DEVELOPMENT OF A MODEL FOR PRODUCTIVITY OF HORIZONTAL DIRECTIONAL DRILLING (HDD)

by

MOHMD SARIREH

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ABSTRACT

DEVELOPMENT OF A MODEL FOR PRODUCTIVITY OF HORIZONTAL DIRECTIONAL DRILLING (HDD)

Mohmd Khaleel A. Sarireh, PhD

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Supervising Professor: Mohammad Najafi

Horizontal Directional Drilling (HDD) is a growing method for installation of pipes in urban areas and where trenching is impossible or undesirable; such as in crossing rivers, lakes, railways, and special areas such as airports. This technique utilizes downhole cutting heads to create a pilot borehole before it is enlarged with back reamers to allow pulling back of a product pipe. The utilization of HDD for the installation of underground infrastructure (i.e., water, wastewater, oil and gas pipes, telecommunication, and power conduits), has shown a rapid growth compared to other trenchless technologies. HDD can install a range of pipe diameters from 2 to 60 inches utilizing different pipe materials including steel, high density polyethylene (HDPE), polyvinyl chloride (PVC), and ductile iron pipe (DIP) with minimum surface and daily life disruptions.

Estimation of HDD productivity, project duration, and quantity of materials required, is a difficult task due to variable productivity conditions such soil, project, contractor, and machine conditions involved in operation. The objectives of this research are to define the significant subconditions that affect HDD productivity by utilizing the analysis of variance (ANOVA) model, to develop HDD productivity prediction model, and to develop HDD user interface as a planning tool for operation. Initially the main productivity conditions and subconditions were identified through literature review and consulting the HDD experts and professionals.

A HDD questionnaire was designed, reviewed, and sent to HDD experts (contractors, design engineers, and consultants) to collect data addressing HDD operation conditions required for testing significance of subconditions and modeling operation productivity. HDD subconditions that show significance by ANOVA model analysis will be used to model HDD productivity in clayey and rocky conditions. This model is applicable in predicting HDD productivity to estimate duration of HDD project, in addition to other project parameters such as quantities of materials required and cost of labor. Applications on HDD productivity model will be useful for consultants and contractors for planning, scheduling, and bidding of HDD projects during preconstruction stage, as well as during installation and construction.

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CHAPTER 1

INTRODUCTION & BACKGROUND

1.1 Introduction

Trenchless Technology (TT) or No-Dig refers to the techniques for underground pipeline and utility construction, replacement, rehabilitation, renovation (renewal), repair, inspection, and leak detection with minimum or no excavation from the ground surface (Najafi, 2010). Over the years, TT methods have become more sophisticated and more widely used in many fields and applications. Mainly, due to its environmental and social benefits, TT is considered to be one of the fastest growing technologies affecting the world's underground infrastructure installation and replacement (Liu et al. 2009). Trenchless Technology is more applicable in urban areas due to the minimum amount of excavations required. Figure 1.1 illustrates HDD position as a technique for trenchless construction and reconstruction among all TT applications in new construction, replacement, and renewal.

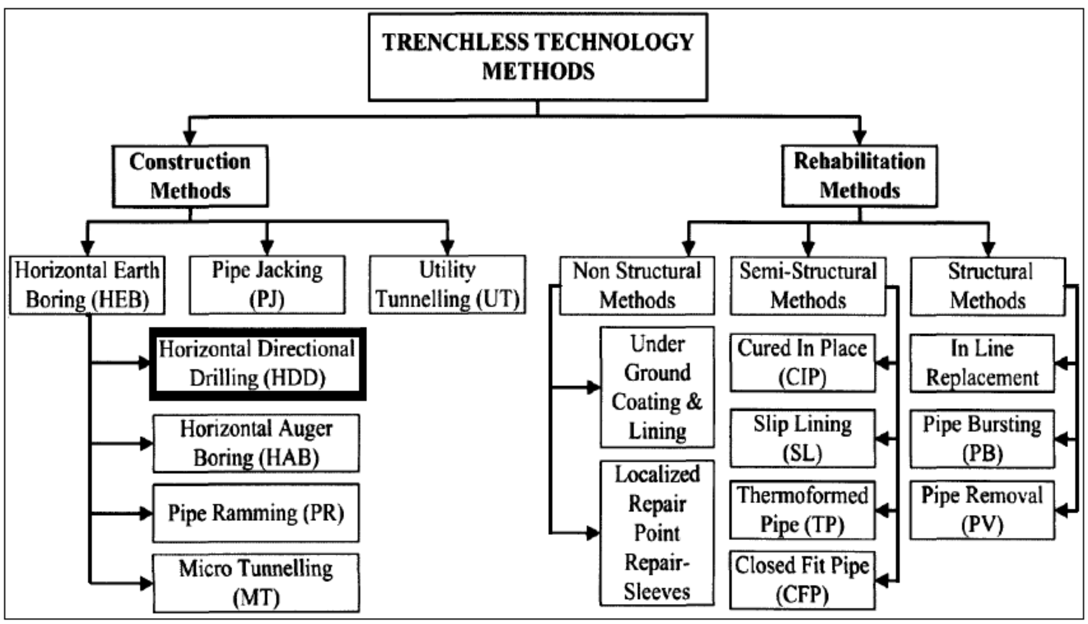


Figure 1.1 Trenchless Technology Applications (Mahmoud, 2009)

Among TT techniques, Horizontal Directional Drilling (HDD) is the most versatile trenchless procedure available that can be widely used for underground telecommunications, electrical conduits, gas and oil pipeline installation, and public infrastructure (water and sewer) construction (Lawson and Najafi, 2003).HDD technique provides significant benefits for urban environments by decreasing disruption caused by streets excavations (Manacorda et al. 2010). In difficult situations such as deep pipeline laying or in case of crossing highways, rivers, or lakes, HDD can be not only more cost effective, but also more feasible and applicable than any other trenchless method (Atalah, 2009).

1.2 Horizontal Directional Drilling

Horizontal Directional Drilling (HDD) is a steerable or a guided boring system for installation of pipes, conduits, and cables involving a surface drilling rig in digging operation. Generally, HDD is divided into three main divisions: large-diameter HDD (Maxi-HDD) in the range of 24-60 inches, medium-diameter HDD (Midi-HDD) in the range of 12-24 inches, and small-diameter HDD (Mini-HDD) in the range of 2-12 inches as it is presented in Table 1.1.

Table 1.1 HDD Main Features (Najafi, 2005)

HDD Size	Diameter (in.)	Depth (ft)	Drive Length (ft)	Torque (ft-Ib)	Thrust (lb)	Machine Weight (ton)
Maxi	24–60	≤ 200	≤6,000	≤ 80,000	100,000-1000,000	≤ 30
Midi	12–24	≤ 75	≤ 1,000	900–7,000	20,000–100,000	≤ 18
Mini	2–12	≤ 15	≤ 600	≤ 950	≤ 20,000	≤ 9

HDD is used to install different types of product pipes including Steel, HDPE, PVC, conduits, and flexible cables considering service type, soil type and severity, and pipeline diameter and depth (Barras and Mayo, 1995). HDD involves at least two stages and can include multi stages of preream depending on the final diameter of product pipe. The first stage involves drilling a pilot borehole using cutting head approximately of 2-6 inches in diameter in hard soils, but it can also be selected to start drilling at 12-16 inches in diameter in soft soils utilizing Midi- to Maxi-HDD rig size. Figure 1.2 illustrates drilling of pilot hole in HDD operation.

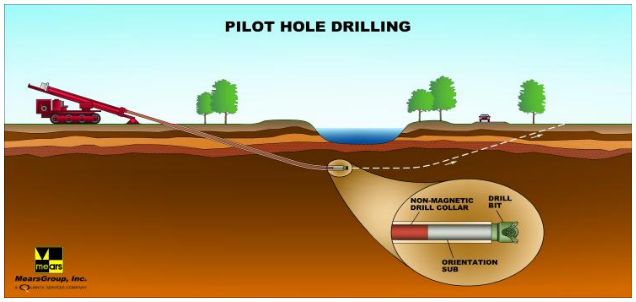


Figure 1.2 HDD Pilot Hole Stage (Najafi, 2010)

The second stage involves prereaming or enlarging of borehole using larger reamer diameter. The increments or jumps in prereaming diameters in soft soil are very large. While in hard soil, the increments are very small; in hard rock increments range from 2-4 inches, in medium rock increments range from 2-6 inches, in soft rock increment can be more. Prereaming stage continues until borehole diameter becomes 1.25 to 1.5 times the size of product pipe. Figure 1.3 illustrates prereaming stage in HDD operation. The last stage is the pulling back of product pipe in borehole and is shown in Figure 1.4.

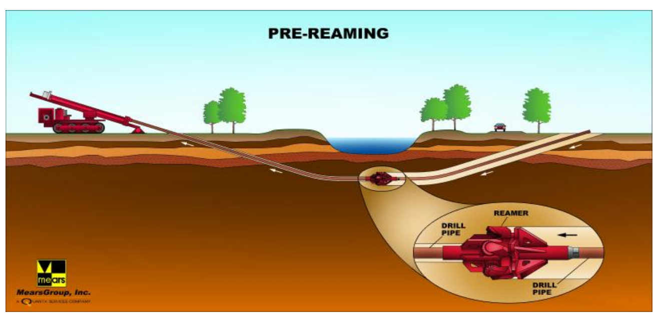


Figure 1.3 HDD Prereaming Stage (Najafi, 2010)

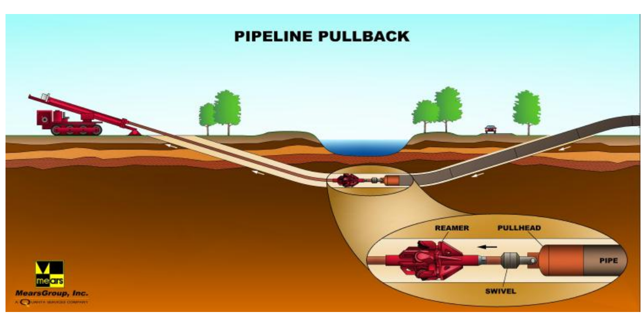


Figure 1.4 HDD Pullback Stage (Najafi, 2010)

1.2.1 HDD History

Horizontal Directional Drilling (HDD) technology originated from oil fields in the 1970s and was developed by emerging technologies to be used in utilities and water well industries. Since then, HDD technology has been widely used in pipeline installation industries. The Pacific Gas and Electric Co. was one of the first HDD users crossing Pajaro River near Watsonville, California in 1971 using HDD technology in operation to install the 4 inch in diameter of steel pipe for a drive length of 615 ft (Najafi, 2005).

Records show that HDD has grown rapidly compared to other trenchless technology methods. The 12 HDD operational units in 1984 increased to 2,000 HDD operational units in 1995 (Allouche et al. 2000). Approximately, 17,800 HDD unites were manufactured and sold during the period between 1992 and 2001 in North America (Baik et al. 2003). Table 1.2 presents number of HDD rigs manufactured worldwide, with 80% of these rigs manufactured in USA.

Table 1.2 HDD Rigs Manufactured and Sold Worldwide (Carpenter, 2011)

Year	Number of HDD Rigs Manufactured and Sold
1992–1995	3,435
1996–2000	13,347
2001–2005	5,427
2006–2011 (2011 projected)	9,926
Sum of HDD Rigs Manufactured Worldwide	32,135
80% Manufactured in USA	25,708

1.2.2 HDD Applicability

Among trenchless technologies, HDD has a standing applicability in most of underground applications (Burman, 2009). Figure 1.5 illustrates utilization of HDD technique in installation of underground infrastructure and utilities, a HDD has a big share in underground construction including telecommunications, sewer and water, gas, and electric projects, in addition to environmental wells' projects.

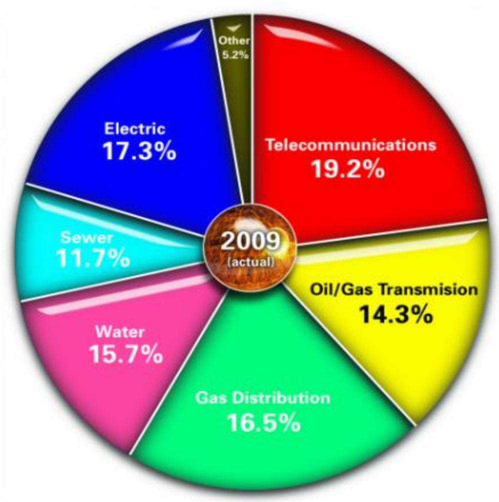


Figure 1.5 HDD Applications in Utilities Installation (Carpenter, 2010)

Allouche et al. (2001) studied HDD among other trenchless technologies including microtunneling, auger boring, pipe ramming, pipe jacking (hand excavation), tunneling (TBM), and tunneling (hand excavation). It was declared that HDD drillability in boulders, cemented soil, and in high specific weight soil is moderate. In flowing sand and in buried structure, HDD drillability is moderate to severe. In gravel and/or cobbles and in artesian aquifers is sever. Therefore, HDD has a standing drillability compared to other TT methods in different soil conditions.

According to North American Society for Trenchless Technology (NASTT) HDD Good Practice Guides (2008), HDD has the highest applicability in TT because of these reasons:

- Method ability to accommodate large diameters.
- Ability to install pipes of different materials including HDPE, PVC, steel and ductile iron pipe.
- Accepted drillability in most of soil conditions including loose sand and solid rock.
- HDD requires less supporting equipment than other trenchless methods.
- HDD is able to meet environmental guidelines (especially in wet lands).
- HDD has less traffic disruption and overall less social costs.
- Applicability to gravity, water and sewer pipelines installation.

1.2.3 HDD Considerations

The nature of underground construction involves comprehensive subsurface investigations. For horizontal construction such as HDD, subsurface investigations help in collecting information about obstructions might be encountered during drilling, and in improving safety which in turn keeps continuity of operation and improving of productivity (Iseley et al., 1999).

HDD bore-path alignment usually continues in different soil conditions within the same project. These changes make the mission of the design engineer difficult when it comes to selecting cutting head, reamer, machine operational conditions including forces, slurry flow rate and mixing ratio. Therefore, considering project conditions, including soil investigations, and HDD machine abilities help engineers to design and implement HDD operation successfully (Royal et al. 2010).

1.2.3.1 Design Considerations of HDD

Drilling using HDD is similar to any engineering operation, starts usually with preconstruction services including surface and subsurface survey or investigation, design, planning, drawings preparation, and specifying of materials to be used in operation (Najafi, 2005). The design and planning of HDD operation is performed to evaluate applicability of proposed work and to avoid or moderate problems such as instability of soil or potentiality of collapse of borehole during drilling, as well as to evaluate the opportunity of “frac-out” occurrence (Hair et al., 2005).

Once HDD is selected for utility construction, a final surface survey is conducted by the contractor team which includes investigating site to determine the work limits required for equipment staging and setup, and pipe layout. Planners also consider the potential impacts on or from adjacent utilities and structures along the proposed drilling path for an approximate width of 100 ft from pipeline’s centerline (Godwin and Valenzano, 2001). Also, the preconstruction survey should contain but not be limited to: existing grade elevation, surface features, test bores locations, waterways, wetlands, culverts, visible subsurface utility landmarks such as manholes, valves’ boxes, and surface structures (Najafi, 2010).

1.2.3.2 Subsurface Considerations in HDD

In horizontal projects such as HDD projects, geotechnical study is usually conducted by drilling vertical bores at spaces of 300-600 ft for a depth that can cover the bore-path alignment to obtain soil information. The analysis of soil bores' profile can provide information on potential collapse or hydro fracouts expected during drilling through the analysis of soil type and strength. Information about soil classification and strength helps to determine cutting head and reamer type needed. Expected drilling problems and obstruction can be moderated by start drilling at smoothed entry and exit angles to hit the softest soil path. Also, determining suitable diameter increments as well as modified slurry flow ratios and pumping rates will assist in cuttings' removal. Accurate and clear subsurface studies can help in avoiding delays, disputes, and conflicts between HDD project parties (Shumaker and Howard, 2008).

Locating subsurface utilities is necessary to complete HDD operation successfully. The process starts with locating visible landmarks. Then approximate search starts with determining the horizontal and vertical position of these utilities. Usually this work is done by contacting the local one-call service. If local one-call systems do not have required information, municipalities and private utility companies are contacted to obtain required information. In general, a minimum 10 ft drilling distance from existing utilities is required when the location is confirmed physically.

1.2.3.3 HDD Restrictions Considerations

There are several challenges associated with HDD in marine environment and river installations. These challenges include construction restrictions such as mud control, expected fracout, limited working area, seasonal restriction for aquatic habitats, and minimizing of disturbance for wet lands in project site and other adjacent sites expected to be affected. To prevent fracout problems, lower pressure should be utilized and deep lay down of pipeline should be applied in alignment selection. An emergency plan must be in place if fracout expected to happen. Also, casing is usually required for product pipe. Effective construction management will improve site accessibility and provision for material storage and fabrication.

1.2.3.4 HDD Planning and Preparation Considerations

The contractor's planning and preparation usually start at site by fencing the work area, and contacting local one-call system to locate existing underground utilities such as water, wastewater, gas, telecommunications, and electric power lines. Contractor can then start potholing and "day-lighting" before proceeding with HDD installation and digging entry and exit pits.

Maxi-HDD preparation and mobilization takes 10-60 days. The upper scale is dependent on the length of pipeline string be joined or welded. For Midi-HDD it can take 1-6 days depending on the pipeline length. While for Mini-HDD, preparations can take from two hours to two days.

Preparation includes setting up HDD machine, slurry or mud system, stationary pump, materials used in operation, transporting and setting up all the equipment and tools required for operation (drilling bits, reamers, mud recycling, backhoes, pumps, product pipe) and making final check on these equipment before start using them (Seneviratne et al., 2005).

HDD Drilling fluid/slurry should be designed to stabilize borehole, to lubricate drilling rod surface, and to transfer cuttings out of borehole. Preparations also include inserting transmitter into housing before the start of pilot drilling, as well as securing other equipment and facilities such as generators, pumps, and emergency lights. On the exit pit side, product pipe, reamers, but-fusion or welding machines, and storage space are kept ready for pre-reaming and pullback stages. Contractor is required to keep working area fenced and closed at all times for those who do not have permission to work within site area (Najafi, 2005).

1.3 Problem Statement

The United States' existing underground infrastructure consists of a very long, complex pipe system, cables, and conduits of different diameters. According to the Environmental Protection Agency (EPA), there are over 921,245 miles of water, sewer, and storm water pipelines in the United States, of which 230,211 miles need to be repaired or replaced immediately (Jung and Sinha 2007).

The annual cost for pipe replacement and reconstruction in the nation's water systems has been estimated at $11 billion; and for sanitary sewer systems, the cost has been estimated at $12 billion. Such expenditures are necessary to replace or maintain systems that have exceeded their design life and cannot comply with existing and future federal requirements (Lawson and Najafi, 2003).

American Society for Civil Engineering (ASCE) has estimated the expected expenditures required for infrastructure projects at $1.3 trillion for the next five years just to maintain the current systems. To address this task successfully, the infrastructure management system should use an advanced technology, and advanced materials, in addition to the best planning and management practice (Moteleb et al., 2004).

The construction industry including underground construction utilizing HDD technique is in need for productivity study and analysis to be improved. The prediction of operation productivity still needs new research and studies on unpredictable or unforeseen soil conditions. Most contractors have no way of changing these conditions. Techniques, equipment, materials, and labor can be managed to improve productivity, especially if advances in equipment, materials, techniques, and efficient labor utilized together (Adrian, 2004).

HDD technique can fulfill the need for reconstruction and replacement of old water and wastewater mains, as well as gas conveyors in both urbanized areas and in crossing marine obstructions such as lakes, rivers, highways, and in problem-specific areas such as airports.

Productivity of HDD rig is defined as the distance drilled, prereamed, or pulled back by HDD machine during a unit of time, denoted as (ft/hr) or (ft/day). Measuring productivity on hourly basis is more accurate than on daily basis. An hourly record allows considering subsurface conditions and changes as well as machine and worker efficiency in different time periods during operation.

HDD is utilized with multi- and interrelated-conditions including management, site, and product pipe (Ali et al., 2007), all of which affect HDD productivity and make HDD operation more critical and specific (Gelinas et al., 2000). Therefore, estimating of operation productivity, duration of project, and cost becomes all critical and specific too. Because the common practice in estimating these project parameters relied on previous project cases without considering significant subconditions in operation, a productivity prediction model is needed for more accurate results and calculations (Mahmoud, 2009).

Significant subconditions should be represented in HDD productivity prediction model to be acceptable and satisfying to contractors, consultants, and engineers. The outcomes of this study will help project parties estimate project parameters such as productivity in order to determine duration, planning, and scheduling. It will also help to bid the project successfully.

1.4 Research Objectives

Prediction of HDD productivity is important for all parties in HDD projects including contractors, consultants, and engineers. Also, measuring productivity is needed in planning, scheduling, and bidding as well as estimating quantities of materials and labor cost. Accordingly, the main goal of the current research is to provide a productivity model for HDD operation considering significant subconditions that affect HDD productivity among soil, project, contractor, and machine conditions tested in terms of significance.

The research has also the following objectives:

1. To identify HDD operational conditions including soil, project, contractor, and machine conditions.
2. To analyze the significance of subconditions subjected in HDD productivity.
3. To develop HDD descriptive statistics in terms of current applications, industry position, product pipe installed, HDD rigs categories, and soil conditions encountered.
4. To help in estimating project duration, quantities of materials required, and labor cost.
5. To develop HDD productivity user interface tool to plan HDD operation.

1.5 Organization of The Dissertation

This dissertation consists of eight chapters to cover the topics addressed, and to achieve the goal and objectives of this research.

Chapter 1 presents an introduction, background, history of HDD operation, problem statement explaining the need for current research, research objectives, and organization to provide the framework of completed research.

Chapter 2 consists of literature review on productivity studies in construction operations, trenchless technology applications, and HDD operation.

Chapter 3 presents methodology and approach utilized to conduct the current research and addressing research stages including literature review, HDD questionnaire design and review, HDD data collection and analysis, HDD model development and validation, and development of HDD user interface.

Chapter 4 provides HDD data collected on two levels including HDD pilot project and HDD questionnaire.

Chapter 5 discusses the analysis of HDD subconditions using the analysis of variance (ANOVA) model to test significance of HDD subconditions.

Chapter 6 presents HDD model development for clayey and rocky conditions using data collected by HDD questionnaire, and also validating developed models.

Chapter 7 presents HDD model applications and development of HDD user interface that can be used by contractors and consultants as a planning tool for HDD prereaming operation.

Chapter 8 provides research conclusions, research contributions, recommendations for future research, and research limitations.

1.6 Chapter Summary

This chapter introduced Trenchless Technology (TT) as an advanced technique to install different pipe products in underground construction, replacement, and renewal operations. Horizontal Directional Drilling (HDD) was introduced as a versatile TT technique in underground infrastructure applications that utilizes new equipment and materials for construction of different pipe sizes and lengths. Additionally, HDD applications and considerations as well as problem statement, research objectives and organization of this dissertation were discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents literature conducted on productivity of construction operations, trenchless technologies, and HDD operations. Results and conclusions of previous studies that provide a model for - HDD productivity as well as HDD conditions will be presented in this chapter.

2.1.1 Productivity of Construction Operation

Usually networks diagrams are used to describe and to analyze the repetitive construction operations in terms of productivity and costs. Halpin and Riggs (1992) described a hierarchy model for project construction in terms of activities, tasks, sequencing, and resources.

Zayed (2005) studied continuous flight auger (CFA) in pile construction and considered factors expected to affect productivity of pile construction. Expected factors included site pre-investigations, soil type, operator and contractor experience, piling machine power, job management, site restrictions and soil disposal method, rebar installation, and concrete placement.

In pile excavation, Zayed determined that soil type, obstructions (tree roots, cobbles, boulders, and so on), depth, and diameter of pile have a direct effect on pile operation productivity. Operator and contractor experience do not have a direct effect, because most operators and contractors are prequalified to do the work described in the bid and technical specifications; and most contractors use similar equipment, and construction techniques.

2.1.2 Simulation of Construction Operation

The idea of queuing was developed and utilized in MicroCYCLONE by Halpin in 1973 for modeling construction operations that are repetitious in nature and have logical sequence. Simulation of such operations can help in developing different scenarios using sensitivity analysis (AbouRizk, 2010). Underground construction such as microtunneling and tunneling, pipe jacking, earth boring, auger boring, and horizontal directional drilling are some examples of repetitive underground construction operations. On the other hand, non-cyclic operations can be analyzed using critical path method (CPM) and program evaluation and review technique (PERT).

