9/11/2012	1.02	0.12			5974		
	0.99	0.11	7:32	7:42	5977	0:10	0:53
	0.95	0.09	8:35	8:47	5982	0:12	0:12
	0.91	0.09	8:59	9:10	5987	0:11	0:10
	0.87	0.08	9:20	9:34	5991	0:14	0:10
	0.82	0.07	9:44	9:57	5996	0:13	0:36
	0.81	0.06	10:33	10:47	6001	0:14	0:16
	0.80	0.04	11:03	11:15	6005	0:12	0:16
	0.76	0.04	11:31	11:45	6010	0:14	0:45
	0.72	0.03	12:30	12:41	6015	0:11	0:13
	0.72	0.04	12:54	1:06	6020	0:12	0:09
	0.70	0.02	1:15	1:27	6025	0:12	0:16
	0.68	0.01	1:43	1:55	6029	0:12	0:09
	0.67	0.04	2:04	2:16	6034	0:12	0:41
	0.65	0.01	2:57	3:05	6037	0:08	0:08
	0.63	0.03	3:13	3:25	6042	0:12	0:19
	0.61	0.05	3:44	3:57	6047	0:13	0:13
	0.62	0.03	4:10	4:22	6052	0:12	0:39
	0.57	0.02	5:01	5:28	6057	0:27	0:17
	0.60	0.01	5:45	6:01	6060	0:16	
9/12/2012	0.27	-0.05			6119		
	0.25	-0.06	7:45	7:57	6123	0:12	0:17
	0.23	-0.09	8:14	8:25	6128	0:11	0:40
	0.22	-0.07	9:05	9:15	6133	0:10	0:10
	0.18	-0.08	9:25	9:35	6137	0:10	0:24
	0.12	-0.01	9:59	10:10	6142	0:11	1:24
	0.11	0.00	11:34	11:48	6147	0:14	0:11
	0.10	-0.03	11:59	12:10	6152	0:11	0:12
	0.12	-0.11	12:22	12:36	6157	0:14	0:28
	0.10	-0.11	1:04	1:21	6161	0:17	0:14
	0.12	-0.15	1:35	1:46	6166	0:11	0:12
	0.12	-0.15	1:58	2:17	6170	0:19	0:10

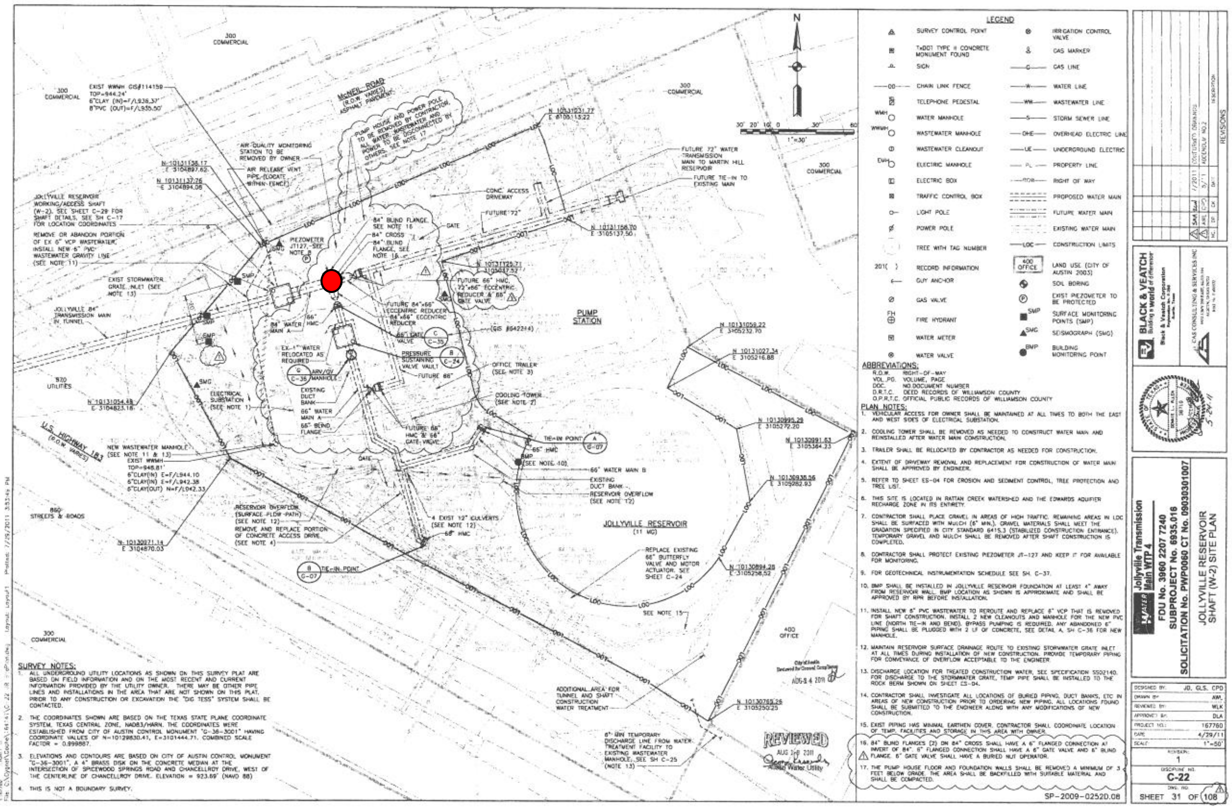
APPENDIX A – Push Time/Downtime – Time Study

	0.11	-0.19	2:27	2:38	6175	0:11	0:21
	0.14	-0.18	2:59	3:10	6180	0:11	0:12
	0.13	-0.19	3:22	3:37	6184	0:15	0:17
	0.13	-0.19	3:54	4:07	6189	0:13	0:11
	0.13	-0.20	4:18	4:33	6194	0:15	0:13
	0.13	-0.20	4:46	5:06	6199	0:20	0:11
	0.11	-0.20	5:17	5:34	6203	0:17	0:15
	0.11	-0.21	5:49	6:04	6208	0:15	0:14
	0.11	-0.19	6:18	6:31	6212	0:13	
9/13/2012	0.09	-0.24			6264		
	0.08	-0.23	1:34	1:50	6268	0:16	0:26
	0.06	-0.20	2:16	2:35	6272	0:19	0:12
	0.06	-0.20	2:47	3:04	6277	0:17	0:13
	0.06	-0.18	3:17	3:32	6281	0:15	0:16
	0.03	-0.17	3:48	4:03	6286	0:15	0:13
	0.02	-0.18	4:16	4:32	6290	0:16	0:09
	0.01	0.17	4:41	4:57	6295	0:16	0:17
	0.01	0.20	5:14	5:30	6300	0:16	0:10
	0.01	0.20	5:40	5:54	6304	0:14	0:21
	0.00	0.19	6:15	6:30	6309	0:15	
9/14/2012	0.06	-0.15			6341		
	0.07	-0.16	5:31	5:50	6346	0:19	0:17
	0.05	-0.15	6:07	6:29	6351	0:22	0:32
	0.09	-0.19	7:01	7:30	6355	0:29	0:10
	0.07	-0.21	7:40	9:47	6360	2:07	0:07
	0.09	-0.20	9:54	9:56	6361	0:02	0:14
	0.08	-0.19	10:10	10:25	6366	0:15	0:12
	0.03	-0.20	10:37	10:53	6370	0:16	0:17
	0.08	-0.19	11:10	11:24	6375	0:14	1:12
	0.08	-0.17	12:36	12:50	6379	0:14	
9/24/2012	0.03	-0.18			6770		
	0.01	-0.17	3:49	4:08	6774	0:19	1:33
	0.49	-0.30	5:41	5:59	6779	0:18	0:31
	0.46	-0.30	6:30	6:42	6783	0:12	