Similar to MicroCYCLONE, SLAM II by Gonzalez-Quevedo (1993) was introduced to simulate activities, resources, and modes of construction operations. Also, simulation of resource change, resource conflict, and delay using Cell-DEVS method of removing existing deck sections and installing new panels on the main span of the bridge was introduced as an example of sensitivity analysis of resources (Pang and Hammad, 2006).

2.2 Productivity Analysis in Trenchless Technology (TT)

This section presents productivity studies conducted in TT applications and methods other than HDD operation. A subsequent section provides productivity studies of HDD.

2.2.1 Productivity of Auger Boring

Auger boring is used to install a steel casing of 4-60 inches in diameter and up to 600-ft in length. However, the typical pipe diameter is 8-36 inches, and the typical drive length is 300-ft. Bores with a diameter of less than 8 inches should be drilled using another trenchless method such as pipe jacking, pipe ramming, or HDD (Najafi, 2005).

Usually with small diameters and drives, auger boring machine can be setup on loose soil, but for large diameters or large drive lengths, concrete block is required to provide thrust force. Auger boring can give excellent practice of line alignment and grade.

Main factors that affect auger boring performance include cutting head, boring machine and equipment, crew and operator experience, soil conditions, drive length, diameter of borehole or diameter of casing be installed, casing section length, accuracy of geotechnical investigations, depth installed, groundwater conditions, appropriateness of auger boring method, obstructions or unusual soil conditions, restrictions to working hours, accuracy of line and grade, existing of underground and above structures and utilities, and pipe alignment.

The length of borehole has a significant effect on productivity and cost. Simulation using MicroCYCLONE and ARENA showed that productivity increases with increase of the length because of the cyclic nature of operation, while the cost decreases with the increase of borehole length. It was declared that productivity in hard clay decreases, with increase in cost. In case of gravel, preparation time for construction of pits and thrust blocks as well as track and boring time increases. It was determined that auger boring productivity in gravel is less than in hard clay (Salem et al. 2003).

2.2.2 Productivity Analysis of Microtunneling

According to Hegab and Salem (2004), microtunneling is used in new underground installation for gravity using a remotely controlled tunneling boring machine (TBM). In microtunneling, pipe jacking technique is employed to provide continuous support to the excavation face without personnel entry into the tunnel. In the project reported, approximately 1.97-ft and 3.28-ft diameter pipes were used for 19,685-ft length of pipeline. Microtunneling was selected because the site was located in the downtown area, which was very crowded with narrow roads and a high water table.

Vitrified clay was used in 1.97-ft diameter of the sewer pipeline, while concrete pipe was used in 3.28-ft diameter. Soil was variable and changed between black hard and gray silty clay, sand, river sediments and buried concrete. Groundwater table depth in site was about 9.84–13.12 ft. Table 2.1 presents productivity achieved in the project. The maximum productivity was achieved in sand conditions, while the minimum productivity was accomplished in hard clay soil.

Table 2.1 Productivity of Microtunneling Machine (Hegab and Salem, 2004)

Soil Type	Productivity (ft/hr)	
	Minimum Productivity	Maximum Productivity
Fill	18.6	26.4
Hard Clay	3.6	5.4
Sand	6.7	27
Silty Clay	10.2	16.8
Soft Clay	15	19.2

According to Hegab (2005), The productivity of microtunneling is the key for profit in operation or project. Unexpected underground conditions can put productivity of microtunneling machine on risk, which decreases profit anticipated in cost estimation of the project. Through data collected, soil is considered the most effective factor in project productivity, followed by drive length, machine diameter, and number of pipe sections installed.

2.2.3 Simulation for Microtunneling Pipe Installation

Luo and Najafi (2007) studied the productivity of pipe installation using microtunneling by utilizing MicroCYCLONE simulation to obtain cost of microtunneling operation. This work included testing the probability distribution of main activity durations in operation. Also, the work utilized information on microtunneling machine functional components such as jacking system, slurry system, spoil system, and guidance and control system. Simulation input also included product pipe installed, labor requirements, and information on project site layout. MicroCYCLONE utilizes the probability distribution for the activity duration which can follow exponential, triangular, uniform, lognormal, or beta distributions. The most powerful tool in the program is the sensitivity analysis for resources involved in activities; this tool can give different scenarios for productivity and cost of construction operations.

2.2.4 Factors Affecting Productivity in Microtunneling Operations

Hegab and Salem (2010) studied factors that can affect productivity of microtunneling operations. A questionnaire was submitted to ten experts with approximately 20 years experience to list factors expected to affect productivity and by ranking these factors from 1 to 5 (1 for not important, and 5 for extremely important).

Authors found that conditions related to microtunneling productivity include soil conditions, geotechnical investigation, soil type, operator experience, lubrication, torque, jacking thrust, slurry separation equipment, alignment, microtunneling machine type, cutting head shape, drive length, technical support, working hours, slurry rate, shaft design, ground water, pipe length, pipe material, and installation depth.

To eliminate the effect of the difference in respondent's experience, an average for respondent rank was applied using Equation 2.1.

$$WAVR_j = \frac{\sum_{i=1}^{n} E_i R_{ij}}{\sum_{i=1}^{n} E_i} \tag{2.1}$$

Where $WAVR_j$ is the weighted average of the jth factor; E_i is the experience of respondent i (years), and R_{ij} is the respondent (i) ranking for factor jth from 1 to 5.

The above work included testing equality of means for raw responses and weighted average responses, and it was concluded that means are significantly different at 95% confidence interval. Further testing was conducted on the dependency between factors, and it was concluded that these factors are independent, i.e., they affect microtunneling productivity independently.

Considering soil conditions, sand has the maximum rank for productivity (good to excellent), followed by silt and clay. This explains the relationship between the friction force in soil type and workable jacking distance. Boulders and backfill materials were found to be the worst soil conditions observed in microtunneling operations.

To increase installed drive length and improve productivity, the use of intermediate jacking systems (IJS) was recommended. IJS can reduce effect of clay adhesion or friction force for long installations. The study provides the following models to calculate time for microtunneling in different soil types encountered. Microtunneling time in fine/soft soil is presented in Equation 2.2.

$$\begin{aligned}\sqrt[3]{TM} &= .068L + .008D + 4.06D - .0017T + 4\times10^{-4}T\sqrt{L} - 10^{-7}TL^2 \\ &- 0.75\log PL + 1.07\log TL\end{aligned} \tag{2.2}$$

Microtunneling time in medium soil is presented in Equation 2.3.

$$\begin{aligned}\sqrt{TM} &= 0.55 - .134P + 40.8D - .009T - .0036PL - .00033TL + .048P\sqrt{L} \\ &+ .0027T\sqrt{L} + 2\times10^{-6}PL^2 + 10^{-6}TL^2 - 7.2\log TL\end{aligned} \tag{2.3}$$

Microtunneling time in coarse/hard soil is presented in Equation 2.4.

$$\sqrt{TM} = 0.47L - .176P + 46.2D - .005T - .00229PL - .000194TL$$
$$+ .0394P\sqrt{L} + .00103T\sqrt{L} - 10^{-6}(PL^2 - TL^2) - 7.27\log PL \quad (2.4)$$

Where TM is the tunneling time (minutes), T is the sheer force of the cutting head (metric tons), P is the jacking force (metric tons), D is the machine diameter (meter), and L is the jacking length (meter).

2.2.5 Fuzzy Logic Model

Adel and Zayed (2009) utilized fuzzy approach (Sowell, 2003) in describing the factors expected to affect HDD operations using a fuzzy logic model.

Qualitative inputs, such as soil type, pipe material, and quantitative inputs, such as product pipe outside diameter, depth, and length were considered to affect productivity of trenchless operation.

Initial arbitrary weights were assigned to inputs, and then adjusted by the network. The assigned value in 1st iteration was the new value in 2nd iteration plus the difference or error in estimation between target and estimated value.

Conditions such as HDD rig specifics or categories, soil types, unseen obstacles, pipe diameter, pipe length, pipe depth, and pipe type were considered significant to productivity of operation.

2.2.6 Effects of Subjective Factors on Productivity

Ali et al. (2007) divided the subjective factors that affect the productivity of trenchless technology of underground infrastructure into three categories: management, environmental, and physical factors.

Management factors include managerial skills, safety regulations, mechanical conditions of equipment, and operator skills. Environmental factors include soil and site conditions, unseen soil obstacles, as well as groundwater level. Physical factors include pipe type, length, usage, and depth.

The analytical hierarchy process (AHP) and fuzzy logic were utilized to develop the productivity index (PI) for efficiency of operation by considering the subjective effect of proposed factors on operation. The relative weight of factors *(SFE)* included in this study was calculated in Equation 2.5.

$$SFE = \sum_{i=1}^{i=n} W_i * E_i(x_i) \qquad (2.5)$$

Where, W_i is the decomposed weight of factor in operation. $E_i(x_i)$ is the effect value of the factor in the project, and n is number of factors. The developed productivity index PI = 1 – SFE represents time efficiency in productivity of operation.

2.2.7 Construction Simulation

Arachchige (2001) developed a simulation application for utility tunneling construction for the purpose of predicting soil types during tunneling operation. A special purpose simulation (SPS) for tunneling was conducted to develop a planning tool and decision making system.

Tunneling operation involves the following main stages: soil excavation, earth removal, and tunnel support. Tunnel boring machine (TBM) is divided into two types: open-face machine used in excavating reasonably stable soils, and closed-face machine used in excavating silty and sandy soils (unstable soils). TBM can be used for worker and non-worker entry operations dependent on the tunnel diameter (Najafi, 2005).

Progress of a tunneling project depends on progress made in the individual activities in operation. The system is totally optimized when the idle time is at a minimum or resources are completely utilized. Therefore, it will be necessary to evaluate the progress in activity that impacts the waiting time and utilization of resources. The repetition of the construction activity helps assess resource changes (sensitivity analysis) needed to improve utilization and productivity optimization (Ruwanpura et al., 2000).

2.2.8 Probabilistic Model for Tunneling Project

Touran (1997) introduced the cumulative density function (CDF) of a tunnel total length that can be excavated in a given time. In general, for any underground utility construction, especially tunneling, the time to excavate a segment is a function of soil type and obstructions encountered, project, and environment conditions.

Estimated schedule and cost of tunneling operation is a rough estimate when considering project variables such as soil, job conditions, and equipment selection. The author describes a probabilistic model of project variables to categorize specific classes which use these variables to predict productivity.

The opportunity to develop and to use the probabilistic models is high considering the periodic and repetitive nature of tunneling operations. The progress rate for tunneling (ft/d or ft/week) is divided into two classes: making progress or working class and zero progress or non-working class. Periodic progress is transformed into progress histogram, and then a theoretical statistical distribution can be fitted in specific soil, project, and tunneling machine conditions. To calculate the total length of tunnel completed in a given time, it is required to add working periods through the specific soil type encountered.

2.2.9 Beta Distribution

AbouRizk et al. (1991) introduced beta distribution for fitting activity durations. Simulation model is utilized to describe the missing part of data using the main parameters: mean, mode, and variance of deterministic model, in addition to the use of maximum, minimum, most likely values of data and/or calculated percentiles in probabilistic model.

Modeler usually faces one of the following situations: (1) sample data are available and can be used into appropriate probabilistic or deterministic model, (2) sample data are not available and input data are based on subjective information provided by experts in the process, or (3) sample data are available but, not enough, so available data should be combined with subjective data to obtain the required data to generate the model.

The type of data studied in this research is more closely aligned with the third situation described above. Therefore, beta distribution is utilized to describe data more clearly. While, the situation will be different for activity duration, it can be described by a continuous probabilistic function within the interval (L, U), where L is the lower activity time and U is the maximum activity time. Then the probabilistic function of time on activity is a unique model or distribution, i.e., totally fits data of activity durations.

2.3 Productivity Analysis in Horizontal Directional Drilling (HDD)

As said earlier, HDD is a trenchless technology that has a wide range of applications in the underground utility construction and industry. HDD is widely used for installation of utility conduits and natural gas pipelines and through municipal applications such as water mains, and pressure pipe applications. Also, utilization of HDD has started in environmental applications (remediation of contaminated sites), geo-construction applications (geotechnical investigations), and hydrological applications (diversion of channels).

HDD shows many advantages compared to direct open-cut method. HDD is able to install underground utilities with minimum level of impact in congested urban areas resulting in significant savings in restoration cost of sidewalks, pavements, brick paving, vegetation, and other surface features. Less disruption in business-related traffic flow and commercial activities usually associated with direct open-cut drilling methods are great advantage for HDD (Ariaratnam and Najafi, 2009). Also, the minimum need for soil support compared to other trenchless applications is another advantage for HDD.

2.3.1 HDD Productivity Factors

According to Mahmoud (2009), HDD productivity factors were classified into managerial, mechanical as well as environmental factors and pipe physical conditions. Analytical hierarchy process (AHP) was utilized to rank factors according to their importance. Then, a Neurofuzzy Model was employed to develop HDD productivity values for clay, rock, and sand. The decision of neuron is based upon the sum of weights associated to the factors considered in operation.

Management conditions included managerial skills, safety regulations, mechanical conditions, and operator skills, while environmental conditions included unseen soil obstacles, water table level, soil conditions, and site conditions, and physical conditions include pipe type, pipe usage, pipe length, and pipe depth.

In this study, drilling time was considered as the major activity duration in HDD operation, while durations of other activities such as pipe layout and connection, changing reamer, and setting of drilling angles were considered minor durations for auxiliary activities usually can be done during site preparation in small projects. While in large projects, the duration of auxiliary activities become major compared to the drilling time that considered minor activity.

In clayey soil, HDD productivity was found to average 51.35 ft/hr, while HDD productivity predicted was 44.85 ft/hr with a validation of 87.34%. In rock, HDD productivity was found to average 35.01 ft/hr, while HDD productivity predicted was 31.07 ft/hr with a validation of 88.75%. In sandy soil, HDD productivity was found to average 37.5 ft/hr, while HDD productivity predicted was 33.5 ft/hr with a validation of 89.32%.

In this study, it was concluded that pipe diameter, soil type, and drilling rig capabilities were considered the most important factors that can affect productivity of HDD operation. While, factors such as site, weather, and fluid properties were considered minor factors in operation.

Simply, because seasonal changes (i.e., weather) does not have direct effect on HDD productivity, groundwater table is said to have no effect on HDD productivity. Also, slurry pumping rate and mixing ratio are functions of soil type. Although pipe material (HDPE, PVC, and steel) affect productivity of pipe connection, during pull back, pipe material has no direct effects on HDD operation as most of pipe materials are floating in borehole. Therefore, HDD productivity can be modeled using HDD rig capabilities, soil type, pipe diameter, and depth.

2.3.2 HDD Productivity Model

Zayed et al. (2007) introduced major and minor factors of HDD productivity (i.e., rig capabilities, pipe material and diameter, soil type, contractor experience and weather conditions) to develop a deterministic model for duration of HDD operation. This research focused on time required for pipe installation. The installation time was partitioned into two parts. First part was considered major, such as time for drilling, prereaming, and pullback. Second part was considered minor, such as time for adjusting drilling angle at entrance, time to connect drilling pipe segments, time to attach reamer with shackle for prereaming, mixing and pumping mud, and time to layout and connects pipe or cable segments.

It was concluded that total cycle time (major, such as drilling and prereaming operations, and minor, such as changing reamer or mixing drilling mud) usually have specific values for similar project conditions (soil, pipeline, and machine). However, in short drive projects drilling activities are considered major or productivity deterrents, while in long drive projects changing parts become major time or productivity deterrent.

Two case studies were selected for HDD productivity in sandy soil; the first was for installation of 1.6-in. diameter polyethylene for a distance of 880-ft, and the second was for installation of 2.36-in. diameter HDPE pipe. The cycle time was studied through the length of the borehole and was regressed for both to give a productivity of 123.4 ft/hr and 88.4 ft/hr, respectively. These results indicated that HDD productivity is a function of soil type, rig size, and pipe diameter. HDD productivity can be lowered in sandy soil when it contains gravel or cobbles. Another conclusion was that HDD productivity is inversely proportional to diameter of borehole. A deterministic model for major time was developed to describe the cycle time as presented in Equation 2.6.

$$T_{major} = T_j = T_p + T_r + T_{pb} \qquad (2.6)$$

where T_{major} or T_j is the total cycle time for the project; T_p is the pilot drilling time, T_r is the prereaming time, and T_{pb} is the pull back time.

2.3.3 HDD Productivity and Cost

Allouche et al. (2000) provided a study on HDD to consider company profile, type of project performed, duration, product pipe installed, bidding and estimating practices, and planning and operation control. The study concluded that HDD is favorable to most contractors, design engineers, and consultants in for the following reasons:

- No surface shafts required as drilling can commence from surface.
- HDD has relatively the shortest setup time.
- Straight alignment is not required, since HDD has the ability to change direction and grade.
- The long drive length installed using HDD compared to other trenchless technologies.

The most important results of the study were the productivity of HDD (ft/hr) associated to specific pipe diameters presented in Table 2.2, in clayey, rock, and sandy soils. In another study (Allouche et al., 2003), HDD operation was covered in terms of product pipe material, size, and applications.

Table 2.2 HDD Productivity vs. Soil Type and Diameter (Allouche et al., 2000)

Diameter Range (in.)	Soil Type		
	Clay	Rock	Sand
2–4	74	42	55
6–8	53	28	41
10–12	42	19	37

Table 2.2 - *Continued*

>12	28	9.5	27

Willoughby (2005) introduced prereaming values for HDD productivity (ft/hr) in clay, rock, and sand as presented in Table 2.3; and it showed that sand and clay have large productivity compared to rock in different prereaming diameter ranges.

Table 2.3 HDD Productivity in Soil Conditions (Willoughby, 2005)

Preream Diameter (in.)	HDD Productivity (ft/hr)		
	Clay	Rock	Sand
< 24	180	30–60	180
24–32	150	30	150
>32	120	18	120

2.4 The Analysis of Variance (ANOVA) Model

In this method a t-test is utilized to compare a pair of population means. However, if there are more than two population means, it is tedious to conduct t-test; also the experimentwise error is not easily controlled. Kinnear and Gray (2006) explained that the comparison between two population means, μ1 and μ2, is stated by the null hypothesis H_0: μ1 = μ2 versus the alternate hypothesis H_1: μ1 ≠ μ2. Thus, if it is found that the t-test indicates significance, H_0 can be rejected, and then alternate hypothesis H_1: $\mu_1 \neq \mu_2$ is used to conclude that significant difference exists between the two population means. However, when there are more than two population means need to be compared, testing the equality of means under the null hypothesis H_0: $\mu_1 = \mu_2 = \mu_3 =.... = \mu_n$. becomes cumbersome for t-test (Montgomery, 2007) and (Walpole et al., 2007).

Alternatively, One-Way ANOVA model is utilized efficiently to test the significance of difference in means of continuous random outcomes or dependent variables (e.g. HDD productivity) that it is affected by predictors or independent variables (e.g., soil type, pipe material, operator and contractor experience, machine size, and other subconditions). In this case, ANOVA model is applicable as a univariate model to explain how treatments affect a single outcome; i.e., HDD productivity. The general form of prediction model is $Y_{ij} = \mu + \tau_i + \varepsilon_{ij}$, where μ is the grand mean, τ_i is the treatment effect, and ε_{ij} is the error (Bancroft and Han, 1981) and (Bird, 2004). This prediction model can bring consistency to outcomes of system or operation. When the treatment effect is significant, multiple comparisons can be used to determine which pair of means differ (Montgomery, 2007).

To understand the analysis of productivity, we must first understand reasons for variability in collected data. Reasons or sources of data variability are as follows:

- Treatment effects: effects of independent variable that the test tries to detect.
- Individual differences: when the experiment involves humans e.g., operators, the human element causes productivity to differ.
- Random residuals or experimental errors. These can be referred to three sources:
    - External conditions; e.g., time of day, weather factors (temperature, humidity, and others).
    - The state of subject (current focus) or attention of relevant individual (e.g., contractor or operator experience and skills).
    - The ability of experimenter or computer to score or record data accurately.

2.5 Chapter Summary

This chapter provided a comprehensive review of studies and research conducted on productivity of construction operations including applications in construction such as Continuous Flight Auger (CAF) that was studied by Zayed (2005).

Also, this chapter included applications in trenchless technology such as microtunneling (Hegab and Salem, 2004) and (Hegab, 2005), auger boring for steel casing installation (Salem et al., 2003), and simulation of microtunneling by Luo and Najafi (2007).

Models were developed to study and simulate cyclic construction operations using construction simulation program such as MicroCYCLONE (Halpin and Rigs, 1992) and SLAM II that was introduced by Gonzales-Quevedo (1993). Both programs are useful in studying productivity of construction operations.

Prediction of missing data utilizing simulation by AbouRizk et al. (1991), the cumulative density function (CDF) for tunneling project conducted by Touran (1997), and sensitivity analysis in simulation presented by Pang and Hammad (2006) are examples on active simulation during construction or utility installation.

HDD performance and critical issues in wetland was covered by Manacorda et al., (2010). Also, average values for HDD productivity in different soil types (clayey, rocky, and sandy conditions) was introduced by Allouche et al. (2000) and Willoughby (2005).

Studies such as factors considered in HDD operation (Zayed, 2007), (Ali et al., 2007), and (Mahmoud, 2009) introduced HDD operation productivity and related factors during installation of utilities in clay, rock, and sand soils.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

The research methodology is illustrated in Figure 3.1, and it is divided into six main milestones: literature review, HDD questionnaire design, data collection, data sorting and classification, data analysis and model development, and development of HDD user interface.

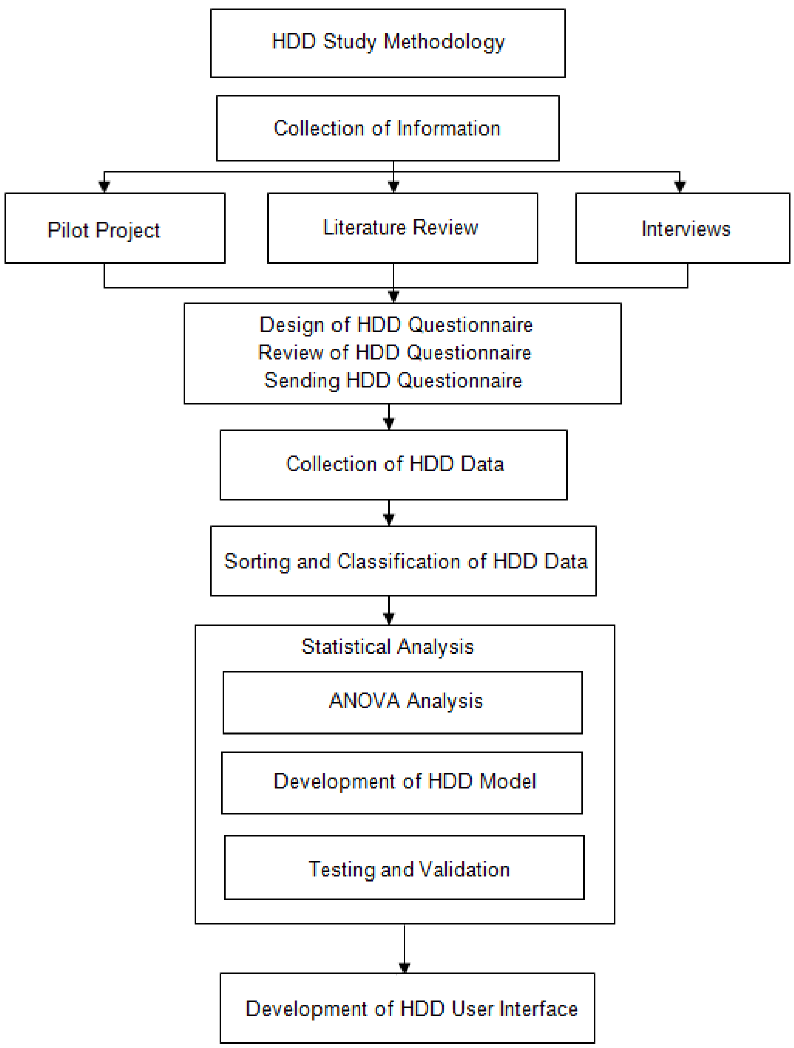


Figure 3.1 HDD Study Methodology

The research methodology as illustrated in Figure 3.1 was conducted in details as follows:

- Collecting HDD background and information.
  - Conducting literature review in construction, trenchless, and HDD operation productivity. The purpose was to know the latest work and studies including HDD affecting factors and developed models for HDD productivity.
  - Observing HDD productivity data in a pilot project to obtain initial data and information about HDD in field, as well as to determine HDD conditions. Additionally the practices of HDD crews when obstruction and obstacles encountered, were observed.
  - Conducting interviews with HDD experts and professionals through site visits, conferences, and conference calls.
- Designing HDD questionnaire by utilizing information gathered through the literature review, pilot project, interviews, and conference calls.
- Reviewing HDD questionnaire with HDD experts through emails, interviews, and conference calls.
- Sending HDD questionnaire through attending conferences and contacting HDD experts and professional.
- Collecting HDD questionnaire data.
- Sorting and classifying of data according to soil type, HDD machine size, diameters, depth, pipe materials, and other conditions.
- Conducting statistical analysis and model development as follows:
  - Testing the significance of subconditions applied in HDD operation by utilizing the analysis of variance (ANOVA) model.
  - Developing HDD productivity prediction model using SPSS[1] 16.0 (2007) for clayey and rocky conditions.
  - Testing and validating of HDD productivity model.