APPENDIX B

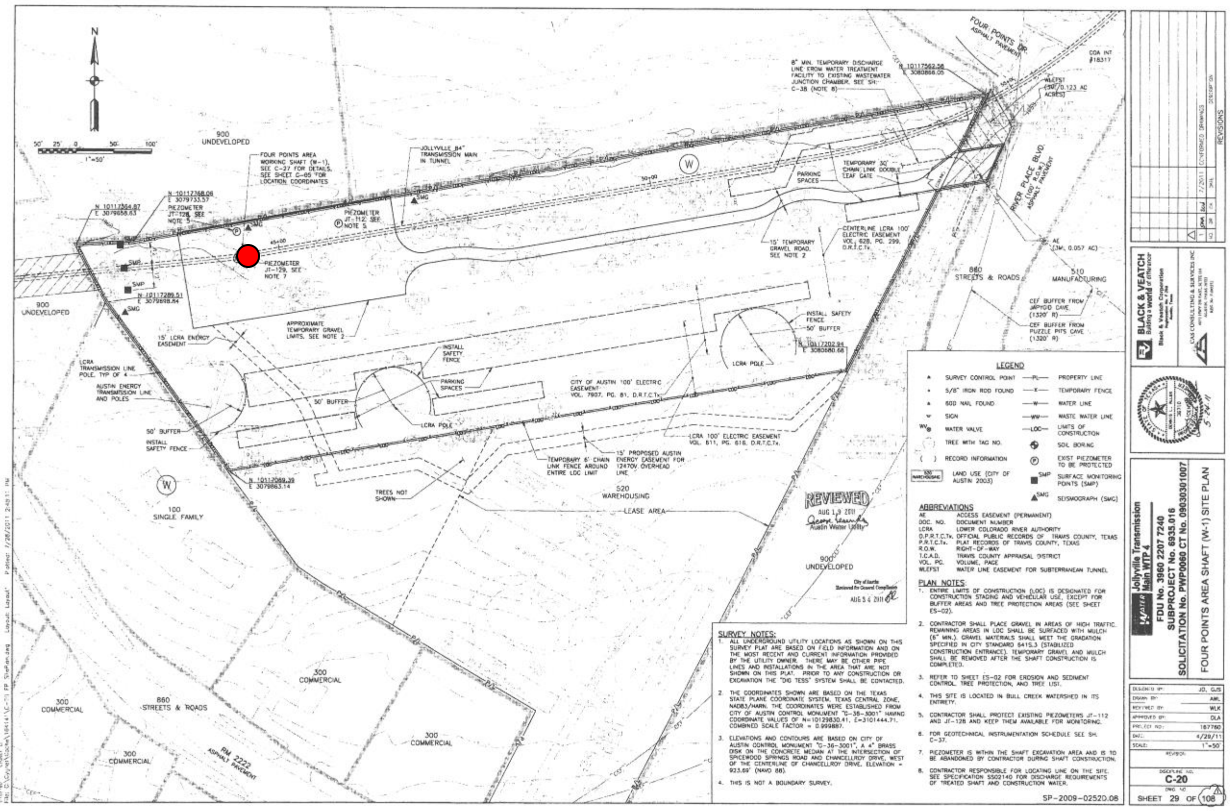
JOLLYVILLE TRANSMISSION MAIN WTP4 PROJECT
SHAFT SITE PLAN

JOLLYVILLE RESERVOIR
FOUR POINTS
SPICEWOOD SPRINGS (PARD)
WTP4



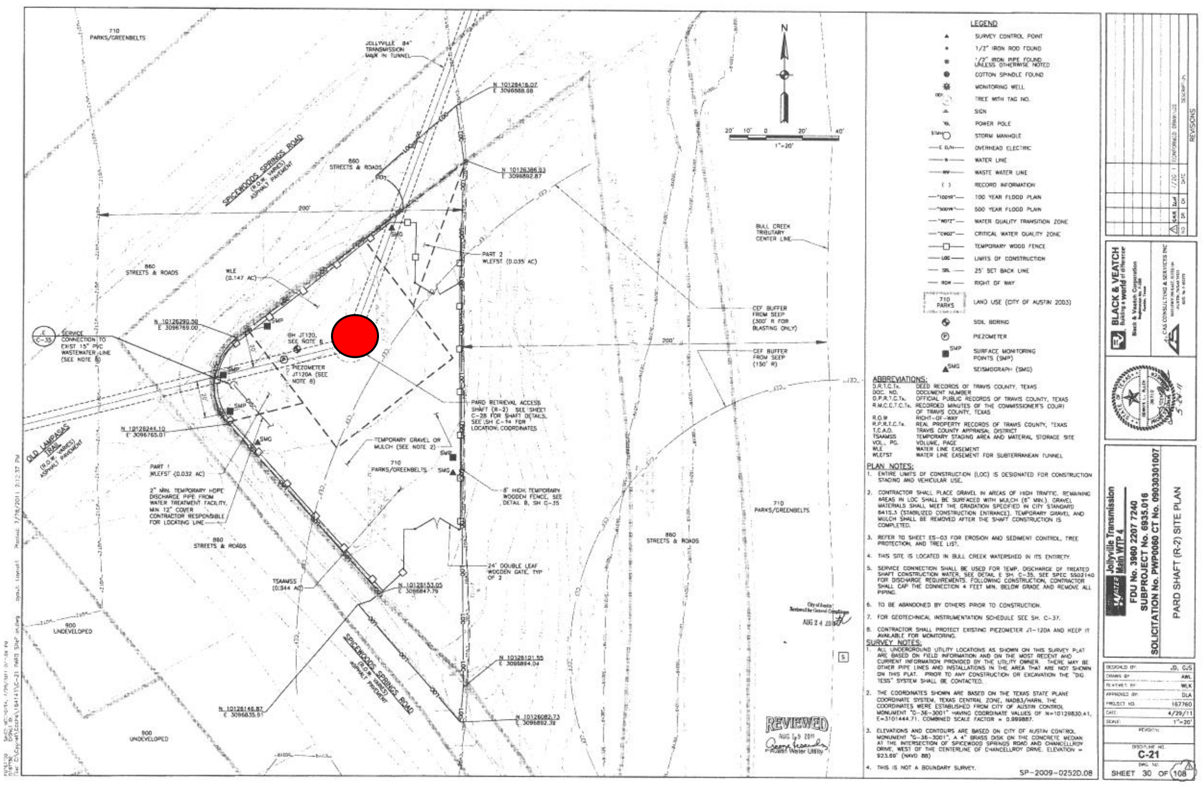
Jollyville Reservoir Shaft Site

The black line is the Limits of Construction. The shaft is located at the red dot.



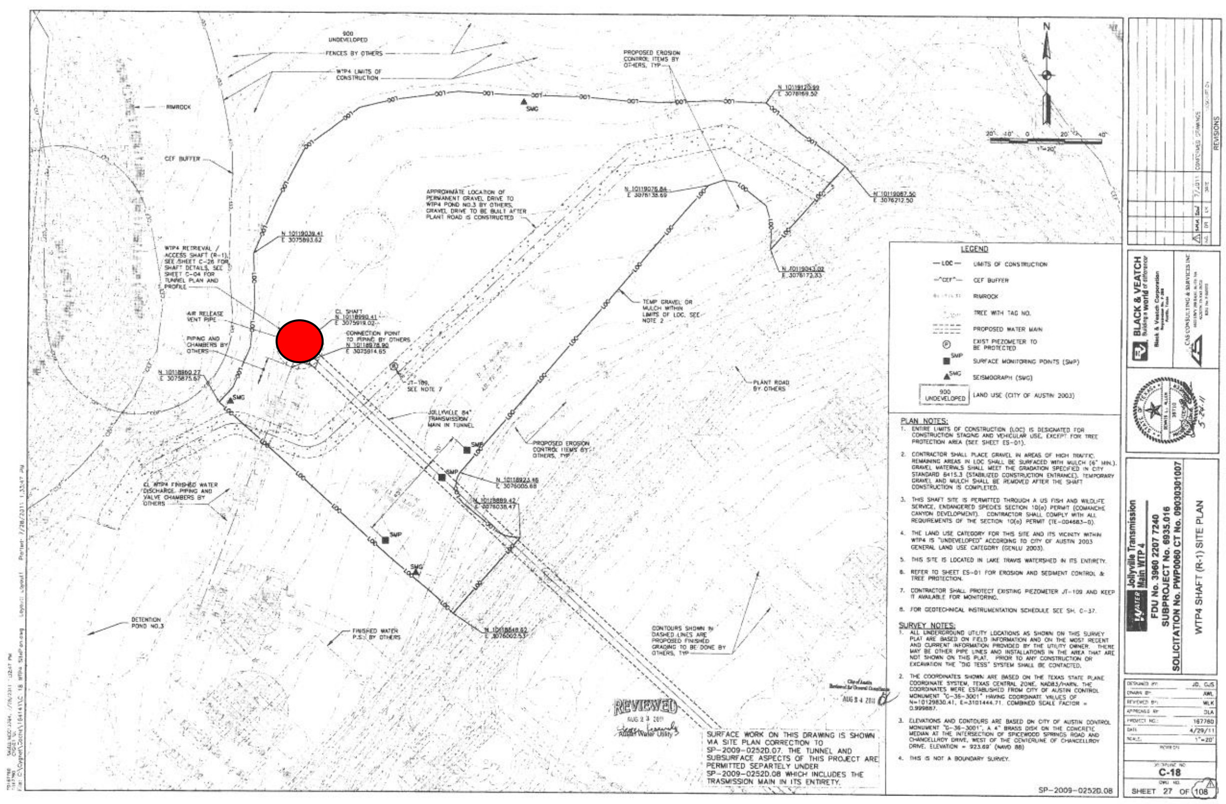
Four Points Shaft Site

The black line is the Limits of Construction. The shaft is located at the red dot.