[1] Statistical Package for the Social Sciences

- Developing HDD user interface as a planning tool to be able to utilize HDD significant subconditions and HDD productivity prediction models.
    - As part of the methodology, developing and calculating HDD modified productivity term as well as calculating quantity of drilling fluid, materials and labor cost for operation was conducted also.

3.2 Designing HDD Questionnaire

Information gathered through literature review, interviews, site visits, conferences, and conference calls were the basis for designing HDD questionnaire. Reviewing HDD questionnaire was conducted through consulting experts and professionals in HDD work and projects.

Appendices A-1 through A-9 show the questionnaire that was designed for HDD operation. The questionnaire included three main parts. The first part required information about participant, company and project profile, and pipeline parameters and soil characteristics. The second part was focused on project durations, HDD crew, HDD machine specifics, and HDD drilling stages. The third part was designed to collect data about project operational conditions during pilot hole drilling, prereaming, and pullback operations.

3.2.1 Site Visits

This part was important in providing both the initial qualitative information and quantitative data required for HDD productivity and conditions in the field. Through observations, the main groups of conditions were determined. Collecting real time data for HDD productivity in the pilot project was the first chance to study the variations in HDD productivity. Site visits extended during the months of November and December 2010, as well as January 2011.

Also, visiting HDD pilot project presented a chance to interview contractor and subcontractor's crews such as, superintendent, safety engineer, and other HDD personnel, as well as field engineer and drilling fluid technician.

3.2.2 Interviews and Conference Calls

Many interviews were made with consultants and experts in HDD works during site visits as well as attending lectures, presentations, and conferences that gave the researcher an opportunity to collect required qualitative data about HDD operation. Also, conference calls were made with HDD professionals, construction managers and field operation engineers.

3.2.3 Underground Construction Technology (UCT) International Conference and Exhibit

The HDD questionnaire was launched mainly during CUIRE HDD School and UCT conference held in Houston, TX, USA, January 23–27, 2011. Many of interviews were made with HDD experts and professionals during the school and conference activities to address them with the HDD study and to explain the way to respond to the HDD questionnaire.

3.2.4 North American Society for Trenchless Technology (NASTT) 2011 No-Dig Show

NASTT 2011 No-Dig Show was held in Washington, D.C., USA March 27–31, 2011. This conference included HDD applications, field evaluation of HDD performance, oil and gas projects utilizing HDD technique, pipe conditions after installation, and risk associated to HDD constructions. The conference provided a great chance for interviewing HDD specialists and continuing the work to collect needed data.

3.3 Reviewing HDD Questionnaire

HDD questionnaire was reviewed with HDD experts and professionals. Also, reviewing process extended through attending UCT and TT conferences, HDD lectures and presentations, and conference calls. The results were promising, i.e., most of the changes were minor and did not change main frame of HDD questionnaire or sections.

3.4 Sending HDD Questionnaire

After designing and reviewing processes were completed, decision was made to launch the questionnaire and providing proposed participants with the link to the questionnaire website through emails. The message to participants was to encourage them to respond to the questionnaire and to provide needed data. Participants were selected among experts and professionals in HDD work.

3.5 Collecting HDD Data

Gathered data was sorted and kept by name of participant and company to make the classification process and analysis organized. Then, a separate file was created to keep information pertaining to all responses classified, mainly according to soil, project, contractor, and machine conditions.

3.6 Sorting and Classifying of HDD Data

Data collected is divided into two levels. The first level presents data gathered in HDD pilot project. This part was employed to study the variations in HDD productivity due to the changes in soil conditions and to test applicability of ANOVA model.

The second level of data is collected through HDD questionnaire. This part was used to study variations in HDD productivity due to changes in HDD subconditions including soil, project, contractor, and machine conditions, and to develop HDD productivity prediction models in soil conditions encountered.

3.7 HDD Productivity Statistical Analysis

The statistical analysis was conducted on three stages. The first stage involved testing significance of HDD subconditions by utilizing the analysis of variance (ANOVA) model. The second stage involved developing HDD productivity models in soil conditions encountered using significant subconditions in HDD operation. And finally, the third stage involved testing and validating HDD model by comparing actual HDD productivity with predicted HDD productivity.

3.7.1 The Analysis Of Variance (ANOVA) One-Way Model

One-Way ANOVA model was described by Bancroft and Han (1981), Bird (2004), and Montgomery (2007) for testing variance among population samples. The model is used to test the significance of treatments effect between samples' means in population considering two different levels of treatments in one factor (Walpole et al., 2007). The ANOVA model is applicable in testing significance of treatment effect for tow levels or more. This model was utilized to test significance of HDD subconditions in order to help in developing the HDD productivity prediction models for soil conditions encountered in HDD projects.

3.7.2 HDD Model Development

SPSS 16.0 (2007) was used to develop HDD productivity prediction models considering subconditions significance. By integrating the results obtained by ANOVA and SPSS, HDD productivity models were developed.

3.7.3 HDD Model Validation

The ANOVA model gives significance that is less than test statistics significance (α) as validation on results. SPSS 16.0 (2007) gives primary validation by providing confidence intervals for model parameters or constants, calculating R^2 and R^2_{adj} values, mean squares (MS), and significance of model (sig.). Another measure on model validity is by comparing actual HDD productivity with predicted HDD productivity using model developed for a complete set of collected data.

3.7.4 HDD User Interface

Results of ANOVA and HDD productivity models were used in the user interface designed for HDD operation in soil conditions encountered in this study. This user interface is able to calculate HDD model productivity (ft/hr), HDD modified productivity considering efficiency of HDD crew and machine, quantity of drilling fluids in gallons, and estimate of labor costs based on average values.

3.8 Chapter Summary

The methodology of current research was based on literature review as well as studying and analyzing of pilot project data and collected data by HDD questionnaire. The research methodology can be summarized as follows:

(1) Conducting literature review addressing techniques, conditions, and modeling of construction operations, trenchless technologies, and HDD operations.

(2) Collecting real time data through pilot project and HDD questionnaire.

(3) Sorting and classifying of collected data.

(4) Utilizing ANOVA model to test the significance of HDD subconditions.

(5) Modeling HDD productivity for clayey and rocky conditions.

(6) Testing and validating of developed HDD productivity models.

(7) Developing HDD modified productivity by factoring in non-productive time in operation.

(8) Developing HDD user interface screen for HDD significant subconditions.

CHAPTER 4

HDD PRODUCTIVITY DATA

4.1 Introduction

This chapter presents collected HDD data through two levels. As mentioned previously, the first level presents data collected by visiting the pilot project. The second level presents data collected by HDD questionnaire. Both sets of data cover and address qualitative and quantitative aspects of subconditions expected to have an impact on productivity of HDD operation.

4.2 HDD Productivity Conditions

As a result of literature review, site visits, interviews, conference attendance, and conference calls, main conditions were determined and divided into four groups including soil, project, contractor, and machine conditions. HDD conditions and subconditions are illustrated in Figure 4.1. HDD questionnaire was designed to address these subconditions during HDD operations.

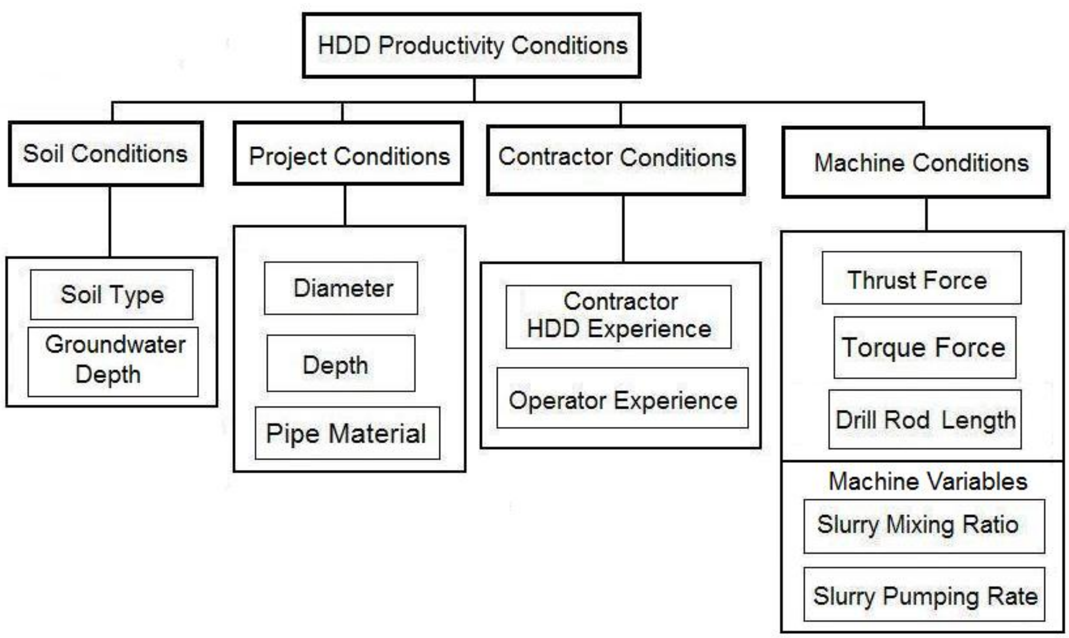


Figure 4.1 Conditions and Subconditions of HDD Productivity

4.2.1 Soil Conditions

Soil is considered the most important condition that can affect HDD productivity. This assumption is simply true as the soil type determines size of equipment to be used, type of cutting head and reamer, mixing ratio and pumping rate of drilling fluids. The soil condition group included type and ground water level.

4.2.2 Project Conditions

This group includes borehole diameter, borehole depth, and pipe material (in pullback operation). Pipe sections are connected (welded in case of steel pipe or fused in case of HDPE and PVC pipe) before the start of pullback operation. Therefore, there is no effect of pipe section length on HDD productivity during prereaming or pullback operation.

The diameter of borehole is expected to have an effect on HDD productivity as designers choose a specific thrust force (kip) to drill or to preream at a specific borehole diameter. The depth of pipeline can clearly affect the HDD productivity as was proved in testing HDD productivity means using ANOVA model. The effect of depth can be moderately smoothed by the distance set back and by modifying entry and exit angles of pipeline alignment. Pipe material is also related to the radius of curvature and pullback force required during pullback stage. Therefore, pipeline depth and diameter were studied during prereaming operation, while the effect of pipe material can be studied in details during pullback operation.

4.2.3 Contractor Conditions

Experience of HDD contractors and HDD rig operators were assumed to have no direct effect on HDD productivity, and ANOVA model was successful to validate this assumption through testing of significance. Knowledge and experience gained can improve ability of HDD operators and crews to face problems and obstructions and respond properly in a critical situation. The effect of operator and contractor experience cannot easily be evaluated, because HDD contractors use similar equipment and follow similar procedures.

4.2.4 Machine Conditions

This group includes thrust force (kip), torque force (ft-kip), in addition to machine variables that includes slurry mixing ratio (lb/100 gal), and slurry pumping rate (gpm). Usually HDD operators use specific thrust and torque force for machine type and job size. Also, when drilling in difficult soil conditions, HDD rigs operate with high power.

4.3 HDD Productivity Data

As said earlier in the research methodology, HDD data was collected through observing a pilot project, and HDD questionnaire. Both data groups were used in testing significance of subconditions, while questionnaire data was used mainly in modeling HDD productivity.

4.3.1 Village Creek Reclaimed Water Pilot Project

Collection of HDD data started with site visits to record project preparation, pilot hole drilling, prereaming, and pullback of product pipe. The project was located at Hwy 360 at Trinity Boulevard, Fort Worth, TX, USA. The project crossed Hwy 360 by installing a 30-in. diameter steel pipe for a distance of 1,100 ft to host a 26-in. diameter ductile iron product pipe to convey reclaimed water. The pilot project was selected to obtain accurate and real-world life data to record variations in HDD productivity due to the changes in soil and project conditions. Table 4.1 presents specifics of the pilot project. Appendix C shows project site layout, bore-path profile, geotechnical report and soil condition description, while Appendix D presents jobsite photos in different stages of HDD operation including preparation, pilot hole drilling, prereaming, and pullback of product pipe, in addition to the resources of machines and equipment involved.

Table 4.1 HDD Pilot Project Specifics

Item	Description
Project Name	Village Creek Reclaimed Water Eastern Delivery System
Project Location	Hwy 360, Trinity Boulevard, Fort Worth, Texas, USA
Pipe Type and Diameter	Steel Pipe, 30 in. Outside Diameter (OD)
Reamer Size and Type	36 in. Milled Tooth Reamer, see Figure 4.2 (b)
HDD Machine Type	Vermeer D 330 x 500
Crew	1 HDD Operator, 2 HDD Workers, 1 Mud System Worker, 1 Trackhoe Operator, 1 Oiler and Mechanical, 1 Water Truck Operator, 1 Pump Worker
Pipeline Length and Depth	1,100 ft, 50 ft at midpoint

Table 4.1 - *Continued*

Type of Soil Conditions (starting from exit pit side)	Shaly Clay, Sandy Shale, Shaly Clay, and Silty Clay	
Preparation Period (days)	4	
Equipment and Tools	HDD Rig, Backhoe, Loader, Forklift, Recycling Unit, Pumps, Trailer, welding equipment, and Water Tank	
Overall Productivity (ft/hr)	Pilot hole	37
	22 in. Prereaming	54
	26 in. Prereaming	91
	36 in. Prereaming[2]	25, 51, 180 min., ave., max.
	42 in. Prereaming	39
	Pullback	576
Working Area	Machine Side (150 ft x 220 ft)	
	Product Pipe Side (50 ft x 110 ft)	
Drilling Fluid Collection Pool Size	35 ft x 35 ft x 5 ft	
Entry Pit Size	18 ft x 20 ft x 6 ft	

After setting up of machines and equipment involved in project as illustrated in Figure 4.2 (a), HDD operation started with drilling a pilot hole.

(a) HDD Resources (b) Milled Tooth Reamer

Figure 4.2 Pilot Study Rig and Reamer

[2] This reamer size was selected for productivity study.

Usually a HDD cycle (drilling of one rod distance) starts by moving drilling rod from the trailer deck by a forklift or backhoe towards the HDD machine. HDD machine pumps drilling fluid into borehole through drilling rod, and stops when the drilling rod is inserted in the ground.

Figure 4.2 (b) illustrates how a routine check on reamer done by pumping drilling fluid through reamer nozzles. Different reamer sizes were used to enlarge diameter of borehole until it became 1.25–1.5 times the product pipe diameter.

HDD project requires minimal surface excavation and soil support system for entry and exit pits. Figure 4.3 illustrates surface excavation required at entry and exit pits. Both pits were used to collect drilling fluid, to note changes on HDD operation, and to serve as part of required working area on both sides. Furthermore, exit pit was used to change cutting head and replace reamers.

(a) HDD Entry Pit (b) HDD Exit Pit

Figure 4.3 HDD Entry and Exit Pits

Since the HDD bore-path usually passes through different soil types, contractors have to study the proposed bore-path profile carefully. Figure 4.4 illustrates an integrated brief summary for bore-path profile for soil conditions encountered.

Based on the geotechnical study, a field engineer usually selects type of cutting head and reamer suitable for soil condition encountered. Also, drilling fluid designer selects mixing ratios for bentonite and polymers and drilling fluid pumping rate to remove the cuttings out of borehole in a short time.

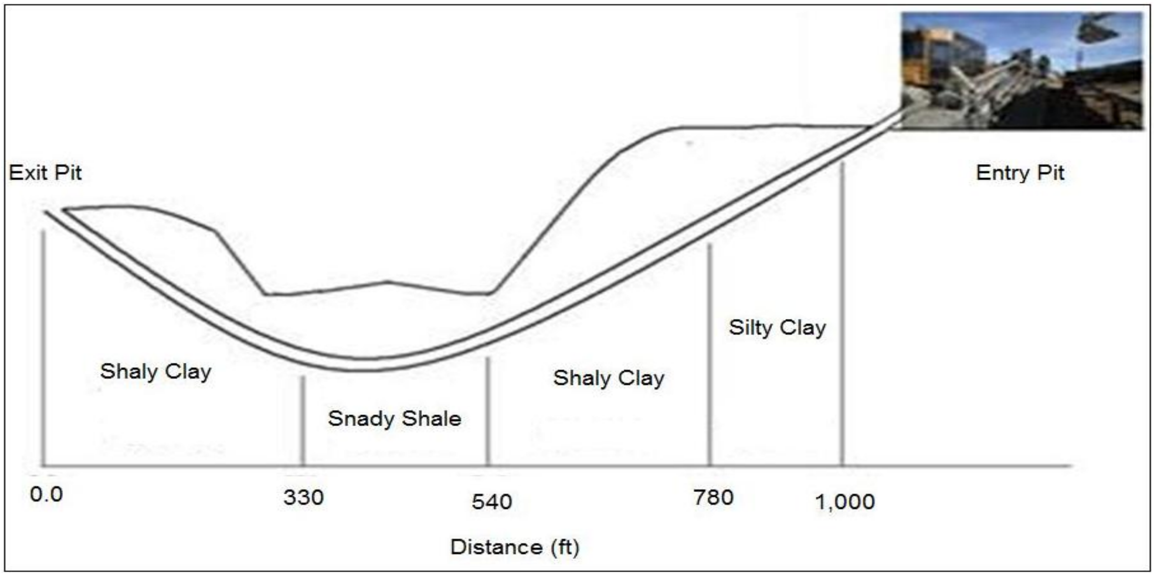


Figure 4.4 Bore-path Profile

4.4 HDD Productivity Data in Pilot Project

Table 4.2 presents collected data for HDD productivity in pilot project during prereaming of borehole. A 36-in. diameter milled tooth reamer was used to preream of borehole. The maximum productivity achieved was 180 ft/hr, and observed within the last soil zone (silty clay), which gives an indication that, for a specific soil condition, HDD productivity will be greater at the beginning and at the end of drilling operation. The minimum productivity value was 25 ft/hr, and occurred at the midpoint of the drive length, in soil condition No. 2 (sandy shale). This soil type required more than one hour for preream a distance of 30-ft.

Table 4.2 Observed HDD Productivity for the Pilot Project (ft/hr)

Soil Condition	Observations									
	1	2	3	4	5	6	7	8	9	10
Shaly Clay	150	150	90	64	75	82	53	46	62	64
Sandy Shale	75	75	64	60	38	25	44	48	---	---
Shaly Clay	82	75	51	49	43	58	56	64	---	---
Silty Clay	106	67	69	150	180	---	---	---	---	---

4.5 HDD Questionnaire Data

This section covers collected data through HDD questionnaire. A total of 250 emails were sent to contractors, consultants, and engineers represent experts and professionals in HDD projects in North America and Canada, Europe, and the Middle East. However, 14 valid responses received.

4.5.1 Soil Condition

Figure 4.5 illustrates numbers and percentages of projects encountered in each soil condition. Two main soil conditions were encountered; clayey and rocky conditions. Two project cases were encountered in sandy conditions, and one project case had a mix of soil conditions including clayey, sandy, and rocky conditions.

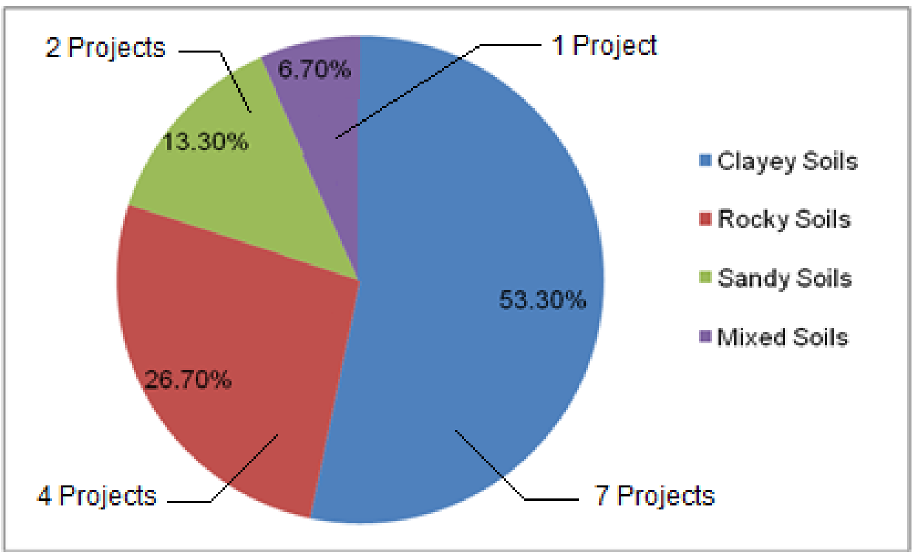


Figure 4.5 Distribution of Soil Conditions in HDD Questionnaire Data

4.5.2 HDD Rig Size

In responses to questionnaire, all HDD rig size categories were presented including Mini-, Midi-, and Maxi-HDD machines. HDD machine size refers to a specific thrust and torque force. For example, torque force (ft-kip) for Mini-HDD is less than 4 ft-kip. For Midi-HDD, torque force takes the range of 4–20 ft-kip, and for Maxi-HDD, torque force is greater than 200 ft-kip. HDD rig size distributions are illustrated in Figure 4.6.

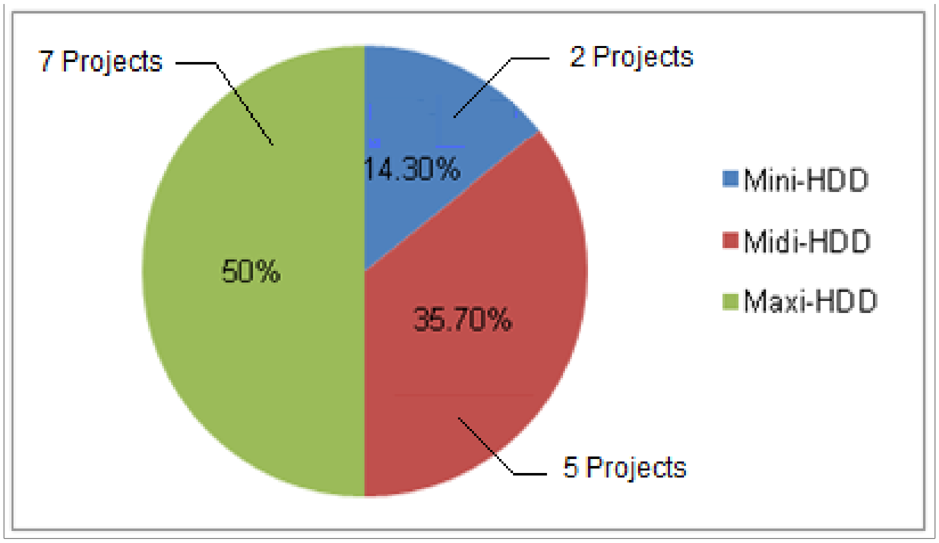


Figure 4.6 Distribution of Rig Size in HDD Questionnaire

HDD rig size can drill and install specific diameter, depth, and length of product pipe according to their capability in terms of thrust and torque force. Usually Mini-HDD is used to drill and to install conduits for power lines and telecommunications and for pipes less than 12 in. in diameter, with a depth of less than 15 ft, and length less than 600 ft. Midi-HDD is able to drill and install product pipes 12-24 inches in diameter, with a depth of 15-75 ft, and length of 600-2,000 ft. Maxi-HDD is able to drill and install product pipes 24-60 inches in diameter, with a depth of 75-200 ft, and length of 2,000-7,000 ft.

According to the questionnaire, 75% of rigs utilized in clayey conditions were Maxi, 12.5% were Mini, and 12.5% were Midi. While in rocky conditions 50% of rigs utilized were Midi, 25% were Maxi, and 25% were Mini. In sandy conditions, only Midi-HDD rig size was utilized.