Spicewood Springs Shaft Site (PARD)

The black line is the Limits of Construction. The shaft is located at the red dot.

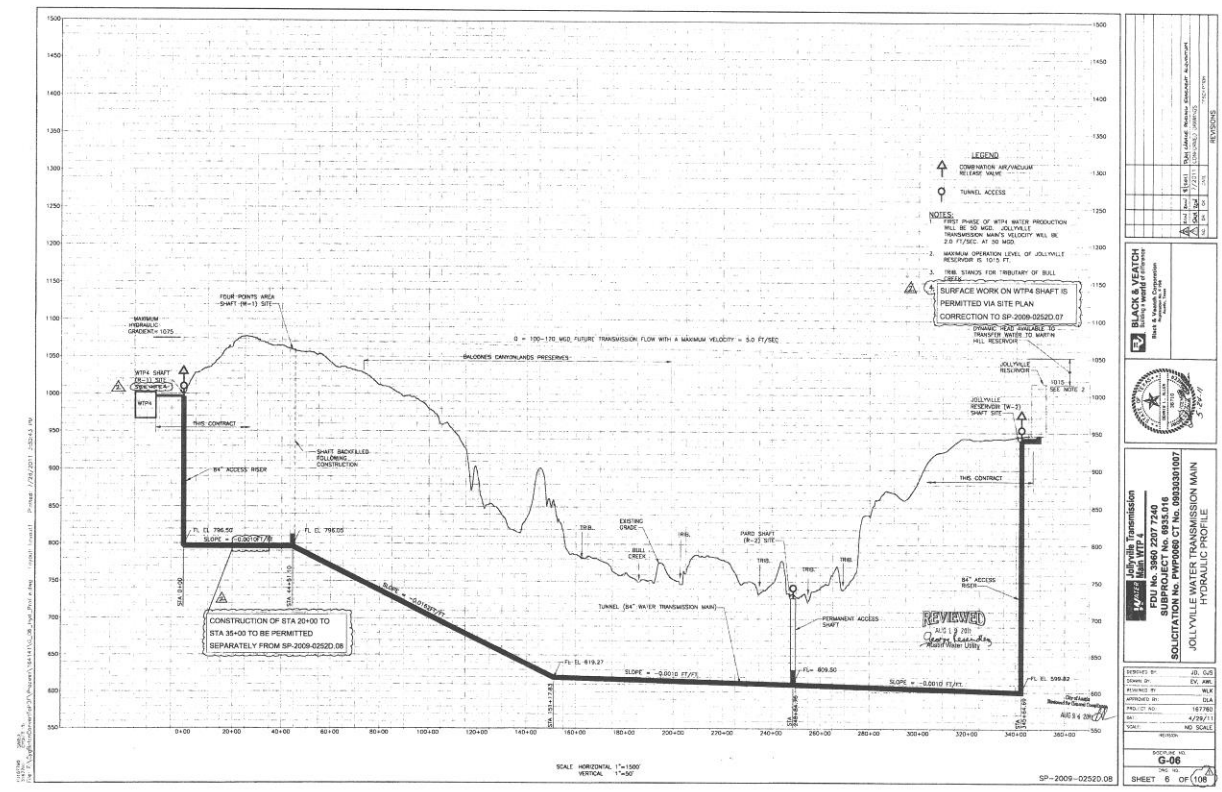


WTP4 Shaft Site

The black line is the Limits of Construction. The shaft is located at the red dot.