4.5.3 Product Pipe Size

Different size categories of pipes were encountered in HDD questionnaire. Table 4.3 presents pipe size categories encountered.

Table 4.3 Pipe Size Classes According to HDD Classification (Najafi, 2005)

Pipe Size Class or Category	Pipe Size Range (in.)
Small	2–12
Medium	12-24

Table 4.3 - *Continued*

Large	24-60

4.5.4 Project Conditions

Pipeline diameter, depth, and material are the most important conditions in HDD project and are considered in design during preconstruction services and during installation. Figure 4.7 illustrates the distribution of pipe sizes within the categories described in Table 4.3.

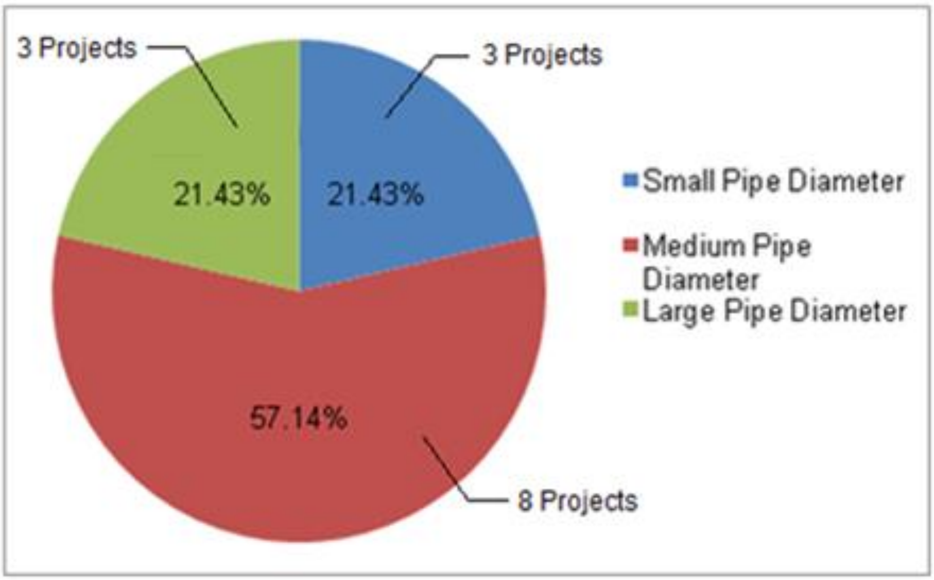


Figure 4.7 Distribution of Pipe Sizes in HDD Questionnaire

Additionally, this research focused on different pipelines diameters, lengths and depths according to HDD rig sizes utilized. Figure 4.8 illustrates distribution of prereaming diameters in clayey conditions. It is shown that large borehole diameters were used in approximately 70% of clayey cases, and this coincides with the ratio of Maxi-HDD rigs utilized in 50% of cases.

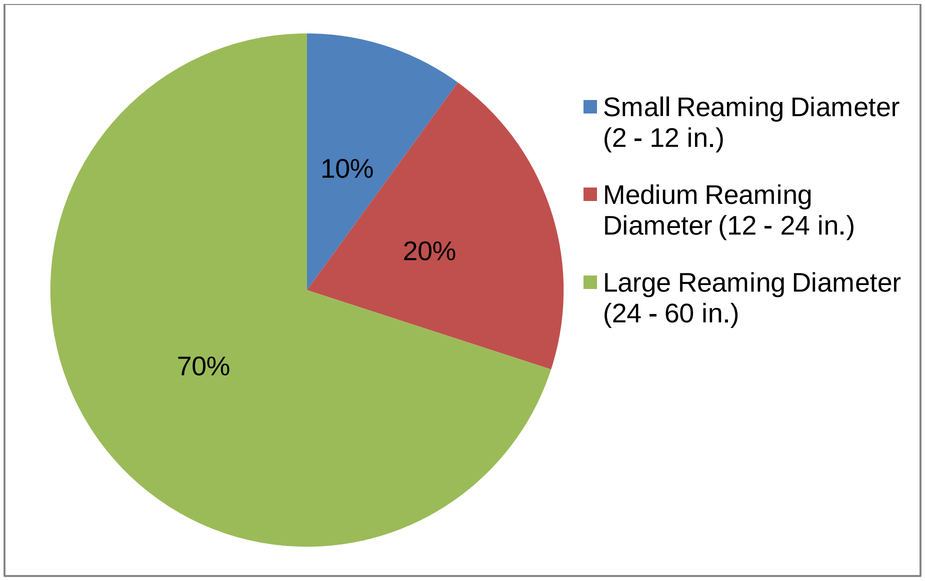


Figure 4.8 Distribution of Prereaming Diameter in Clayey Conditions

Figure 4.9 illustrates distribution of the drive lengths in clayey conditions. It shows that long drive length takes the largest, or 67% of cases.

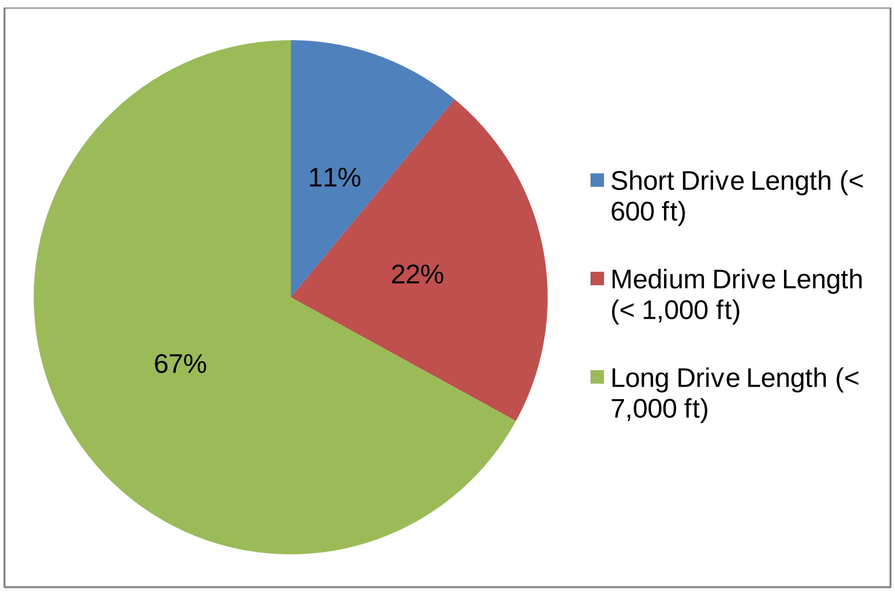


Figure 4.9 Distribution of Drive Length in Clayey Conditions

Figure 4.10 illustrates distribution of depths of borehole in clayey conditions. Maxi-HDD rigs were utilized in 37.5% of cases reported in the questionnaire.

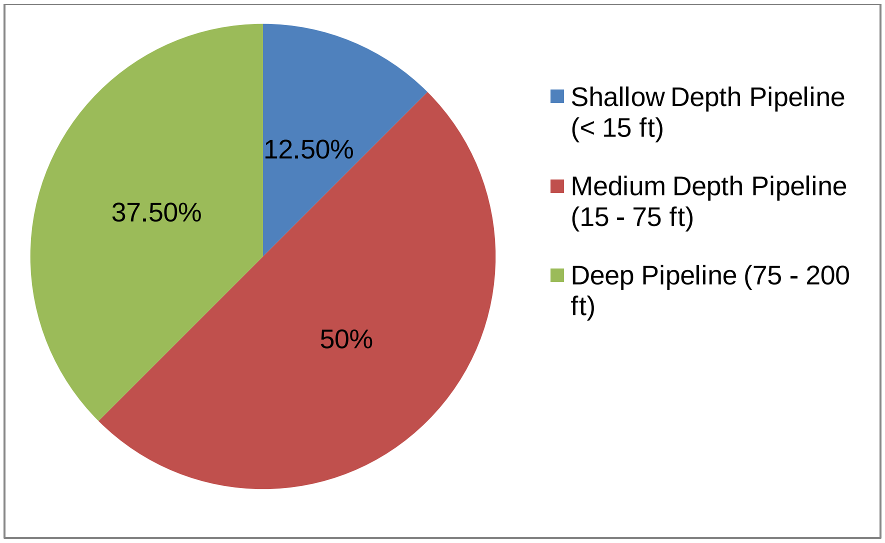


Figure 4.10 Distribution of Pipeline Depth in Clayey Conditions

For rocky conditions, Figure 4.11 illustrates distribution of diameters of borehole, wherein medium-diameter size had the maximum ratio in 62% of cases.

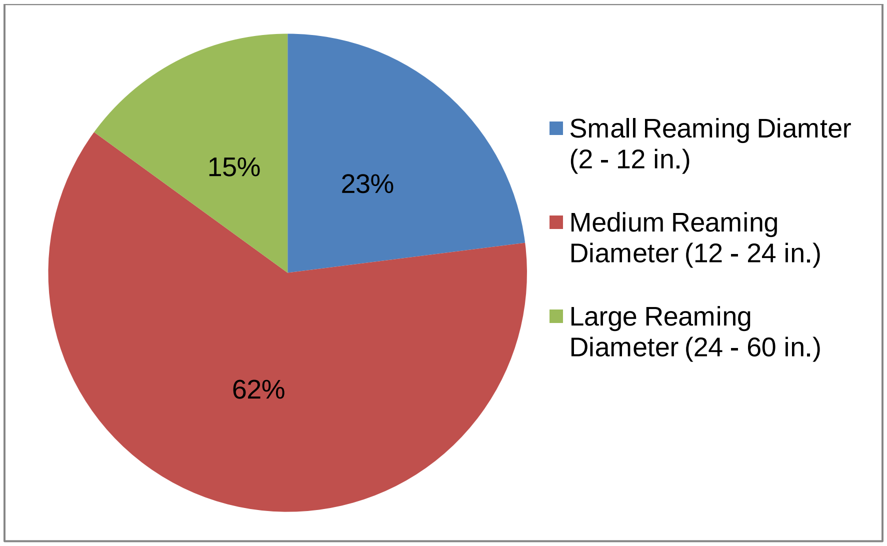


Figure 4.11 Distribution of Prereaming Diameter in Rocky Conditions

Figure 4.12 illustrates the distribution of drive lengths, where medium drive lengths had the maximum ratio of 50% of cases.

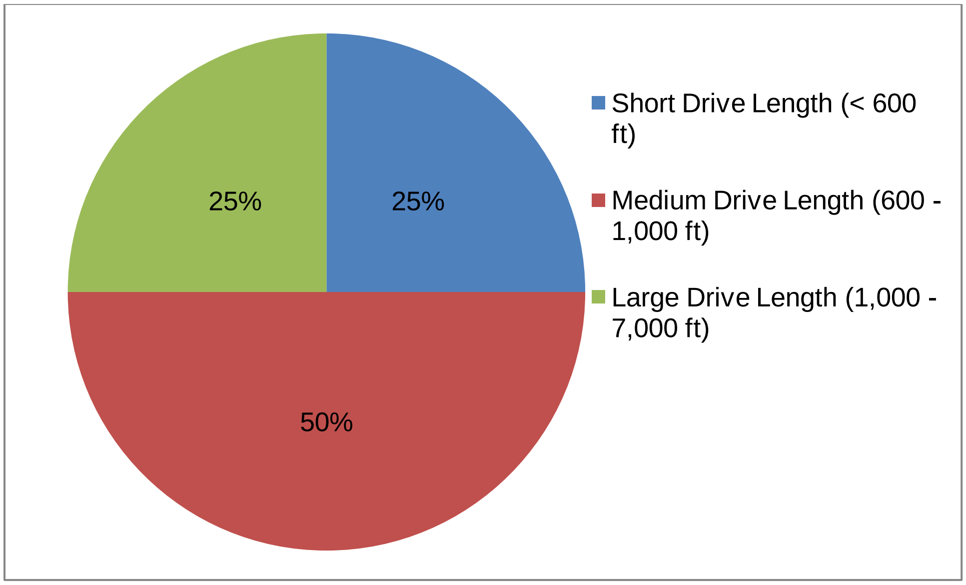


Figure 4.12 Distribution of Drive Length in Rocky Conditions

Medium depth of borehole happened in 75% of rocky conditions as illustrated in Figure 4.13.

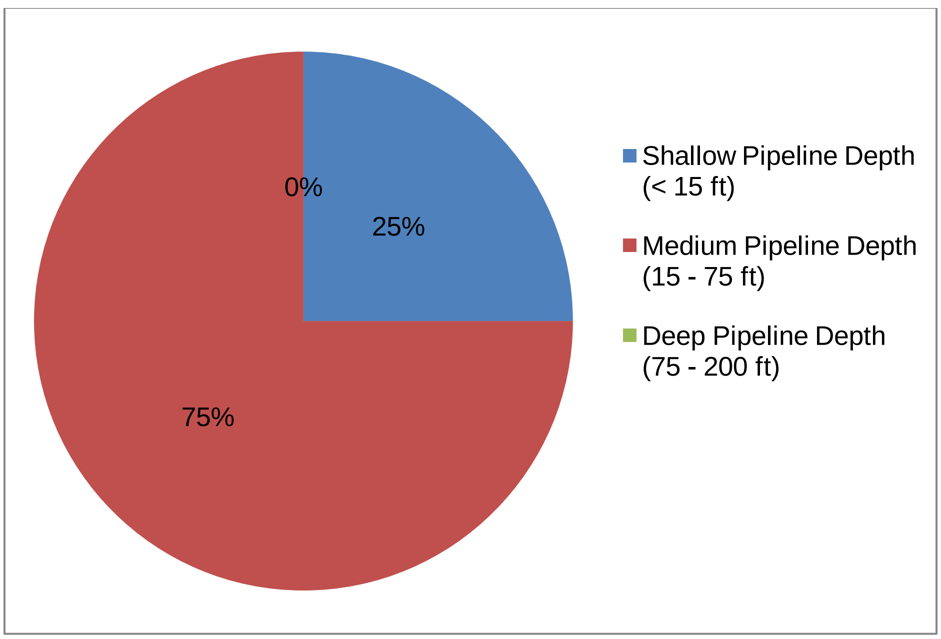


Figure 4.13 Distribution of Pipeline Depth in Rocky Conditions

4.5.5 Pipe Material

Pipe materials encountered in HDD questionnaire included steel, HDPE, and PVC pipes. Figure 4.14 illustrates distribution of pipe materials installed in HDD questionnaire and shows that steel pipe was used in 64.3% of project cases. This happens because steel pipe is mostly used as a product pipe and sometimes as a casing pipe for large diameter and critical installations.

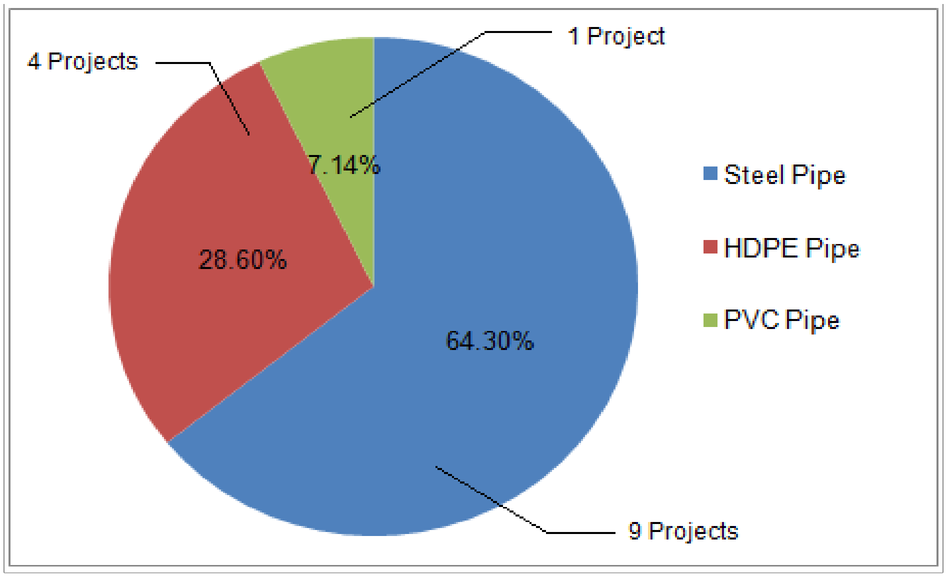


Figure 4.14 Distribution of Pipe Material in HDD Questionnaire

4.6 Preparation Requirements and Non-productive Time

Part of HDD questionnaire addressed time elapsed for solving problems encountered and non-productive time spent by workers and operators. Table 4.4 presents obstructions encountered, fixing time required, and non-productive time spent by construction team in prereaming operation through clayey and rocky conditions.

It should be noted that, preparation time depends on job size, total drive length, pipe diameter, depth of pipeline, and other conditions. Some jobs get complicated when it requires pulling back more than one product pipe or conduit. Also, HDD job gets complicated when the scope of work involves other construction operations and activities as part of main contract. Preparation period also depends on required work load. Table 4.5 presents distribution of preparation period among job size according to the classification of HDD categories (Mini-, Midi-, and Maxi-HDD) (Najafi, 2010) in clayey, sandy, and rocky conditions.

Table 4.4 Obstruction and Non-productive Time

Soil Condition	Obstruction Type in HDD Project	Obstruction Solving Time (hr)	Non-productive Time %
Clayey Conditions	Machine Breakdown	2	4
	NA	NA	4
	NA	NA	7.5
	NA	10	45
	NA	2	7.5
Rocky Conditions	Gravel & Cobbles	NA	15
	Hydrofracture	NA	2
	Hole Collapse	10	7.5
	Groundwater Seepage	6	15
	Machine Breakdown	6	15

Table 4.5 Preparation Time in HDD Projects

Soil Condition	Job Size	Job Length (ft)	Preparation period (day)
Clayey	Maxi	2,700	7
		4,000	60
		5,500	NA
		1,100	12
		3,212	60
		3,782	60
	Midi	350	5
	Mini	600	0.125 (2 hr)

Table 4.5 - *Continued*

Sandy	Midi	750	6
		220	1
Rocky	Maxi	2,000	3
	Midi	800	3
		731	3
	Mini	300	0.125 (2 hr)

4.7 HDD Productivity Data Primary Analysis

4.7.1 HDD Questionnaire Data

This section presents collected data through HDD questionnaire. The data presented in this section is complementary with data collected through the pilot project.

Data collected by the questionnaire mainly contains cases in clayey and rocky conditions, in addition to two cases in sandy conditions (one of them for pulling a cable), and one case the soil was a mix of clayey, rocky, sandy, silty, limestone, and gravel materials. The last case was excluded from data analysis and modeling. Collected data by questionnaire mainly addressed subconditions expected to have an effect on HDD productivity.

4.7.1.1 HDD Productivity Data in Clayey Conditions

Table 4.6 presents data collected for HDD productivity in clayey conditions. It is shown from table that minimum value is 20 ft/hr, maximum value is 183 ft/hr.

Table 4.6 HDD Productivity Data for Clayey Conditions

Diameter (in.)	Depth (ft)	Drilling Rod Length (ft)	Thrust Force (kip)	Torque Force (ft-kip)	HDD Productivity (ft/hr)
12	6	10	25	11	120
16	70	30	130	25	76

Table 4.6 - *Continued*

20	22	30	215	25	77
22	30	30	280	45	28
24	120	30	230	25	183
26	148	10	260	35	27
28	22	30	215	25	79
28	70	30	130	25	76
34	150	30	1,200	100	42
36	120	30	230	25	183
36	30	30	280	45	28
38	148	10	260	35	23
42	30	30	280	45	24
48	148	10	260	35	20
48	150	30	1,200	100	42

Subconditions such as prereaming diameter (in.), depth of pipeline (ft), drilling rod length (ft), thrust force (kip), and torque force (ft-kip), have significant impacts to HDD productivity. This topic will be covered in more details in Chapter 5, using ANOVA model.

4.7.1.2 HDD Productivity Data in Rocky Conditions

Table 4.7 shows data obtained for HDD productivity in rocky conditions. The minimum value of HDD productivity in rocky conditions was 18 ft/hr which occurred using a 9-in. prereaming diameter, 14-ft depth, and 731-ft length of borehole. The maximum productivity value was 75 ft/hr, which occurred using a 12-in. prereaming diameter, 25-ft depth, and 800-ft length of borehole, using Midi-HDD.

Table 4.7 HDD Productivity Data for Rocky Conditions

Diameter (in.)	Depth (ft)	Drilling Rod Length (ft)	Thrust Force (kip)	Torque Force (ft-kip)	HDD Productivity (ft/hr)
9	14	14	35	9	18
10	25	15	70	9	67
12	25	15	35	5	75
13	14	14	35	9	18
14	25	15	70	9	33
16	25	15	70	9	33
18	25	15	70	9	33
18	14	14	35	9	18
18	30	30	70	5	33
22	25	15	70	9	33
24	30	30	70	5	27
30	30	30	70	5	25
36	30	30	70	5	20

4.8 Chapter Summary

This chapter covered data collection through two levels. The first level of data collection was data obtained during visiting the pilot project. The second level of data collection was through sending a questionnaire to HDD experts and professionals. Collected data addressed HDD subconditions in four main groups of soil, project, contractor, and machine conditions.

Collected data by questionnaire was classified according to soil conditions and project size to present main data categories encountered in clayey, rocky, and sandy conditions. Non-productive time during HDD operations was included in the analysis.

CHAPTER 5

HDD SUBCONDITIONS ANALYSIS

5.1 Introduction

This chapter covers testing procedure applied in evaluating the impacts of HDD subconditions on productivity by applying the analysis of variance (ANOVA) model. Results obtained through ANOVA analysis will determine HDD significant subconditions that will be considered in developing HDD productivity model.

5.1.1 Identifying HDD Productivity Subconditions

Collected HDD data through pilot project and questionnaire are used to describe four main conditions in HDD operation including soil, project, contractor, and machine conditions. The number of subconditions (12) is relatively large to have enough data in order to be completely defined and modeled. Using a statistical modeling technique such as ANOVA to determine significance of subconditions is more practical. Therefore, ANOVA model was utilized to refine and reduce these subconditions considering their contributions into the HDD productivity model.

5.2 Identifying HDD Main Activity

Preream operation is the main HDD activity that current research considered for the purpose of studying and modeling of HDD productivity. Duration of preream activity is too long compared to other activities such as changing the cutting head, or changing the reamer. Also, other operation activities such as adding or removing drilling rod, connecting wireline of tracking system, or oiling and greasing HDD machines do not provide sufficient data or information for productivity analysis. This does not mean that these minor activities are not important or cannot be considered, but these activities usually take deterministic durations and are considered to be too short compared to the main activity durations (drilling or preream), even in short drive length projects.

5.3 The Analysis of Variance for HDD Subconditions

Data analysis and results using the analysis of variance (ANOVA) model are presented in this section for testing significance of subconditions contributing in developing HDD productivity model.

5.3.1 ANOVA Model Theory

ANOVA model is an updated t-test that is used to compare pair of population means (Kinnear and Gray, 2006). Simply, that the analysis involves a comparison between the two population' means μ_1 and μ_2 under the null hypothesis H_0: $\mu_1 = \mu_2$. Therefore, if it is found that the t-test indicates significance, null hypothesis can be rejected and alternate hypothesis H_1: $\mu_1 \neq \mu_2$ can be accepted to conclude that the significance exists between the two population means. Both, null and alternate hypothesis are covered in ANOVA model to test means' variance by comparing *F-Value* in *F-distribution table* under degrees of freedom of $a-1$ and $N-a$ with the calculated *F-test statistics value* using the following formula $F_0 = \frac{SS_{Treatments}/(a-1)}{SS_E/(N-a)} = \frac{MS_{Treatments}}{MS_E}$, which follows *F-distribution* with $a-1$ and $N-a$ degrees of freedom also. F_0 is the test statistics for the hypothesis of no difference in treatment means as well as a is the number of treatments and N is number of total observations.

In general, Mean Squares Error (MS_E) is unbiased estimator of σ^2, and under the null hypothesis, $MS_{Treatments}$ is unbiased estimator of σ^2. This implies that it is possible to reject H_0 and conclude that there is a difference in treatment means if $F_0 > F_{\alpha,a-1,N-a}$. Also, the same decision can be made using the *P-Value* associated to *F-* and F_0 *- Value* (Montgomery, 2007).