APPENDIX C

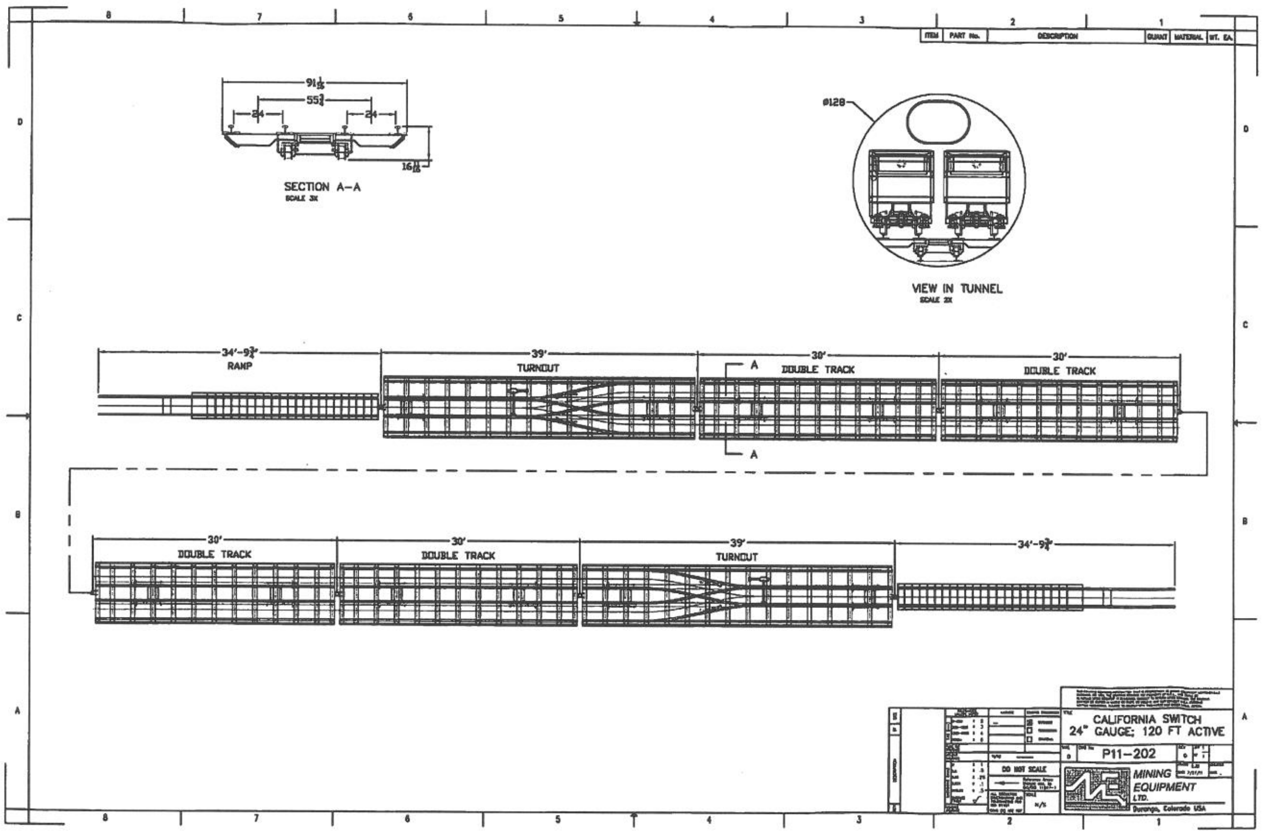
JOLLYVILLE TRANSMISSION MAIN WTP4 PROJECT
COMPLETE PROJECT PROFILE



Project profile of the Jollyville Transmission Main project. The ends portray the vertical shafts, while the horizontal line shows the tunnel and tunnel slope. The thin black line on top shows the variations in elevation depending on terrain.

APPENDIX D

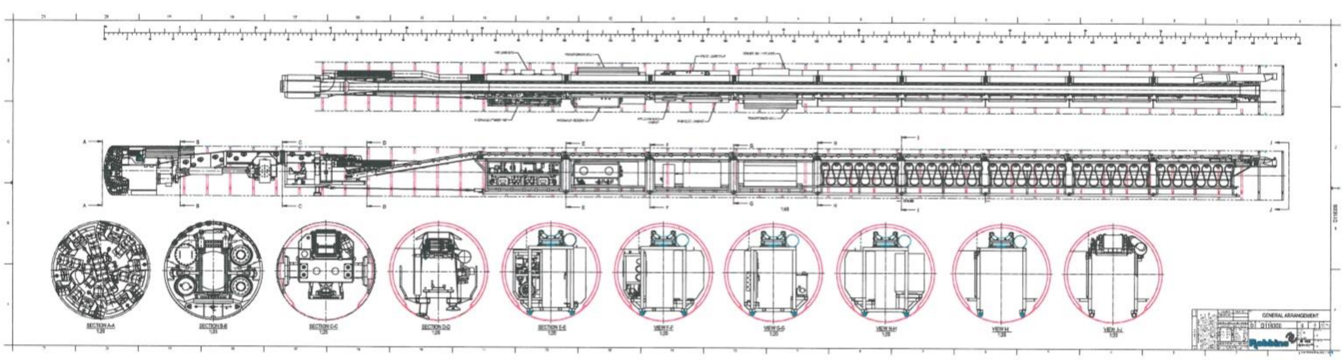
JOLLYVILLE TRANSMISSION MAIN WTP4 PROJECT
CALIFORNIA SWITCH DRAWINGS



The California Switch is shown in the drawings. A view of the general arrangement of the switch track, as well as a tunnel cross section is provided.