For a number of treatments, the term $y_{i..}$ represents the sum of observations in *ith* treatment for i = 1, 2,…, a_i; $\bar{y}_{i.}$ is the average of the *ith* treatment; $y_{..}$ is the total sum of observations; and $\bar{y}_{..}$ is the overall average for all observations. The sum of squares between treatments is defined as $SS_{Treatments} = \sum_{i=1}^{a} n_i(\bar{y}_{i.} - \bar{y}_{..})^2$; where, a is the number of treatments, and N is the total number of observations; in case of $n_1 = n_2 = ... = n_a$, then N= $n.a$.

The total sum of squares is equal to $SS_T = \sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij} - \bar{y}_{..})^2$ for all observations (y_{ij}) in experiment. Now, it is possible to calculate SS_E, the error sum of squares as $SS_E = SS_T - SS_{Treatments}$.

The mean squares *(MS)* is computed as follows, the first is the treatments *MS*; $MS_{Treatments} = \frac{SS_{Treatments}}{a-1}$ with $a-1$ degrees of freedom (df), and the second is the error *MS*; $MS_E = \frac{SS_E}{N-a}$ with $N-a$ degrees of freedom. Then F_0 is calculated and compared with *F- Value* in *F-distribution* table under $a-1$ and *N – 1*, the degrees of freedom as stated earlier.

5.3.2 Soil Conditions

Soil conditions are considered the most important factor especially in horizontal projects such as HDD. Soil type and groundwater level are included under soil conditions. Soil type determines size of HDD rig, type of cutting head or reamer, and type of material used in drilling fluid, mixing ratio, and pumping rate. Groundwater level is not expected to have significant effects on HDD productivity, based on conclusions in literature review, consulting HDD experts, and ANOVA results.

5.3.2.1 Soil Type Subcondition

Table 5.1 presents HDD productivity data for preream in soil conditions encountered in the pilot project. Maximum productivity was 180 ft/hr within No. 4 soil (silty clay). Minimum productivity was 25 ft/hr in No. 2 soil (sandy shale). Most of observations in middle of bore-path are very low, primarily due to soil type (shaly clay). To continue analysis of soil type impact on HDD productivity, a 2^2 ANOVA factorial design was conducted to test the effects of depth, length, and depth-length interaction during preream in pilot project. Therefore, the effects of soil on HDD productivity are considered to be major.

Table 5.1 HDD Productivity in Soil Condition

Soil	Productivity Sampling (ft/hr)										Tota	Average
Type*	1	2	3	4	5	6	7	8	9	10	l $y_{i.}$	$\bar{y}_{i}.$
1	150	150	90	64	75	82	53	46	62	64	836	84

Table 5.1 - *Continued*

2	75	75	64	60	38	25	44	48	---	---	429	54
3	82	75	51	49	43	58	56	64	---	---	478	60
4	106	67	69	150	180	---	---	---	---	---	572	114
$y_{..}$ = 2315												$\bar{y}_{..}$ = 75

* 1: shaly clay; 2: sandy shale; 3: shaly clay; 4: silty clay

The results of variance analysis for HDD productivity samples in soil conditions are presented in Table 5.2.

Table 5.2 ANOVA Analysis for Soil Type

Source of Variation	Sum of Squares	Degree of Freedom (df)	Mean Squares	F_0	P-Value
Soil Condition	14,014	3	4,671	4.86	< 0.01
Error	25,955	27	961	--	--
Total	39,969	30	--	--	--

Using ANOVA analysis, it was obtained that F_0 value, i.e. $F_0 = \frac{MS_{Treatments}}{MS_E} = \frac{4{,}671}{961} = 4.86$. This F_0 was compared with $F_{\alpha,a-1,N-a} = F_{0.05,3,27} = 2.96$. Since $F_0 > F_{0.05,3,27}$, null hypothesis H_0 can be rejected and it can be concluded that there is a difference between population means (at least one pair of means is different). Therefore, it can be concluded to use different models for HDD productivity through bore-path or soil profile.

When ANOVA test of treatments is significant within multi variables, it cannot be determined which pairs of means are different. Therefore, in this case, multiple comparisons should be considered. The comparison of means treatment effect has the null hypothesis H_0: $\mu_i = \mu_j$ for all $i \neq j$ and the alternate hypothesis H_1: $\mu_i \neq \mu_j$. For unequal sample sizes, Tukey-Kramer procedure (Montgomery, 2007) declares the two means are significantly different if the absolute value of their difference exceeds the value

$T_\alpha = \frac{q_\alpha(a,f)}{\sqrt{2}}\sqrt{MS_E(\frac{1}{n_i}+\frac{1}{n_j})}$, where T_α is the critical value for significance level α, $q_\alpha(a,f)$ is the upper percentage point of the studentized range statistic with a treatments and *f* degrees of freedom, MS_E is the error mean squares, and n_i and n_j are the sample sizes. In this case the critical value is calculated as $T_{0.05} = \frac{q_{0.05(4,27)}}{\sqrt{2}}\sqrt{961*(\frac{1}{n_i}+\frac{1}{n_j})}$, and the upper percentage of studentized range statistic is found as $q_{0.05(4,27)} = 3.87$.

Table 5.3 presents the comparison of critical value and means difference. It can be noticed that HDD productivity means of No. 2 and No. 4 conditions are significantly different as well as the HDD productivity means of No. 3 and No. 4 conditions.

While for other pairs, the difference in means is not significant. Therefore, ANOVA can determine if the difference in means is significant or not.

Table 5.3 Comparison of Studentized Range and Absolute Means Difference

Pairs of Means	$T_{0.05}$ Value	Means Difference $\lvert \bar{y}_i. - \bar{y}_j. \rvert$	Significance
$\bar{y}_{1.} - \bar{y}_{2.}$	40	30	No
$\bar{y}_{1.} - \bar{y}_{3.}$	40	24	No
$\bar{y}_{1.} - \bar{y}_{4.}$	47	31	No
$\bar{y}_{2.} - \bar{y}_{3.}$	42	6	No
$\bar{y}_{2.} - \bar{y}_{4.}$	48	61	Yes
$\bar{y}_{3.} - \bar{y}_{4.}$	48	55	Yes

As means of HDD productivity values are not significantly different in soil conditions No. 1, 2, and 3 as shown in Table 5.3, it can be concluded that HDD productivity through these conditions should be modeled separately.

5.3.2.2 Depth-Length Effect Analysis in Pilot Project

To confirm the ANOVA results presented in Table 5.2 and Tukey-Kramer procedure comparison conducted in Table 5.3, the *2^2 Factorial Design* (Montgomery, 2007) was conducted to test the effects of depth, length, and depth-length interactions on HDD productivity. For example, if the test is significant for any of these factors, it will be included in the HDD productivity model for the whole bore-path profile as the soil effect is not significant. Table 5.4 presents the *2^2 Factorial Design* organized table.

Table 5.4 2^2 Factorial Design for Depth-Length of HDD Bore-path

Factor		B = Depth		Calculations	
		Low	High	Sum	Average
A = Length	Low	(1) Obserns Sum	(b) Obserns Sum	(1)+(b)	---
	High	(a) Obserns Sum	(ab) Obserns Sum	(a)+(ab)	---
Calculations	Sum	(1)+(a)	(b)+(ab)	Total	---
	Average	---	---	---	Overall Average

2^2 Factorial Design implies there is a 2-factor effect (A = length, and B = depth) distributed into two levels (low, and high). Calculations are presented as subtotal and total of HDD productivity observations in Table 5.5. Finally, results of ANOVA analysis are presented in Table 5.6. Results of ANOVA *2^2 Factorial Design* are able to tell to or not to use any of these subconditions or terms in HDD productivity model among the whole bore-path of soil profile in pilot project.

Table 5.5 2^2 Factorial Design for Depth-Length Effect

Factor	Depth (ft)				
Length (ft)	Level of Factor	Low	High	Sum	Average
	Low	150	62		
		90	64		
		64	75		
		75	75		
		82	64		
		53	60		
		46	38		
	Sum	560	438	998	71
	High	58	25		
		44	44		
		48	48		
		106	82		
		67	75		
		69	51		
		150	43		
Sum		542	368	910	65
Total Sum		1,102	806	1,908	---
Average		69	50	---	68

As stated earlier, Table 5.6 presents the significance of depth, length, and depth-length on HDD productivity in pilot project. The results obtained by 2^2 *Factorial Design* confirmed results obtained in soil subconditions discussed earlier.

Table 5.6 ANOVA Analysis for 2^2 Factorial (Depth-Length)

Source of Variation	Sum of Squares	Degree of Freedom	Means Square	F_0	P-Value
Length	277	1	277	0.35	> 0.25
Depth	3,129	1	3,129	4	> 0.05
Length-Depth	97	1	97	0.12	> 0.25
Error	19,034	24	793	---	---
Total	22,537	27	---	---	---

From *F-Distribution* table, for factor A = Length, and factor B = Depth, it was found that $F_{\alpha,\ (a\text{-}1),\ ab\ (n\text{-}1)} = F_{\alpha,\ (b\text{-}1),\ ab\ (n\text{-}1)} = F_{0.05,\ 1,\ 24} = 4.26$. Also, for the factor AB = Length - Depth Interaction, it was found that $F_{\alpha,\ (a\text{-}1)\ (b\text{-}1),\ ab\ (n\text{-}1)} = F_{0.05,\ 1,\ 24} = 4.26$.

As for depth, length, and depth-length interaction $F_0 < F_{0.05,\ 1,\ 24}$, then the test fails to reject H_0, and concludes that the HDD productivity means through borehole (depth, length, and interaction in path profile) are not significantly different, i.e., HDD productivity means through the whole bore-path are not affected by the change of depth and length. This result supports the results were obtained in previous section.

5.3.2.3 Groundwater Level Subcondition

Table 5.7 presents HDD productivity observations in rocky conditions through projects implemented within medium diameter and short drive length. The first projects had been implemented under 20 ft of groundwater above borehole, while the level of groundwater in the second projects is 0.0 ft.

Table 5.8 presents the ANOVA analysis for HDD productivity observations that were distributed between projects implemented under 20 ft and 0.0 ft of groundwater.

Table 5.7 HDD Productivity vs. Groundwater Level

Groundwater Level (ft)	HDD Productivity Observations (ft/hr)				
	1	2	3	$y_{i.}$	$\bar{y}_{i.}$
20	67	33	33	133	44
0	18	18	18	54	18
$\sum y_{j.}$	85	51	51	$y_{..} = 188$	$\bar{y}_{..} = 31$

Table 5.8 ANOVA Analysis for Groundwater Level

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Groundwater Level	1027	1	1027	5.5	> 0.05
Error	741	4	185	---	---
Total	1,768	5	---	---	---

From *F*- Distribution table, it is found that $F_{0.05,\,1,\,6}$ = 5.99, and since $F_0 < F_{0.05,\,1,\,6}$ then the test fails to reject H_0 and concludes that the difference in HDD productivity means is not significant or means are the same. Also, similar decision can be made considering *P*-Value that is greater than $\alpha = 0.05$.

5.3.3 Project Conditions

5.3.3.1 Prereaming Diameter Subcondition

Borehole diameter has a major role in HDD drilling through soil conditions. It was observed that in soft soil conditions (loose sand, soft clay); the increment in preream diameter is too large compared to that in hard soil conditions such as rock. Table 5.9 presents HDD productivity through different diameters classes in clayey conditions within large drive length.

Table 5.9 HDD Productivity in Clayey Conditions

Diameter Range (in.)	HDD Productivity Observations (ft/hr)			
	1	2	$y_{i.}$	$\bar{y}_{i.}$
20–28	77	79	156	78
38–48	23	20	43	22
$\sum y_{j.}$	100	99	$y_{..} = 199$	$\bar{y}_{..} = 50$

Applying the ANOVA analysis to study the variation in means due to prereaming diameter effect, Table 5.10 presents results of analysis.

Table 5.10 ANOVA for Prereaming Diameter in Clayey Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Diameter	3,207	1	3,207	1,049	< 0.01
Error	6	2	3	---	---
Total	3,213	3	---	---	---

From *F*- Distribution table, it was found that $F_{0.05,\,1,\,2} = 18.51$, and as $F_0 > F_{0.05,\,1,2}$ then H_0 can be rejected and concluded that the difference in HDD productivity means is significant or HDD productivity means are different. Also, similar decision can be made considering *P*-Value which is less than 0.01 and less than $\alpha = 0.05$. The last test on the effect of borehole diameter on HDD productivity was applied on rocky conditions. Table 5.11 shows HDD productivity observations in rocky conditions.

Table 5.11 Productivity Observations in Rocky Conditions

Diameter Range (in.)	HDD Productivity Observations (ft/hr)			
	1	2	$y_{i.}$	$\bar{y}_{i.}$
9–13	18	18	36	18

Table 5.11 - *Continued*

24–30	27	25	52	26
$\sum y_{j.}$	46	43	$y_{..} = 89$	$\bar{y}_{..} = 22$

Table 5.12 presents ANOVA analysis for HDD productivity vs. prereaming diameter changes in rocky conditions.

Table 5.12 ANOVA Analysis for Prereaming Diameter in Rocky Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Diameter (in.)	63	1	63	44	< 0.01
Error	3	2	1.5	---	---
Total	66	3	---	---	---

From *F*- Distribution table, it was found that $F_{0.05,\,1,\,2} = 18.51$, and as $F_0 >>> F_{0.05,\,1,2}$ then H_0 can be rejected and concluded that the difference in HDD productivity means is significant and that HDD productivity means are different. Similar decision can be made considering *P*-Value which is less than 0.01 and less than $\alpha = 0.05$ in this test.

5.3.3.2 Pipeline Depth Subcondition

Depth of pipeline is expected to have a significant impact on HDD productivity. Designers may be able to select soft soil for bore-path alignment. But for some reasons such as existence of underground utilities, building foundations or basement barriers at that depth, designers may have to change the bore-path profile avoid these obstructions. This issue may force designers to select a different bore plan which encounters hard soils. Problematic entry/exit angles to/from borehole, machine setback requirements, and limited available working areas are examples of few problems related to pipeline depth. Table 5.13

presents HDD productivity observations for depth of borehole in clayey conditions in large diameter category. ANOVA analysis and results are presented in Table 5.14.

Table 5.13 Productivity Observations for Pipeline Depth in Clayey Conditions

Depth (ft)	HDD Productivity Observations (ft/hr)				
	1	2	3	$y_{i.}$	$\bar{y}_{i.}$
148	27	23	20	70	23
22	77	79	---	156	78
$\sum y_{j.}$	104	102	20	$y_{..} = 226$	$\bar{y}_{..} = 45$

Table 5.14 ANOVA Analysis for Pipeline Depth in Clayey Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Depth (ft)	3,632	1	3,632	434	< 0.01
Error	25	3	8	---	---
Total	3,657	4	---	---	---

From *F*- Distribution table, it was found that $F_{0.05,\,1,\,3}$ = 10.13, and as F_0 >>> $F_{0.05,\,1,\,3}$ then H_0 can be rejected and it can be concluded that the difference in HDD productivity means is significant; i.e., HDD productivity means are different. Similar decision can be made considering *P-Value* which is less than 0.01 and less than α = 0.05.

5.3.3.3 Pipe Material Subcondition

Steel, HDPE, PVC are the most common pipe materials installed in HDD operation. Therefore, it is important to test the impact of pipe material on HDD productivity during pull-back of product pipe. Table 5.15 presents a comparison of HDD productivity observations for installation of steel and HDPE pipes in clayey conditions.

From *F*- Distribution table, it was found that $F_{0.05, 1, 4}$ = 7.71, and as $F_0 < F_{0.05, 1, 4}$, the test fails to reject H_0 and concludes that the difference in HDD productivity means is not significant; i.e., HDD productivity means are the same. Similar decision can be made considering *P*-Value which is greater than α = 0.05 and also greater than 0.25. ANOVA analysis is presented in Table 5.16. This test is related to the resultant of forces during pullback including thrust force, friction force between pipe and soil, product pipe and fluid unit weight, and buoyancy force. Therefore, further analysis is required in this area.

Table 5.15 HDD Pullback Observations for Pipe Material in Clayey Conditions

Pipe Material	HDD Productivity Observations (ft/hr)					
	1	2	3	4	$y_{i.}$	$\bar{y}_{i.}$
Steel	373	201	275	300	1149	287
HDPE	275	220	---	---	495	248
$\sum y_{j.}$	648	421	275	300	$y_{..} = 1644$	$\bar{y}_{..} = 273.93$

Table 5.16 ANOVA Analysis for Pipe Material Pullback in Clayey Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Pipe Material	2,095	1	2,095	0.5	> 0.25
Error	16,626	4	4,157	---	---
Total	18,721	5	---	---	---

5.3.4 Contractor' Conditions

Contractor' conditions are important in terms of qualifications, abilities, and capabilities that usually come from years of experience. This main group includes contractor' experience and operator' experience in years.

5.3.4.1 Contractor’ Experience Subcondition

Level of knowledge and experience determine classes of jobs that contractors can bid and implement. Usually practices, techniques and means, as well as equipment and materials utilized are similar for most contractors. Therefore, the current research expects that contractor’ and operator’ experience will not have significant effect on HDD productivity. Part of the reason for this has to do with the volume of investment in HDD equipment and salaries paid for labor.

Table 5.17 presents HDD productivity observations vs. contractor experience in rocky conditions. From *F*- Distribution table, it was found that $F_{0.05,\,1,\,4} = 7.71$, and as $F_0 < F_{0.05,\,1,\,4}$, so the test fails to reject H_0 and concludes that the difference in HDD productivity means is not significant; i.e., HDD productivity means are the same. Similar decision can be made considering *P*-Value which is greater than α = 0.05 as ANOVA analysis shows in Table 5.18.

Table 5.17 HDD Productivity Observations for Contractor’ Experience

Contractor Experience (year)	HDD Productivity Observations (ft/hr)					
	1	2	3	4	$y_{i.}$	$\bar{y}_{i.}$
24	33	27	25	20	105	26
11	18	18	---	---	36	18
$\sum y_{j.}$	51	45	25	20	$y_{..} = 141$	$\bar{y}_{..} = 24$

Table 5.18 ANOVA Analysis for Contractor’ Experience

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Contractor Experience (year)	89	1	89	4	> 0.25
Error	92	4	23	---	---

Table 5.18 - *Continued*

Total	181	5	---	---	---

5.3.4.2 HDD Operator' Experience Subcondition

It can be stated that HDD operator experience does not have effect on HDD productivity since most Maxi and Midi HDD operators receive an intensive training program by manufacturers or contractors. Therefore, HDD operators for these rigs will have similar level of knowledge and experience in operating HDD machine, safety instructions, and in trouble shooting. This issue will eliminate most of differences of experience effects on HDD productivity.

Table 5.19 presents HDD productivity observations vs. HDD operator experience in rocky conditions. ANOVA analysis is presented in Table 5.20. From *F*- Distribution table, it was found that $F_{0.05, 1, 6} = 5.99$, and as $F_0 < F_{0.05, 1, 6}$, so the test fails to reject H_0 and conclude that the difference in HDD productivity means is not significant; i.e., HDD productivity means are similar. Similar decision can be made considering *P*-Value which is greater than 0.25.

Table 5.19 HDD Productivity for Operator' Experience

HDD Operator Experience (year)	HDD Productivity Observations (ft/hr)					
	1	2	3	4	$y_{i.}$	$\bar{y}_{i.}$
4	33	27	25	20	105	26
8	18	18	18	75	129	32
$\sum y_{j.}$	51	45	43	95	$y_{..} = 234$	$\bar{y}_{..} = 29$

Table 5.20 ANOVA Analysis for Operator' Experience

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Operator Experience	73	1	73	0.18	> 0.25

Table 5.20 - *Continued*

Error	2,505	6	418	---	---
Total	2,578	7	---	---	---

5.3.5 HDD Machine Conditions and Variables

Machine conditions (mainly abilities) play a big role in HDD drilling as a specific HDD machine size (thrust and torque force) and drilling rod length must be selected to dig in specific soil and project conditions (diameter and depth). While machine variables in this group also include bentonite and polymer mixing ratio, and drilling fluid pumping rate are the proposed subconditions in this group supposed to be highly related to soil conditions and soil specifics.

5.3.5.1 Thrust Force Subcondition

Thrust force (kip) is categorized according to machine size depending on soil conditions encountered and project conditions. Table 5.21 presents HDD productivity observations vs. thrust force (kip) variation in rocky conditions within medium diameter and short drive length category, and results are shown in table 5.22.

Table 5.21 HDD Productivity Observations for Thrust Force in Rocky Conditions

Thrust Force (kip)	HDD Productivity Observations (ft/hr)				
	1	2	3	$y_{i.}$	$\bar{y}_{i.}$
70	33	27	25	85	28
35	18	18	18	54	18
$\sum y_{j.}$	51	45	43	$y_{..} = 139$	$\bar{y}_{..} = 23$

Table 5.22 ANOVA Analysis for Thrust Force in Rocky Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value

Table 5.22 - *Continued*

Thrust Force	159	1	159	18	< 0.025
Error	37	4	9	---	---
Total	196	5	---	---	---

From *F*- Distribution table, it was found that $F_{0.05, 1, 4} = 7.71$ and as $F_0 > F_{0.05, 1, 4}$ then it is able to reject H_0 and conclude that the difference in HDD productivity means is significant; i.e., HDD productivity means are different. Similar decision can be made considering *P*-Value which is less than 0.025 as it is presented in Table 5.22.

5.3.5.2 Torque Force Subcondition

It can be stated that torque force (ft-kip) is related to thrust force, and also related to HDD machine size and specific model. Therefore, it is assumed that HDD machine characteristics and performance are related to change of torque force. Table 5.23 validates this assumption, which contains. pairs of thrust force and torque force.

Table 5.23 Thrust Force and Torque in HDD Rigs

Thrust Force (kip)	Torque Force (ft-kip)
>260	30–100,000
200–220	20–30
30–40	2–6

5.3.5.3 Slurry Mixing Ratio Subcondition

Slurry or drilling fluid is composed mainly of bentonite and water. It is used during drilling to help in facilitating cutting, reducing friction, cuttings' removal, stabilizing borehole sides, cooling drilling head, and lubricating installation of product pipe during pull back. Slurry mixing ratio (lb/100 gal) is a function of soil type, and it is not related to the HDD productivity because in hard rock the thrust force is high while the mixing ratio of the fluid is constant through the whole operation. Table 5.24 presents HDD productivity observations vs. slurry mixing ratio in rocky conditions.

Table 5.24 HDD Productivity Observations for Slurry Mixing Ratio

Slurry Mixing Ratio (lb/100 gal)	HDD Productivity Observations (ft/hr)					
	1	2	3	4	$y_{i.}$	$\bar{y}_{i.}$
50	33	27	25	20	105	26
40	18	18	18	---	54	18
$\sum y_{j.}$	51	45	43	20	$y_{..} = 159$	$\bar{y}_{..} = 23$

From *F*- Distribution table, it was found that $F_{0.05,\,1,\,5} = 6.61$ and as $F_0 < F_{0.05,\,1,5}$ and the test fails to reject H_0 and concludes that the difference in HDD productivity means is not significant; i.e., HDD productivity means do not differ on different slurry mixing ratio. Similar decision can be made considering *P*-Value that is greater than 0.05 as shown in Table 5.25.

Table 5.25 ANOVA Analysis for Slurry Mixing Ratio in Rocky Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Slurry Ratio	114	1	114	6.3	> 0.05
Error	92	5	18	---	---
Total	206	6	---	---	---

5.3.5.4 Slurry Pumping Rate Subcondition

The volume of drilling fluid pumped (gpm) through cutting head or reamer nozzles is function of soil type, and volume of cuttings. Drilling fluid pumping rate can be assumed to be constant for a specific borehole size, and rarely is changed.

For example, in clayey conditions pumping rate during pilot hole drilling is around 400 gpm, while during preream operation, it is around 120 gpm. During pullback, pumping rate is around 80 gpm. Table 5.26 presents HDD productivity observations vs. slurry pumping rate in clayey conditions within large diameter and large drive length category.

Table 5.26 HDD Productivity for Slurry Pumping Rate in Clayey Conditions

Pumping Rate (gpm)	HDD Productivity Observations (ft/hr)			
	1	2	$y_{i.}$	$\bar{y}_{i.}$
300	76	76	152	76
88	77	79	156	78
$\sum y_{j.}$	153	155	$y_{..} = 308$	$\bar{y}_{..} = 77$

Table 5.27 presents ANOVA analysis for slurry pumping rate effect, it was calculated that F_0 = 5.40 < $F_{0.05,\ 1,\ 5}$ = 18.51, and the test fails to reject H_0 and concludes that the difference in HDD productivity means is not significant. For example, HDD productivity means do not differ on different slurry pumping rate. Also, similar decision can be made considering *P*-Value that is greater than 0.10.

Table 5.27 ANOVA Analysis for Slurry Pumping Rate in Clayey Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Slurry Ratio	7	1	7	5	> 0.1
Error	3	2	1.5	---	---
Total	10	3	---	---	---

5.3.5.5 Drilling Rode Length Subcondition

HDD machine uses different length drilling rods depending on rig and job size and pipe material and diameter. It takes HDD crew 3 minutes to change a rod of30 ft in ream/preream and pullback. However, it takes 6 minutes to change same rod in pilot hole. Therefore, if 10-ft drilling rod is used, it will add about 8-12 minutes to cycle time and drilling rod length can affect productivity of HDD operation. Table 5.28 presents HDD productivity observations vs. drilling rod length and Table 5.29 presents the ANOVA analysis with the required test in term of *F-Distribution* and *P-Value*.

Table 5.28 HDD Productivity Observations for Drilling Rod Length

Drilling Rod Length (ft)	HDD Productivity Observations (ft/hr)				
	1	2	3	$y_{i.}$	$\bar{y}_{i.}$
10	27	23	20	70	23
30	77	79	---	156	78
$\sum y_{j.}$	104	102	20	$y_{..} = 226$	$\bar{y}_{..} = 45$

As presented in Table 5.29 that F_0 = 433.79 > $F_{0.05,\,1,\,3}$ = 10.13, and H_0 can be rejected and it can be concluded that the difference in HDD productivity means is significant; i.e., HDD productivity means differ by different drilling rod length. Similar decision can be made considering *P*-Value which is less than 0.01.

Table 5.29 ANOVA Analysis for Drilling Rod Length

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Drilling Rod Length (ft)	3,632	1	3,632	434	< 0.01
Error	25	3	8	---	---
Total	3,657	4	---	---	---

5.4 HDD Significant Subconditions

In this section, significant and non significant subconditions in HDD operations are listed in Table 5.30. Only significant subconditions will be used to model HDD productivity in clayey and in rocky conditions.

Table 5.30 ANOVA Significance for HDD Productivity Conditions

<table>
<tr><th>HDD Conditions Main Group</th><th>HDD Sub Condition</th><th>Significance</th></tr>
<tr><td rowspan="2">Soil Conditions</td><td>Soil Type</td><td>Yes</td></tr>
<tr><td>Groundwater Level (ft)</td><td>No</td></tr>
<tr><td rowspan="3">Project Conditions</td><td>Prereaming Diameter (in.)</td><td rowspan="2">Yes</td></tr>
<tr><td>Pipeline Depth (ft)</td></tr>
<tr><td>Material (Pullback)</td><td>No</td></tr>
<tr><td rowspan="2">Contractor Conditions</td><td>Contractor Experience (yr)</td><td rowspan="2">No</td></tr>
<tr><td>Operator Experience (yr)</td></tr>
<tr><td rowspan="3">Machine Conditions</td><td>Thrust Force (kip)</td><td rowspan="3">Yes</td></tr>
<tr><td>Torque Force (ft-kip)</td></tr>
<tr><td>Drilling Rod Length (ft)</td></tr>
<tr><td rowspan="2">Machine Variables</td><td>Slurry Mixing Ratio (lb/100 gal)</td><td rowspan="2">No</td></tr>
<tr><td>Slurry Pumping Rate (gpm)</td></tr>
</table>

5.5 Chapter Summary

This chapter presented ANOVA model analysis for testing the significance of proposed subconditions expected to impact productivity of HDD operations. Main groups of conditions included soil, project, contractor, and machine conditions. Through the utilization of ANOVA model analysis, the proposed 12 subconditions in HDD productivity were reduced from 12 to 6. These subconditions include prereaming diameter, pipeline depth, thrust force, torque force, and drilling rod length, in addition to soil conditions.

CHAPTER 6

HDD PRODUCTIVITY MODEL DEVELOPMENT

6.1 Introduction

This chapter presents development of HDD productivity model in clayey and rocky conditions, considering significant subconditions that were tested by ANOVA model stated earlier in Chapter 5. SPSS 16.0 (2007) software was selected to model HDD productivity (ft/hr) in soil conditions encountered using significant subconditions. HDD productivity in sandy conditions was developed by calculating average value of collected data.

6.2 HDD Productivity Model

Modeling of HDD productivity was developed through two levels. The first level was conducted through utilizing and testing of ANOVA model applicability in studying the productivity variations in the pilot project. The second level was conducted by modeling productivity using significant subconditions developed by the ANOVA model.

6.2.1 HDD Productivity Data in Pilot Project

A pilot project was selected to study HDD operation and to observe variations in HDD productivity due to the change in soil profile during preream operation. The pilot project specifics were presented in Section 4.3.1, Table 6.1 presents HDD productivity for different soil conditions, and depth, and length of borehole.

The main soil condition encountered in the pilot project was clay. However, four distinguished zones of clayey conditions were recognized as shaly clay, sandy shale, and silty clay. The analysis for preream operation using a 36-in. reamer was conducted by MicroCYCLONE simulation and presented in Appendix E.

Table 6.1 Actual HDD Productivity through Soil Types in Pilot Project

Soil Type	Length (ft)	Depth (ft)	HDD Productivity (ft/hr)
Type 1: Shaly Clay	60	36	150
	90	39	150
	120	42	90
	150	44	64
	180	47	75
	210	48	82
	240	50	53
	270	52	46
	300	52	62
	330	53	64
Type 2: Sandy Shale	30	54	75
	60	54	75
	90	53	64
	120	53	60
	150	52	38
	180	51	25
	210	49	44
	240	48	48
Type 3: Shaly Clay	30	46	82
	60	44	75
	90	41	51

- Table 6.1 - *Continued*

	120	38	49
	150	35	43
	180	31	58
	210	27	56
	240	24	64
Type 4: Silty Clay	30	19	106
	60	14	67
	90	9	69
	120	7	150
	150	5	180

6.2.2 HDD Productivity Modeling in Pilot Project

Recalling information presented and discussed in Section 5.3.2.1 for soil conditions encountered in pilot project and included in Table 5.1, as well as recalling ANOVA analysis results presented in Tables 5.2, and 5.3 for Tukey-Kramer procedure, it was concluded that there were no models for HDD productivity along the bore-path that can explain the relation between productivity and depth or length of borehole.

Recalling also ANOVA 2^2 *Factorial Design* for studying the effects of depth, length, and depth-length interactions presented in Section 5.3.2.2, and Tables 5.5 and 5.6 for productivity data and significance analysis, it was found that the effect of soil is a major factor on productivity. Therefore, ANOVA model declared that HDD productivity cannot be modeled successfully following the whole bore-path, nor using length, neither using depth, or depth-length interactions or terms. ANOVA results presented earlier were validated and tested using SPSS 16.0 (2007) to justify the use of ANOVA model for testing the significance of other HDD productivity subconditions in the upcoming section.

6.2.2.1 Validation of ANOVA Results in Pilot Project

This section presents a comparison between the proposed HDD productivity models in separate soil conditions with other potential models by following the whole bore-path. It is clear from Figure 6.1 that HDD productivity cannot be modeled on borehole length as it is shown by the R^2 values for linear, 2nd order, and 3rd order polynomial respectively. Another note is that HDD productivity equals 150 ft/hr at 60-ft, 90-ft as well as 930-ft distance from pipe entry point. Neither linear nor 2nd order polynomial can describe this relation on borehole length.

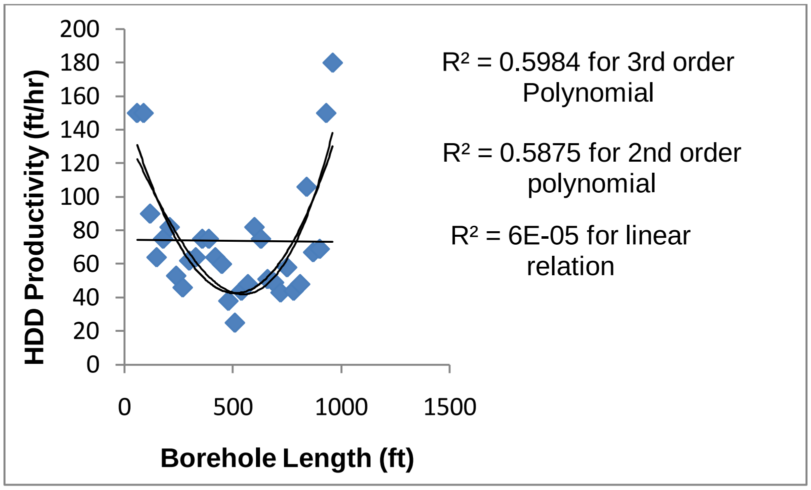


Figure 6.1 HDD Productivity vs. Borehole Length in Pilot Project

Similar note can be observed in Figure 6.2. It is dfficult to model HDD productivity on borehole depth as R^2 values in linear and 2nd order polynomial that are too low.

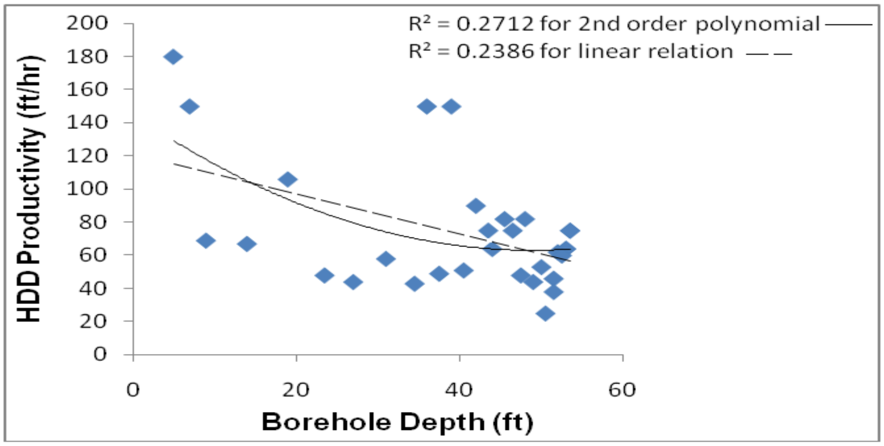


Figure 6.2 HDD Productivity vs. Borehole Depth

Appendix F includes results of modeling HDD productivity in pilot project using the whole set of data as discussed in Section 5.3.2.1 earlier. Appendix G shows SPSS model findings for modeling HDD productivity using separate data sets following soil conditions in pilot project that was presented in Section 5.3.2.2 .

6.2.2.2 Improving of HDD Productivity Model by ANOVA Analysis

This section presents the improvements that can be achieved in modeling when applying ANOVA conclusions. Furthermore, SPSS 16.0 (2007) provides initial validation to the model such as confidence intervals for model parameters or constants, calculated R^2 and R^2_{adj} values, mean squares (MS), and significance of model (sig.). Table 6.2 presents linear and power function suggested and the associated model findings.

Table 6.2 HDD Model for Shaly Clay Condition*

Model Formula	R^2	R^2_{adj}	Mean Squares	Significance
$P = 531.15 + 0.006(LD) - 10.889(D)$	0.84	0.78	365.01	0.01
$P = \frac{3939}{L^{0.775}}$	0.84			
$P = \frac{1.695*10^7}{D^{3.23}}$	0.85	NA	NA	0.001
$P = \frac{2.817*10^4}{(LD)^{0.668}}$	0.86			

*D: Depth of borehole (ft); L: Distance (ft) on borehole

Figure 6.3 illustrates HDD productivity graph in shaly clay condition for models listed in Table 6.2. It shows how the results of SPSS 16.0 (2007) were improved by using separate models as recommended by ANOVA model.

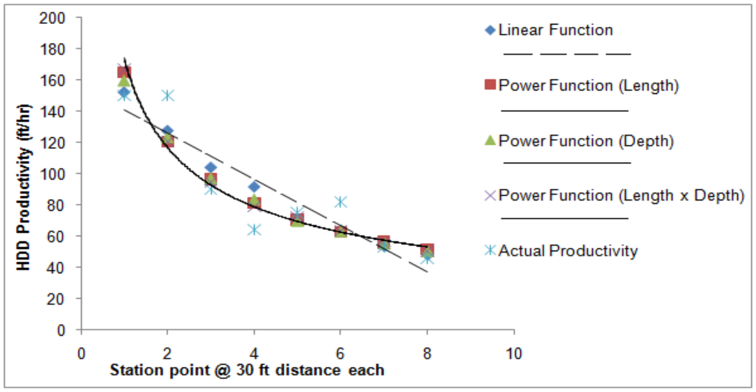


Figure 6.3 HDD Productivity Model in Shaly Clay Condition

Table 6.3 presents proposed HDD productivity linear functions in sandy shale condition, that the model parameters were improved in this soil conditions.

Table 6.3 HDD Model for Sandy Shale Condition*

Model Formula	R^2	$R^2_{adj.}$	Mean Squares	Significance
$P = 92.667 - 0.348(L)$	0.91	0.89	45.9	0.003
$P = 93.703 - 0.007(LD)$	0.9	0.87	54.32	0.004

*D: Depth of borehole (ft); L: Distance (ft) on borehole

Figure 6.4 illustrates HDD productivity graph in sandy shale condition for actual productivity and predicted productivity by functions presented in Table 6.3. Both functions have similar power on prediction as most of the functions' parameters in table are very close.

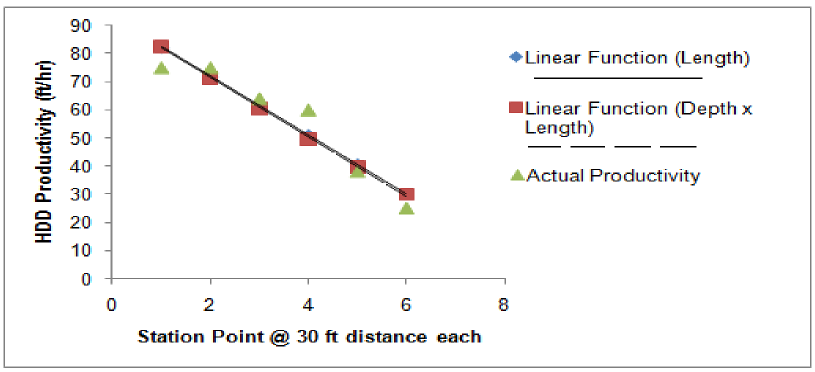


Figure 6.4 HDD Productivity Models in Sandy Shale Condition

Table 6.4 presents linear functions proposed for HDD productivity in shaly clay condition.

Table 6.4 HDD Model for Shaly Clay Condition*

Model Formula	R^2	$R^2_{adj.}$	Mean Squares	Significance
$P = 109.167 + 0.712(L) - 0.033(LD)$	0.9	0.83	40.39	0.032
$P = 341.08 - 0.024(LD) - 4.874(D)$	0.87	0.79	50.7	0.045

*D: Depth of borehole (ft); L: Distance (ft) on borehole

Figure 6.5 illustrates HDD actual productivity and predicted productivity by linear functions presented in Table 6.4 in shaly clay condition.

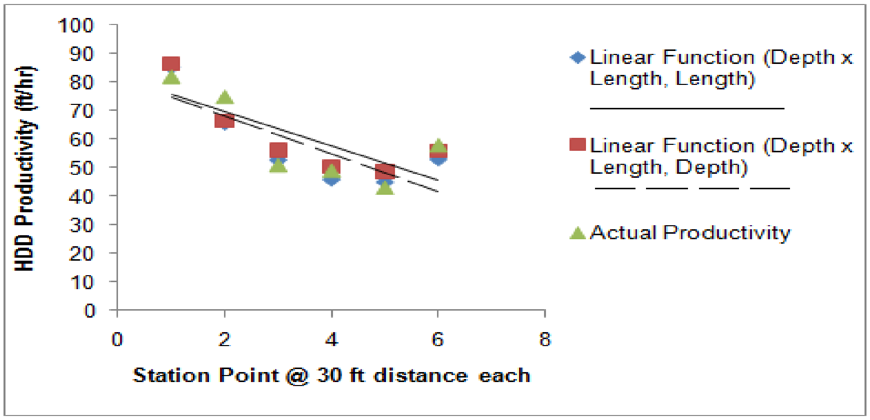


Figure 6.5 HDD Productivity in Shaly Clay Condition

Table 6.5 presents proposed linear function for HDD productivity in silty clay condition.

Table 6.5 HDD Model for Silty Clay*

Model Formula	R^2	$R^2_{adj.}$	Mean Squares	Significance
$P = -511.6 + 4.774(L) + 29.067(D) - 0.137(LD)$	1	---	0.0	0.0

*D: Depth of borehole (ft); L: Length of borehole (ft)

Figure 6.6 illustrates HDD actual and predicted productivity by linear function presented in Table 6.5 for silty clay condition. Here actual productivity value can be 100% predicted by proposed linear function as it gives the value of mean squares equal to zero and so significance level.

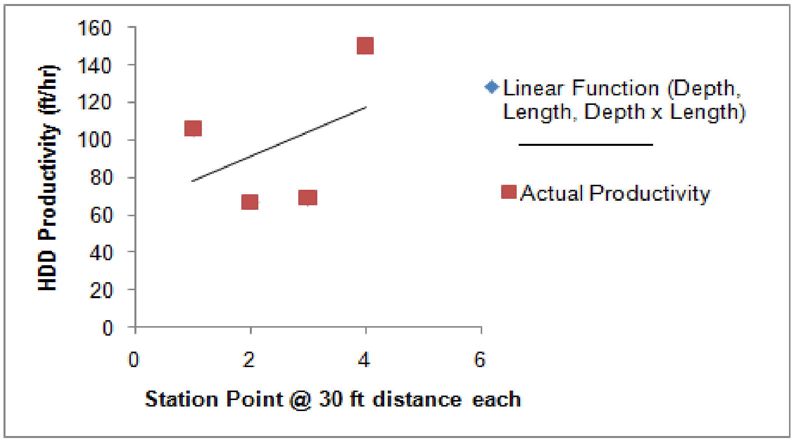


Figure 6.6 HDD Productivity in Silty Clay Condition

6.3 HDD Productivity Extended Model Development

Recalling the results declared by ANOVA model and presented in Table 5.30 in Chapter 5, it was concluded that HDD productivity (ft/hr) is a function of the significant subconditions including diameter of prereaming (in.), depth of borehole (ft), drilling rod length (ft), thrust force (kip), and torque force (ft-kip). Therefore, it is expected that developed HDD productivity models for clayey and rocky conditions will be significant if modeled using subconditions concluded by ANOVA analysis. Table 6.6 presents HDD subconditions that were developed by studying HDD productivity variation due to the variation in HDD subconditions.

Table 6.6 HDD Productivity Model Subconditions

HDD Model Subcondition	Section Number in Research	Tables' Number	Significance (P-Value)	Note
Prereaming Diameter (in.)	5.3.3.1	(5.9 and 5.10) (5.11 and 5.12)	< 0.01	< α = 0.05
Depth of Borehole (ft)	5.3.3.2	(5.13 and 5.14)		
Thrust (kip)	5.3.5.1	5.21and 5.22	< 0.01	
Torque (ft-kip)	5.3.5.2	5.23		
Drilling Rod Length (ft)	5.3.5.5	5.28 and 5.29	<0.01	

6.3.1 HDD Productivity Model in Clayey Conditions

Table 6.7 presents collected data for HDD productivity and significant subconditions that will be used to develop HDD productivity model in clayey conditions.

Table 6.7 HDD Productivity Data in Clayey Conditions

Diameter (in.)	Depth (ft)	Drilling Rod Length (ft)	Thrust Force (kip)	Torque Force (ft-kip)	Productivity (ft/hr)
9	30	30	280	45	22
9.875	150	30	1200	100	56
12	6	10	25	11	120
16	70	30	130	25	76
20	22	30	215	25	77
22	30	30	280	45	276
24	120	30	230	25	183
26	148	10	260	35	27
26	125	30	40	4	238
28	22	30	215	25	79
28	70	30	130	25	76
34	150	30	1200	100	42
36	120	30	230	25	183
36	30	30	280	45	28
38	147	10	260	35	23
42	30	30	280	45	24
48	147	10	260	35	20
48	150	30	1200	100	42

As it is illustrated in Figure 6.7, HDD productivity (ft/hr) decreases with the increase in prereaming diameter (in.), no matter the relation type (linear, power, or quadratic) used to describe this function. Figure 6.8 illustrates HDD productivity in clayey conditions vs. depth of pipeline (ft). It is shown from the figure that HDD productivity shows a tendency to decrease with the increase of pipeline depth.

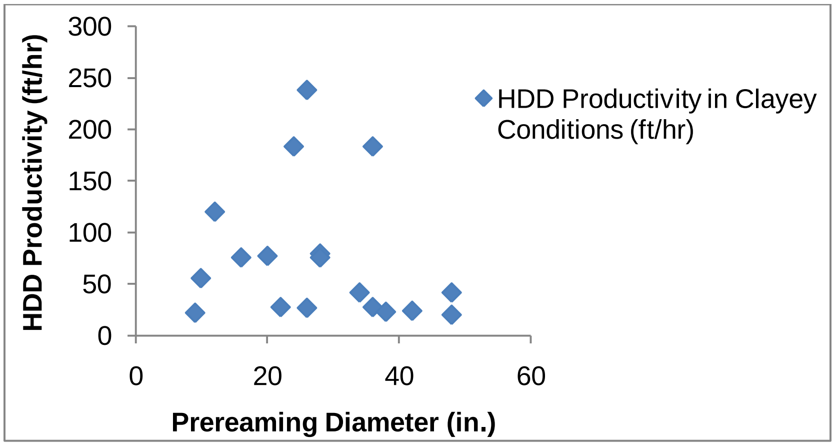


Figure 6.7 HDD Productivity vs. Diameter of Prereaming in Clayey Conditions

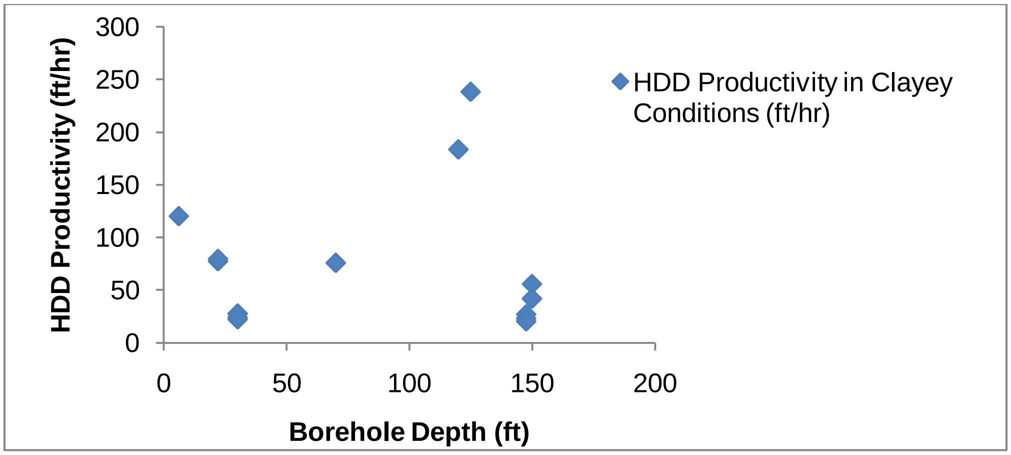


Figure 6.8 HDD Productivity vs. Pipeline Depth in Clayey Conditions

Figure 6.9 illustrates HDD productivity vs. length of borehole in clayey conditions. This figure shows that HDD productivity decreases as the length of borehole increases given the thrust force required to override the load exerted on machine.

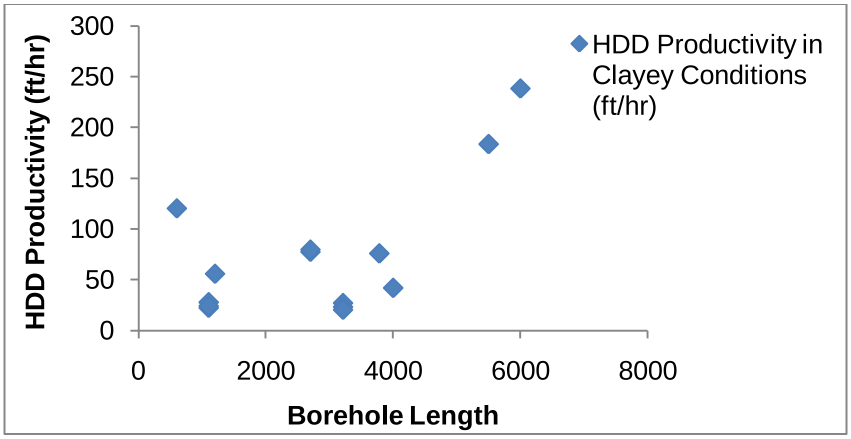


Figure 6.9 HDD Productivity vs. Length of Borehole in Clayey Conditions

Figure 6.10 illustrates HDD productivity vs. drilling rod length. It shows that if contractors use short drilling rods (10–15 ft), HDD productivity will be in the range of 20–55 ft/hr. However, if full length of 30 ft drilling rod is used, productivity will be in the range of 20–180 ft/hr, considering the 3–4 minutes needed to remove or to add one drilling rod.