APPENDIX E

JOLLYVILLE TRANSMISSION MAIN WTP4 PROJECT
ROBBINS TBM DRAWINGS



General arrangement drawing of the Robbins TBM used on Reach #2 of the Jollyville Transmission Main. It presents the layout, as well as providing cross sectional drawings at various points throughout the length of the machine.

APPENDIX F

JOLLYVILLE TRANSMISSION MAIN WTP4 PROJECT
PROJECT PHOTOGRAPHS

A view down Four Points Shaft.

Full muck train arriving at the shaft.

Dumping the muck on surface.

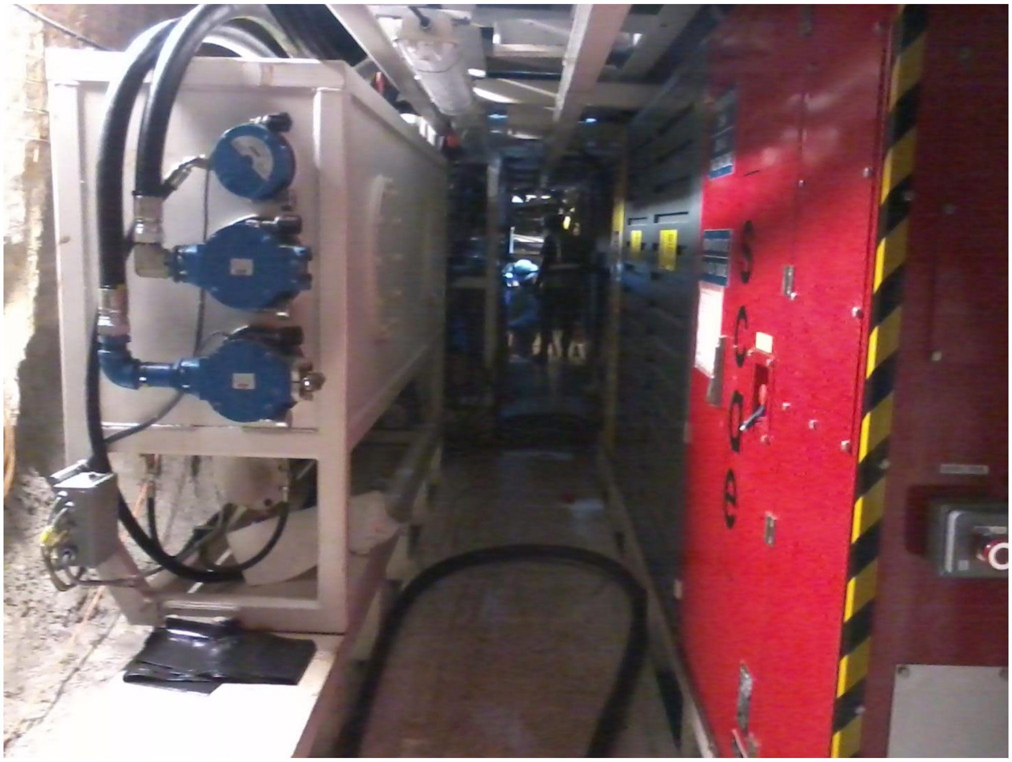
The dust suppression system spraying inside the cutter head.

The conveyor belt inside the TBM can of Reach #1 during operations.

A view of the excavated tunnel. Rail in the invert, ventilation in the crown, and utilities along the wall.

Operator's cab on the Reach #2 TBM.