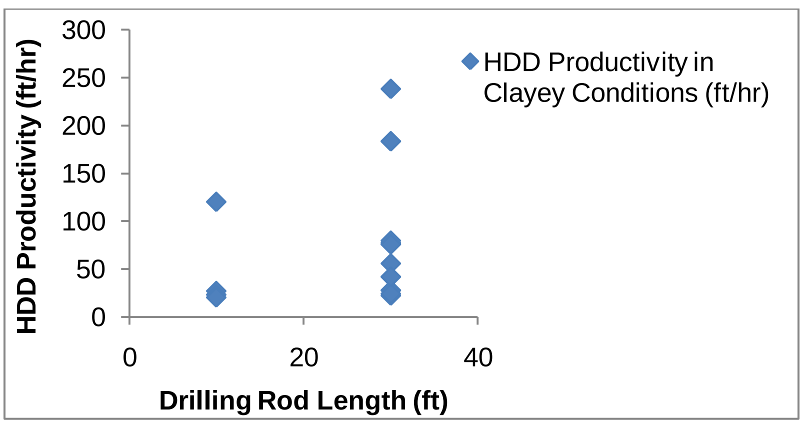


Figure 6.10 HDD Productivity vs. Drilling Rod Length in Clayey Conditions

Figure 6.11 illustrates HDD productivity vs. thrust force (kip). This figure shows that as the thrust force increases, the productivity will decrease as Midi- and Maxi-HDD with large thrust force are used to drill or preream in hard clayey conditions.

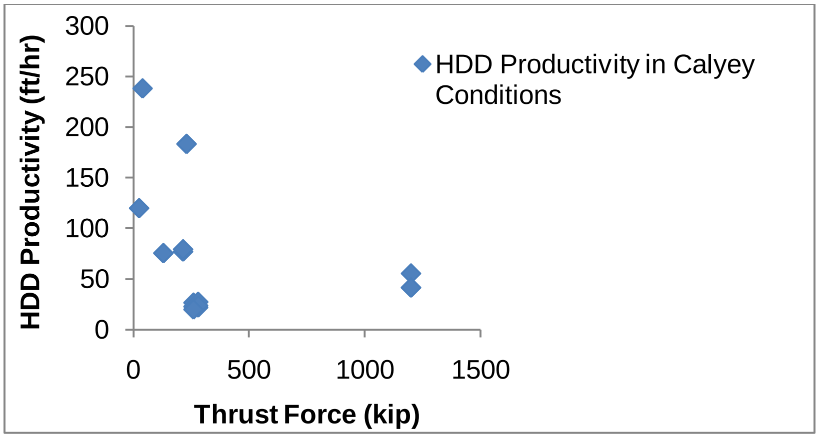


Figure 6.11 HDD Productivity vs. Thrust Force in Clayey Conditions

Figure 6.12 illustrates HDD productivity vs. torque force (ft-kip), confirming that torque force provides same indication about HDD productivity in clayey conditions.

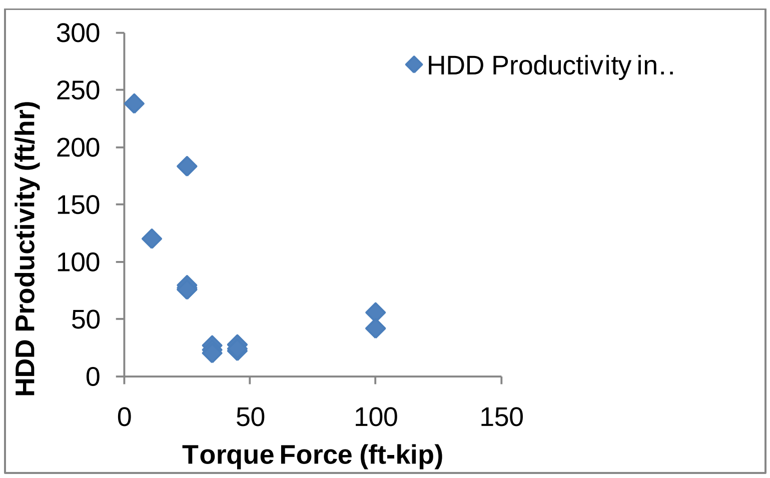


Figure 6.12 HDD Productivity vs. Torque in Clayey Conditions

A HDD productivity model was developed using data presented in Table 6.7 for clayey conditions. HDD productivity model has the following equation:

HDD PC = 110.68 – 0.315 (Diam.) + 0.309 (Depth) + 3.148 (DRL) + 0.408 (Th.F.) - 6.83 (Trq.F.)

Where:

HDD PC is HDD productivity in clayey conditions (ft/hr)

Diam. is prereaming diameter (in.)

Depth is depth of borehole at midpoint (ft)

DRL is drilling rod length (ft)

Th.F. is thrust force (kip)

Trq.F. is torque force (ft-kip)

Appendix H includes collected data in clayey conditions entered in SPSS screen, in addition to SPSS model findings and parameters.

6.3.2 HDD Productivity Model in Rocky Conditions

Table 6.8 presents data used for modeling HDD productivity in rocky conditions including reported HDD productivity and significant subconditions. The values of HDD productivity in rocky conditions are very low compared to clayey conditions. For example, at 24-in. prereaming diameter, productivity in rocky conditions is equal to 27 (ft/hr) at 30-ft depth, while HDD productivity is equal to 183 (ft/hr) for clayey conditions at depth of 120-ft. Another major difference between clayey and rocky conditions is that HDD machine force in rocky conditions including thrust and torque is very high especially in hard rock conditions compared to that used in clayey conditions.

Table 6.8 HDD Productivity Data in Rocky Conditions

Diameter (in.)	Depth (ft)	Drilling Rod Length (ft)	Thrust Force (kip)	Torque Force (ft-kip)	Productivity (ft/hr)
8.75	30	30	70	5	40
9	14	14	35	9	18
10	25	15	70	9	67
12	25	15	35	5	75
13	14	14	35	9	18
14	25	15	70	9	33
16	25	15	70	9	33
18	14	14	35	9	18
18	25	15	70	9	33
18	30	30	70	5	33

Table 6.8 - *Continued*

22	25	15	70	9	33
24	30	30	70	5	27
30	30	30	70	5	25
36	30	30	70	5	20

Figure 6.13 illustrates HDD productivity (ft/hr) for rocky conditions vs. diameter of prereaming (in.). This figure shows that HDD productivity decreases with the increase of reamer diameter as the contact surface between reamer and borehole increases.

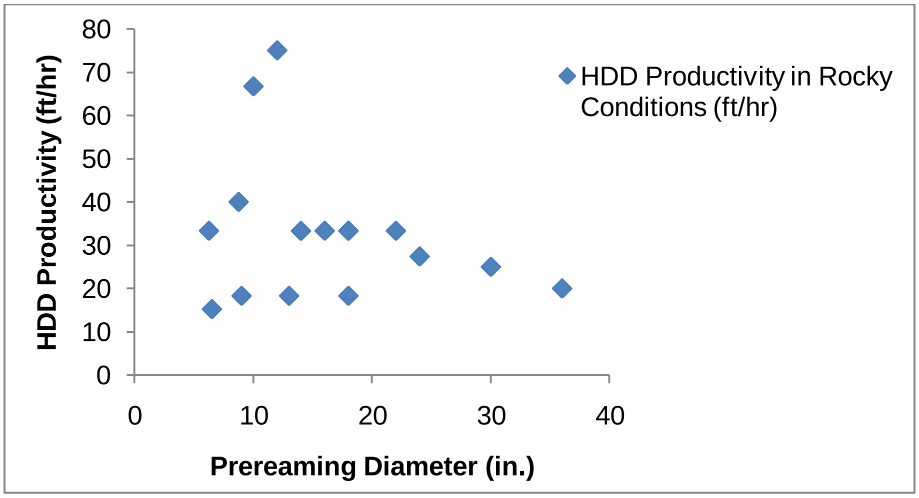


Figure 6.13 HDD Productivity vs. Prereaming Diameter in Rocky Conditions

Figure 6.14 illustrates HDD productivity vs. depth of borehole, and shows that HDD productivity increases with the increase of depth. But, does not have good correlation, as the depth takes the value from 14-ft to 30-ft, which is a close range. Deeper borehole installations, may cause HDD productivity to decrease.

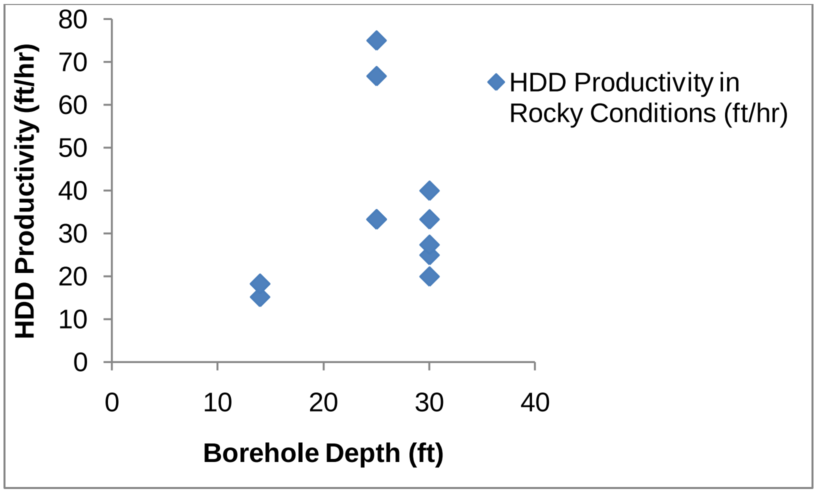


Figure 6.14 HDD Productivity vs. Depth of Borehole in Rocky Conditions

Figure 6.15 illustrates HDD productivity vs. length of borehole. It shows that HDD decreases with the increase of the borehole length. Obviously, the increase in length increases friction force exerted by the borehole sides on the reamer. It should be noted that HDD productivity outlier of 75 (ft/hr) is achieved by a Midi-HDD rig with a 70 kip of thrust force, this case will be discussed in details in validation of research results.

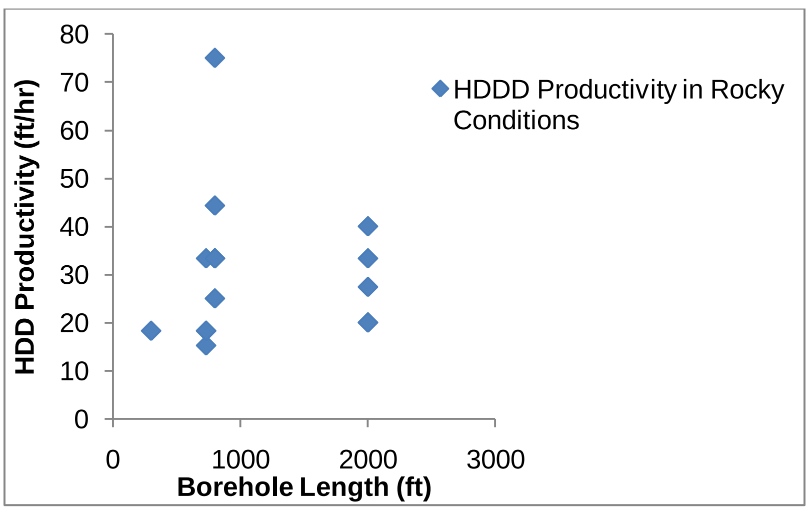


Figure 6.15 HDD Productivity vs. Length of Borehole in Rocky Conditions

Figure 6.16 illustrates HDD productivity vs. drilling rod length. It seems that drilling rod length is inversely related to HDD productivity in rocky conditions, or at least it has some of constant value as drilling rod length takes the values of 15 ft and 30 ft. Also, productivity can be lower in more problematic soil conditions, such as hard rock. Preream in hard soil conditions such as rock is detrimental to drilling bit, because large force must be used to maintain productivity.

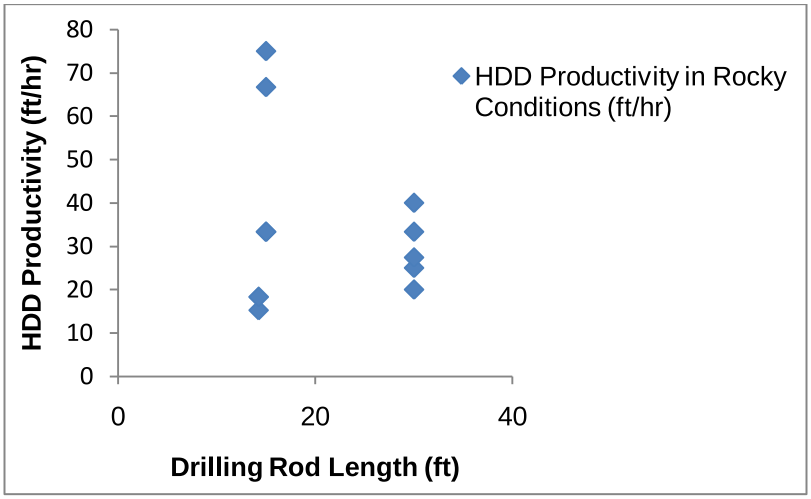


Figure 6.16 HDD Productivity vs. Drilling Rod Length in Rocky Conditions

Figure 6.17 shows that HDD productivity increases with increase of thrust force (kip).

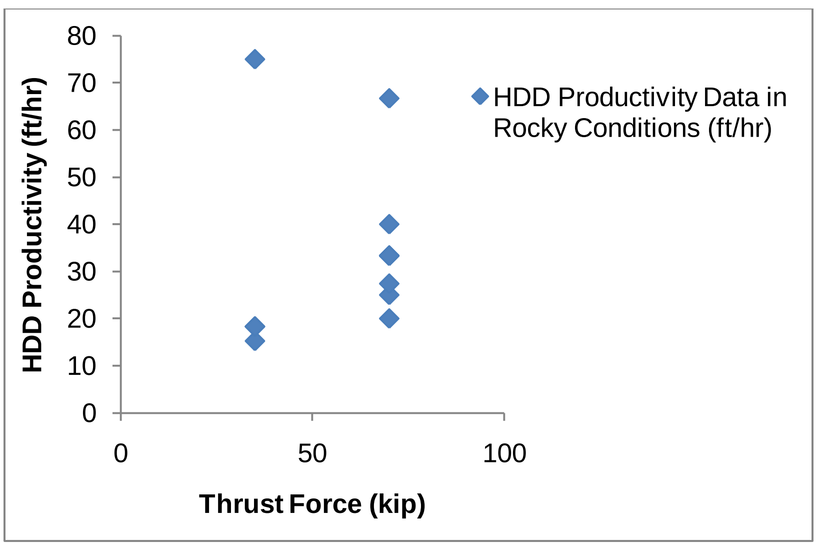


Figure 6.17 HDD Productivity vs. Thrust Force in Rocky Conditions

Figure 6.18 illustrates HDD productivity vs. torque force (ft-kip). It shows that HDD productivity in rocky conditions for torque force has similar trend as for thrust force. This is simply because thrust force and torque force are related in HDD machine size and design, job size, and soil type.

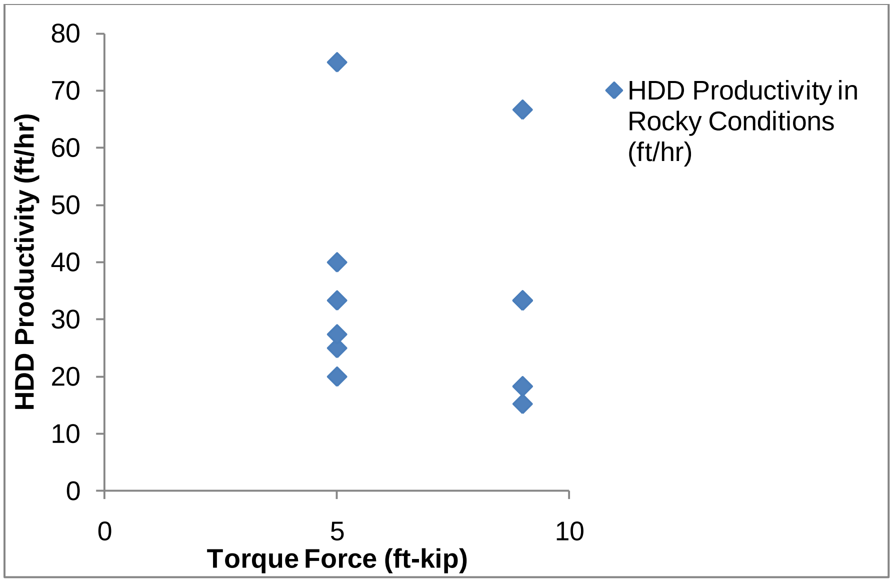


Figure 6.18 HDD Productivity vs. Torque Force in Rocky Conditions

The developed model for HDD productivity in rocky conditions includes prereaming diameter (in.), thrust force (kip), torque force (ft-kip), and drilling rod length (ft) and has the following equation:

HDD PR = 197.48 – 0.669 (Diam.) – 4.313 (DRL) + 0.755 (Th.F.) – 15.238 (Trq.F.)

Where:

HDD PR is HDD productivity in rocky conditions (ft/hr)

Diam. is prereaming diameter (in.)

DRL is drilling rod length (ft)

Th.F. is thrust force (kip)

Trq.F. is torque force (ft-kip)

Appendix I include collected HDD data in rocky conditions entered in SPSS screen in addition to SPSS model findings on data and parameters.

6.3.3 HDD Productivity Model Prediction and Validation

In this section, developed HDD productivity model for clayey and rocky conditions shown above, are tested and validated using the whole set of collected data.

6.3.3.1 HDD Clayey Conditions Productivity Model

Table 6.9 presents the validation of HDD productivity model in clayey conditions by comparing reported and predicted HDD productivity values. Figure 6.19 shows a comparison between reported and predicted HDD productivity.

Table 6.9 Validation of HDD Productivity Model in Clayey Conditions

Reported Productivity (ft/hr)	Predicted Productivity (ft/hr)	% Difference	Validation Factor
22	19	16.16	1.19
56	55	1.08	1.01
120	75	37.25	1.59
76	104	-37.49	0.73
77	12	-58.91	0.63
28	14	47.82	1.92
183	158	13.96	1.16
27	47	-74.17	0.57
238	225	5.69	1.06
79	120	-51.19	0.66
76	100	-32.49	0.76
42	47	-13.66	0.88
183	154	16.03	1.19
28	10	63.85	2.77
23	43	-86.73	0.54
24	8	66.34	2.97
20	40	-97.71	0.51
42	43	-3.08	0.97

Table 6.9 - *Continued*

Average (74.57)	Average (76.87)	Average (-10.40)	Average (1.17)

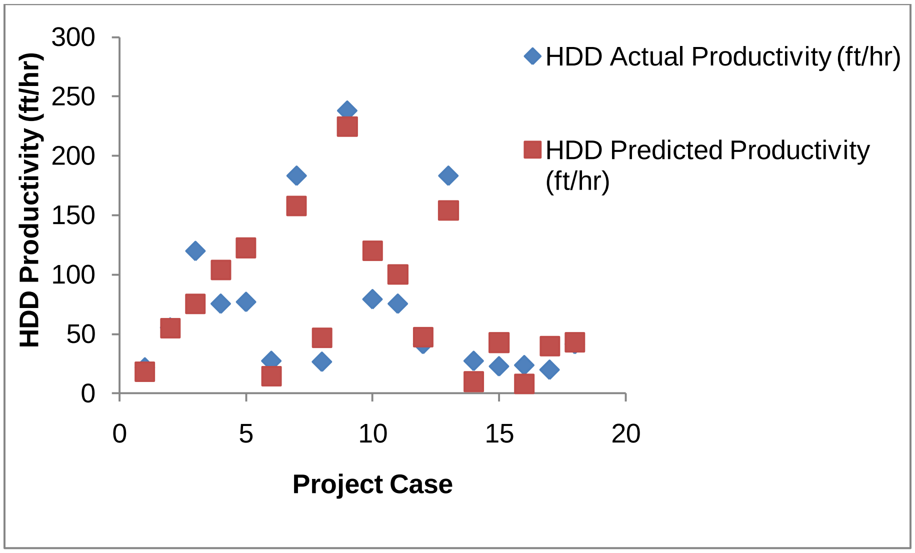


Figure 6.19 HDD Predicted and Reported Productivity in Clayey Conditions Model

6.3.3.2 HDD Productivity Rocky Conditions Model

Table 6.10 presents validation of HDD productivity model in rocky conditions. It is shown that validation factor is still high in this model averaging 105%, and the model is able to predict HDD productivity in rocky conditions.

Table 6.10 HDD Productivity Model Validation in Rocky Conditions

Reported Productivity (ft/hr)	Predicted Productivity (ft/hr)	% Difference	Validation Factor
40	39	0.03	1.03
18	19	-0.05	0.95
67	42	0.4	1.6
75	75	0.00	1.00

Table 6.10 - *Continued*

18	17	0.09	1.10
33	39	-0.18	0.85
33	38	-0.13	0.88
18	13	0.28	1.38
33	37	-0.09	0.91
33	33	0.02	1.02
33	34	-0.01	0.99
25	25	0.013	1.013
20	21	-0.03	0.97
27	29	-0.05	0.95
Average (34)	Average (32.77)	Average (0.02)	Average (1.05)

Figure 6.20 illustrates HDD predicted and reported productivity in rocky conditions. It is shown how HDD model and reported productivity are so close.

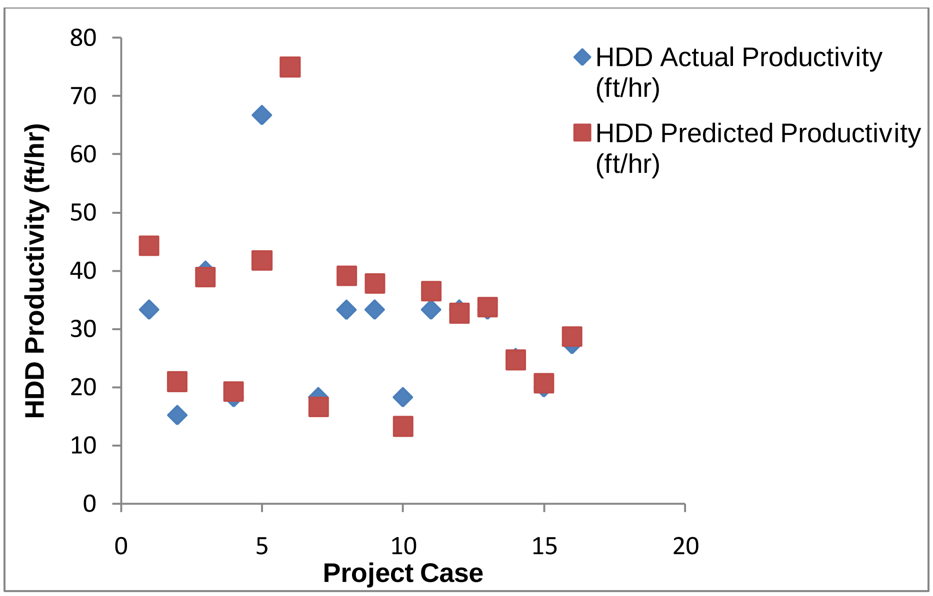


Figure 6.20 HDD Reported Productivity vs. Predicted Productivity in Rocky Conditions

6.3.4 HDD Productivity Data in Sandy Conditions

HDD productivity (ft/hr) in sandy conditions are high because most sand formations are loose, if found at shallow depth. Otherwise sandy soil might be dense to very dense when found on deep strata, but still may not provide a stable borehole.

Table 6.11 presents HDD productivity data collected in sandy conditions. The minimum value was 54 ft/hr which happened at 30-in. diameter of prereaming, 35-ft depth, and 750-ft length. The maximum value of 220-ft/hr occurred at 16-in. diameter, 6-ft. depth, and 220-ft length. The average productivity value was 100 ft/hr. Although sandy conditions provides good drilling ability, but it may face borehole collapse that consumes more drilling fluid to remove cuttings and holding sides of borehole wall.