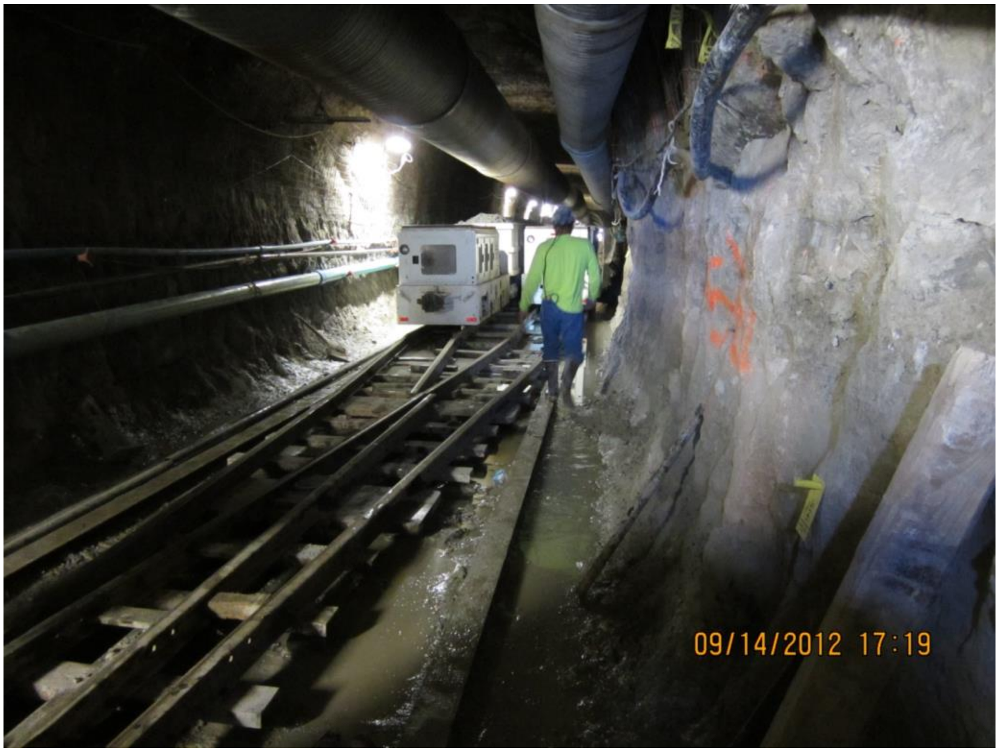
View from the back of the operator's cab towards the trailing gear.



Transformers and hydraulics located on the TBM trailing gear.

The back-up system with a muck car being pushed under the conveyor system.

Filling up a muck car during TBM operations.



The switch track located in the starter tunnel of Reach #2.

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Jollyville Transmission Main WTP4 Project Documents (Southland Contracting/Mole Constructors Joint Venture):

- GBR
- Final Drawings
- Final Specifications
- Purchase Orders/Vendor Quotes
    - Mining Equipment – PO 40350, PO 40364, PO 40429
    - The Robbins Company – Executed Contract
- Submittals
    - S501-SS02311-03-02 Tunnel Excavation Reach #1
    - S501-SS02311-05-01 Tunnel Excavation Reach #3
    - S501-SS02311-06-01 Tunnel Excavation Reach #2
    - S501-SS02341-01-01 Four Points Shaft Support
    - S501-SS02341-02-01 Jollyville Shaft Support
    - S501-SS02341-03-01 Tunnel Support Systems
    - S501-SS02341-04-01 Spicewood Springs Shaft Support
    - S501-SS02341-05-01 WTP4 Shaft Support
    - S501-SS02445-05-01 WTP4 Shaft Construction
- Photos

BIOGRAPHICAL INFORMATION

Nicholas Jencopale graduated with a Bachelor of Arts in Mathematics from Texas Tech University in 2009. After graduation, he remained at Texas Tech University to pursue his Masters in Civil Engineering. After completing the required undergraduate engineering courses for leveling purposes, Nick moved to his hometown in the Dallas/Fort Worth area in order to start a family. The Summer of 2010, the same year he began graduate level courses at the University of Texas at Arlington, he was blessed with his daughter, Emma. Nicholas decided to pursue his Masters of Science in Civil Engineering with a focus on Construction Engineering and Management. While raising a family and working odd jobs, he maintained a strong academic standing throughout his graduate career. He was fortunate to be chosen as an intern for Beck in the Summer of 2011 and completed his required coursework for graduate school that Fall. In December of 2011, Nicholas was offered a job with Southland Contracting, a nationwide tunneling contractor based out of Fort Worth. He made the move to Austin, Texas to begin his career as a Project Engineer on the Jollyville Transmission Main Tunnel Project, as well as being blessed with his first son, Eli. Since entering the industry, he has exponentially expanded his knowledge on TBMs as well as tunneling. He foresees a successful future in the industry and is looking forward to long career excavating tunnels.