Figure 6.21 illustrates HDD productivity vs. prereaming diameter. It shows that HDD productivity decreases with the increase of diameter in prereaming as the contact surface between reamer and borehole sides increases. And this holds true unless a blockage of borehole happens by sand collapse especially in weak or loose sandy conditions.

Table 6.11 HDD Productivity Data Collected in Sandy Conditions

Prereaming Diameter (in.)	Pipeline Depth (ft)	Pipeline Length (ft)	Drilling Rod Length (ft)	Thrust Force (kip)	Torque Force (ft-kip)	HDD Reported Productivity (ft/hr)
16	6	220	14	25	2.5	220
18	35	750	30	35	3	94
22	35	750	30	35	3	63
30	35	750	30	35	3	54
56	100	4,300	30	30	35	72
Average HDD Productivity in Sandy Conditions						100

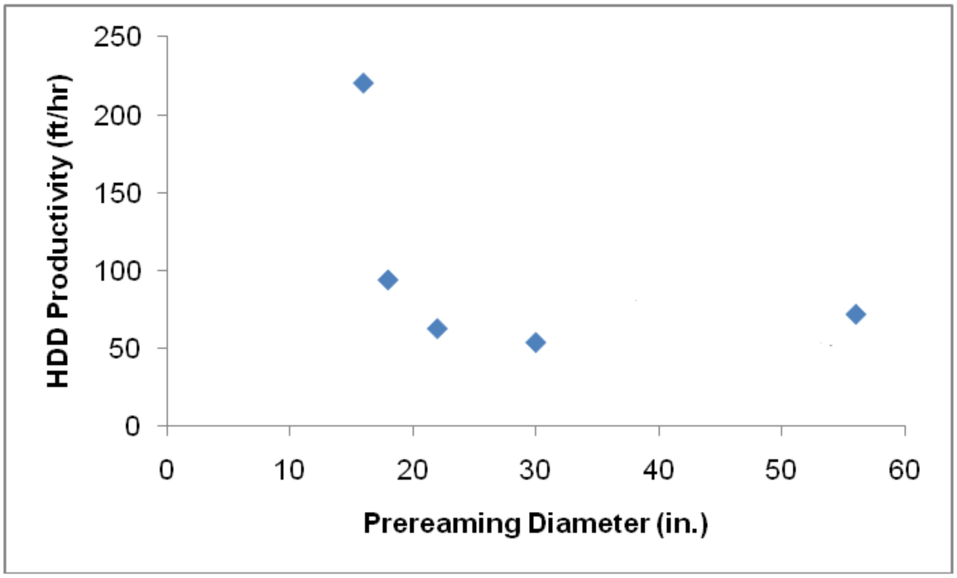


Figure 6.21 HDD Productivity vs. Prereaming Diameter in Sandy Conditions

Figure 6.22 illustrates HDD productivity vs. borehole depth. It shows that HDD productivity decreases with the increase in borehole depth. This is reasonably true as the radius of curvature required for pipe will be very high in deepest applications and there might be restrictions on the work area available. In this case, high operational force will be required just to maintain the low productivity values during prereaming.

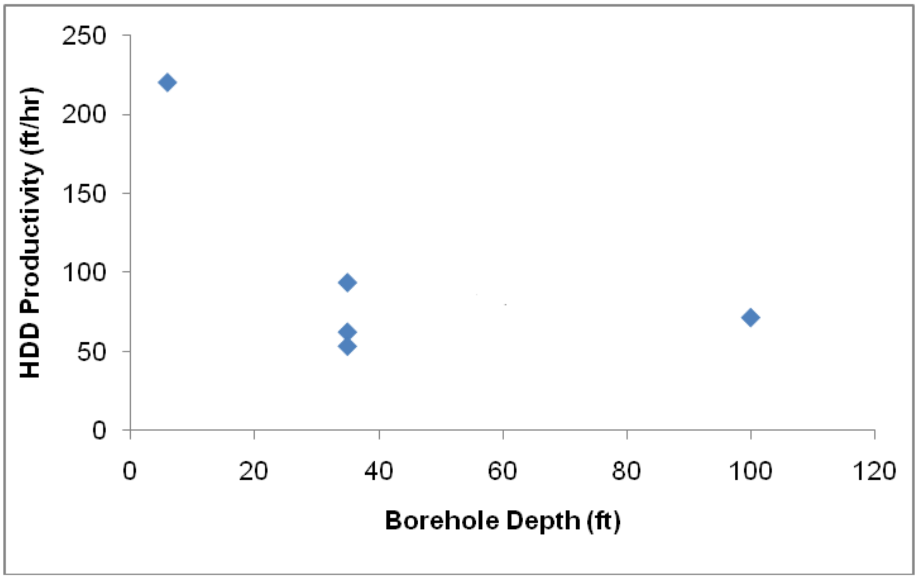


Figure 6.22 HDD Productivity vs. Borehole Depth in Sandy Conditions

Figure 6.23 illustrates HDD productivity decreases with the increase in borehole length, which explains the increase of load exerted on drilling rod and machine by friction and momentum especially if the entry and/or exit angles are steep.

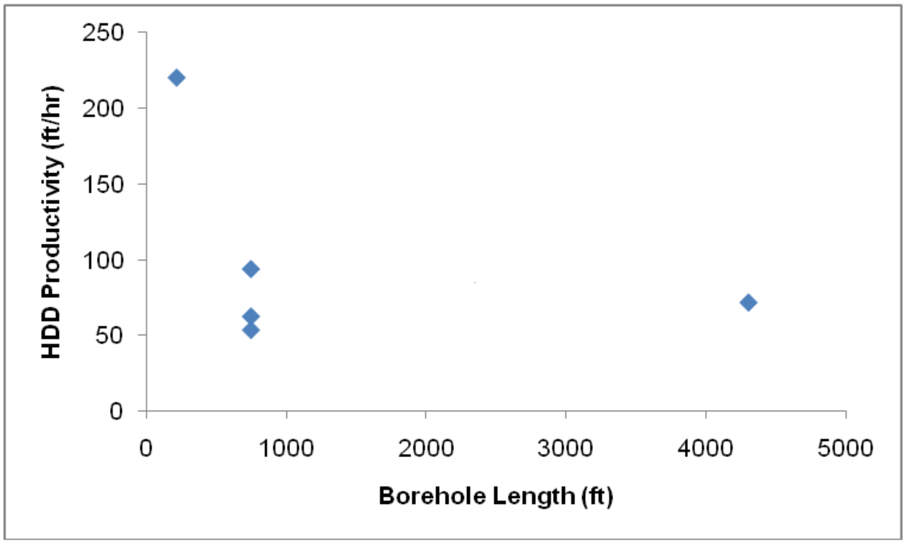


Figure 6.23 HDD Productivity vs. Borehole Length in Sandy Conditions

As Figure 6.24 illustrates HDD productivity vs. drilling rod length in sandy conditions that does not provide a good relationship.

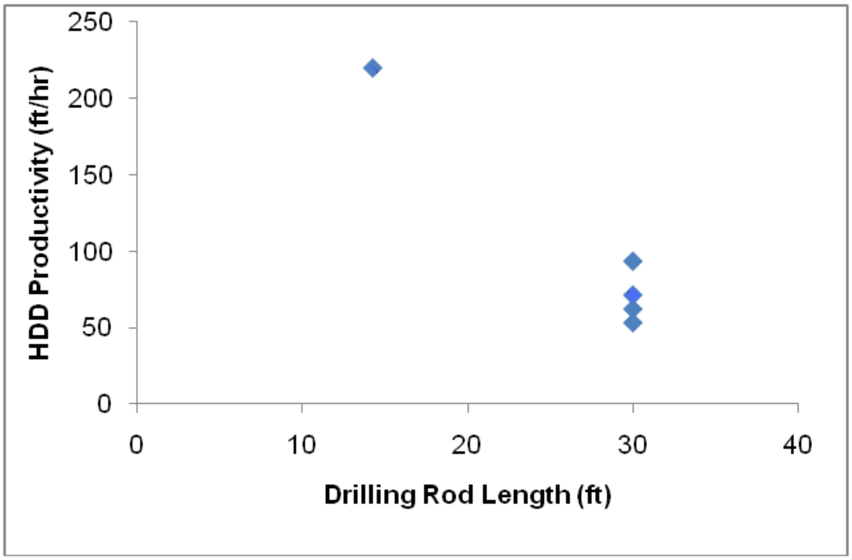


Figure 6.24 HDD Productivity vs. Drilling Rod Length in Sandy Conditions

Figure 6.25 illustrates HDD productivity vs. thrust force and shows that, for sandy conditions, the survey did not provide good correlations for these parameters.

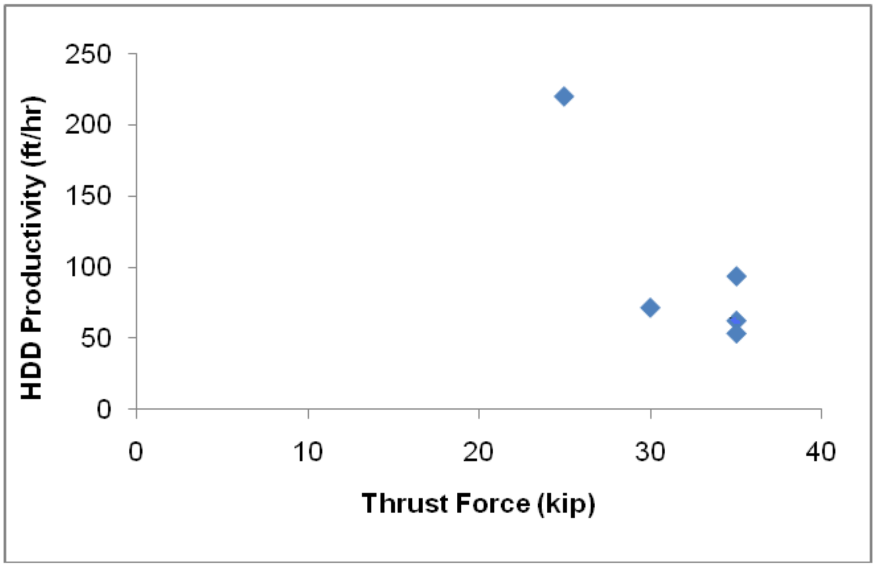


Figure 6.25 HDD Productivity vs. Thrust Force in Sandy Conditions

Figure 6.26 illustrates that HDD productivity vs. torque force, data did not provide good correlation in sandy conditions, due to lack of enough data.

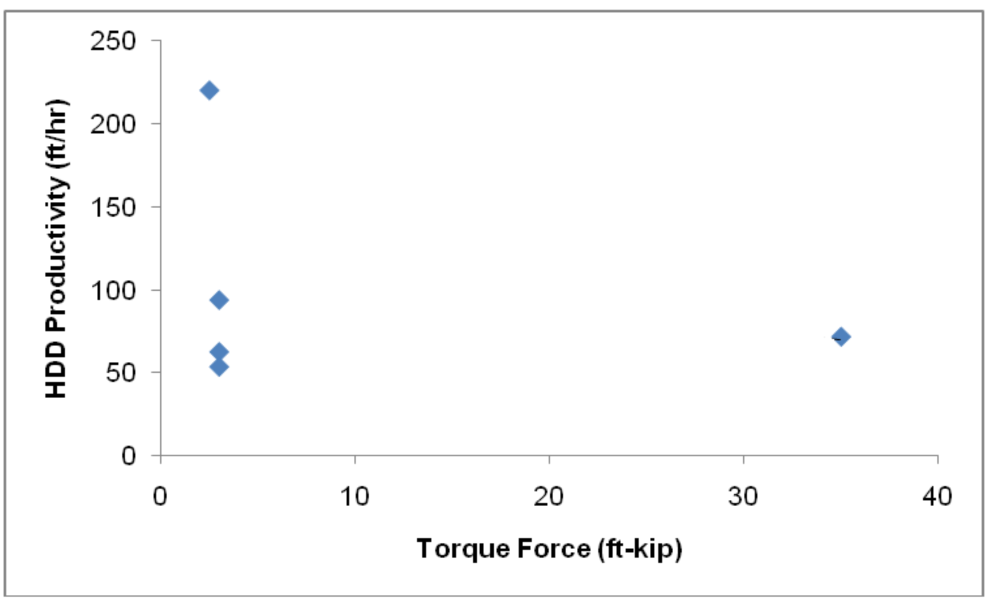


Figure 6.26 HDD Productivity vs. Torque Force in Sandy Conditions

6.4 Reality Validation for HDD Productivity Models

Table 6.12 presents a comparison and summary of HDD productivity results obtained in the literature search and results obtained in current research.

Table 6.12 Comparison of HDD Productivities

Soil Type	Allouche (2000)		Willoughby (2005)		Zayed (2007)		Mahmoud (2009)		Current Research (2011)	
	Actual	Model	Actual	Model	Actual	Model	Actual	Model	Actual	Model
Clay	44	NA	150	NA	NA	NA	51	45	75	77
Rock	25	NA	31	NA	NA	NA	35	31	34	33
Sand	40	NA	150	NA	123 and 88	NA	37	34	100	NA

The differences among the current research and previous studies shown in Table 6.12 might be due to a variety of HDD rigs' sizes and models, and project site and specific conditions. In trenchless technology industry, and mainly in HDD technique, 2–3 years is the usual expected life of HDD rigs. Most changes and improvements are usually done on wear and tear parts such as cutting heads, reamers and drilling rods. Also, studies are conducted on improving drilling fluid specifications for different soil conditions.

Another reality check comes with the results of previous studies in considering significant subconditions in HDD productivity operation and other trenchless operations. Table 6.13 and 6.14 present the results obtained by previous studies conducted on HDD and other trenchless construction operations regarding HDD's significant subconditions.

Table 6.13 Significant Factors in Trenchless Operations

Study	Significant Subconditions
Tunneling, Touran (1997)	Soil type, job environment, and equipment abilities (force)
TBM, Arachchige (2001)	Soil Type
Auger Boring, Salem (2003)	Soil type, length, obstruction, and diameter
Microtunneling Hegab and Salem (2004)	Soil type and conditions, drive length, diameter, no. of driven pipes, and jacking force
Continuous Flight Auger (CFA) Zayed (2005)	Soil type, obstructions, depth, diameter, and machine abilities (force)
Microtunneling Hegab and Salem (2010)	Soil type and soil conditions, diameter, length, and shear force

Table 6.14 Significant Factors in HDD Previous Studies

<table>
<tr><td colspan="2">Study</td><td>Significant Subconditions</td></tr>
<tr><td colspan="2">HDD
Adel and Zayed (2009)</td><td>HDD rig capabilities (thrust and torque), soil type and unseen conditions, pipe diameter, length, and depth</td></tr>
<tr><td colspan="2">HDD
Zayed et al. (2007)</td><td>Soil type, pipeline diameter, and machine size</td></tr>
<tr><td rowspan="2">HDD
Mahmoud (2009)</td><td>Significant Factors</td><td>Soil type, pipeline diameter, and machine capabilities (thrust and torque)</td></tr>
<tr><td>Insignificant Factors</td><td>Season, weather, groundwater level, fluid ratios, and fluid pumping rate</td></tr>
</table>

6.5 Chapter Summary

This chapter focused on developing HDD productivity models for clayey and rocky conditions. Modeling process was extended on two levels, the pilot project level and HDD questionnaire level, which resulted in a detailed analysis to refine subconditions that have significance to be used in HDD model.

Mainly, five subconditions showed significant effect on HDD productivity. These subconditions included diameter of prereaming (in.), depth of borehole (ft), drilling rod length (ft), thrust force (kip), and torque (ft-kip).

Predicted HDD productivity for clayey conditions was found to be 77 ft/hr compared to average reported HDD productivity of 75 ft/hr with a validation factor of 117%. Predicted HDD productivity in rocky conditions was found to be 33 ft/hr compared to average reported productivity of 34 ft/hr with a validation factor of 105%. Average HDD productivity reported in the questionnaire in sandy conditions was calculated to be 100 ft/hr.

Soil conditions have the largest impact on the HDD productivity. Therefore, HDD productivity operation was first modeled on soil conditions, in addition to other subconditions.

CHAPTER 7

HDD MODEL APPLICATIONS AND USER INTERFACE

7.1 Introduction

This chapter presents application of models developed for HDD productivity in clayey, rocky and sandy conditions. By estimating productivity using developed models' in clayey, rocky and sandy conditions, a user interface is developed as a planning tool for HDD prereaming operations. Using this user interface, quantities of materials and HDD labor costs can be calculated for prereaming operations.

7.1.1 HDD Productivity

In addition to the HDD productivity model presented previously, a modified productivity model is introduced in this chapter. The following formula provides modified productivity by factoring non-productive time in model productivity:

HDD Modified Productivity (ft/hr) = HDD Model Productivity (ft/hr) x (1 – Non-productive time %).

7.1.2 HDD Prereaming Operation Parameters

Current research introduced quantity of materials applied in preream operations as well as labor costs for HDD crew as presented in Table 7.1. Collected data included HDD crew rate ($/hr), bentonite mixing ratio (lb/100 gal), polymer mixing ratio (lb/100 gal), fluid pumping rate (gpm), and percentage of non-productive time associated to the encountered soil conditions.

Table 7.1 HDD Prereaming Operation Parameters

Soil Conditions	Data Collected by HDD Questionnaire (Average)				
	HDD Crew Rate ($/hr)	Bentonite Mixing Ratio (lb/100 gal)	Polymer Mixing Ratio (lb/100 gal)	Fluid Pumping Rate (gpm)	Non-Productive Time %
Clayey Conditions	169.7*	12	2.5	180	13

Table 7.1 - *Continued*

Rocky Conditions		29	40	145	10
Sandy Conditions		20	3.25	62	15

* HDD Crew Rate details is presented in Table 7.2

Table 7.2 presents the breakdown of HDD crew rate ($/hr) as collected from pilot project and questionnaire.

Table 7.2 HDD Crew Rate

HDD Crew Description	Crew Rate ($/hr)	No.	Rate Sum ($/hr)	Total Rate ($/hr - Crew)
Forman	30	1	30	169.7
HDD Driller	23	1	23	
Backhoe Operator	19.5	1	19.5	
Mechanical Operator	19	1	19	
Mud Recycling Worker	16.2	1	16.2	
Pump Worker (2)	16	2	32	
HDD Worker (2)	15	2	30	

7.2 HDD User Interface

The HDD user interface is developed by Java. Java is a programming language and computing platform that was first developed by James Gosling and released by Sun Microsystems in 1995 (Oracle, 2011). HDD user interface is able to conduct HDD productivity calculations in clayey, rocky, and sandy conditions. Figure 7.1 illustrates the screen of HDD user interface.

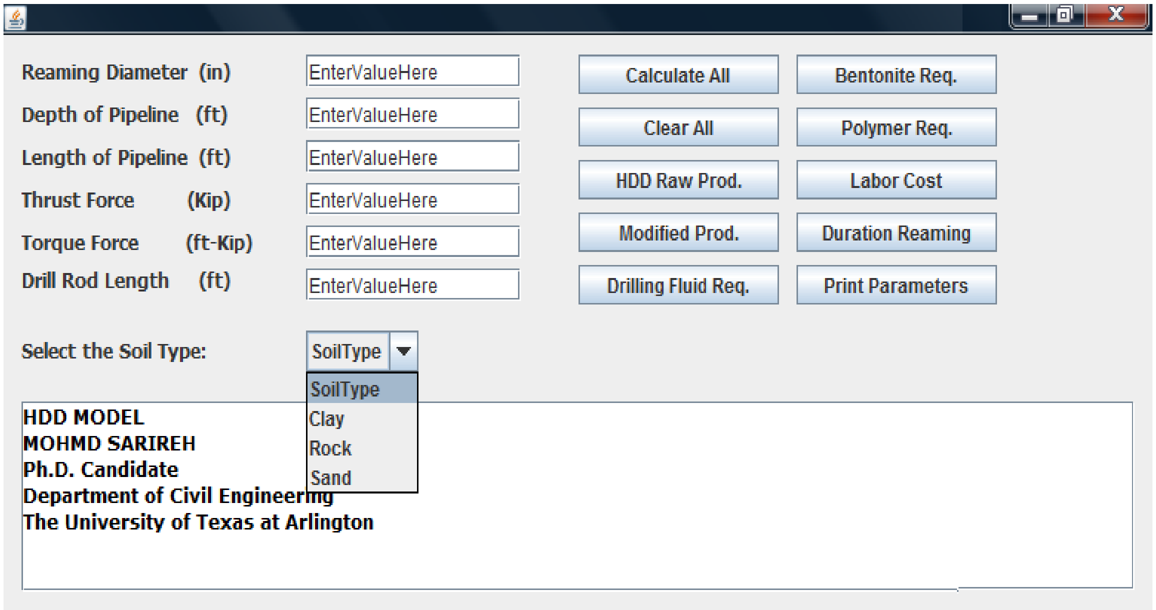


Figure 7.1 HDD Productivity User Interface Screen

7.2.1 HDD User Interface Calculations

The calculations of the HDD user interface are organized as follow:

- Calculating HDD model productivity (ft/hr) using developed models in clayey, rocky conditions and sandy conditions.
- Calculating HDD modified productivity considering non-productive time percentage using above formula.
- Calculating duration of preream operations (hr) using the following formula:

  HDD Prereaming Duration (ft/hr) = Drive Length of Project (ft) / HDD Modified Productivity (ft/hr)
- Calculating drilling fluid required for total prereaming pass (gal) using the following formula:

  Fluid (gal) = [Fluid Pumping Rate (gpm) x 60 (min/hr) x Drive Length (ft)] / Modified Productivity (ft/hr)
- Calculating required bentonite quantity (lb) using the following formula:

  Bentonite (lb) = Drilling Fluid Required (gal) x [1/Bentonite Mixing Ratio (lb/100 gal)]
- Calculating quantity of polymer required (Ib) using the following formula:

  Polymer (lb) = Drilling Fluid Require (gal) x [1/Polymer Mixing Ratio (lb/100 gal)]

- Calculating labor cost ($) using the following formula:

  Labor Cost ($) = Labor Rate ($/hr) x [Drive Length (ft) / Modified Productivity (ft/hr)]

Figure 7.2 illustrates an example of HDD user interface calculations for prereaming operation using a 30 inch reamer. Clayey subconditions or inputs are shown in as well as all results and calculations are shown in output screen.

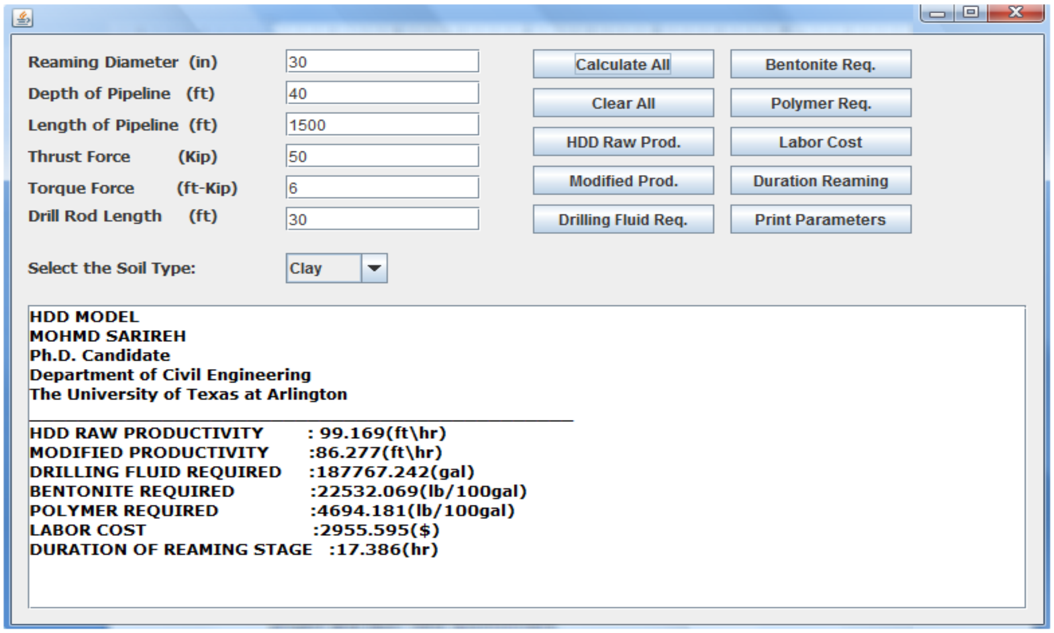


Figure 7.2 HDD User Interface Example Calculations

7.3 Chapter Summary

This chapter presented a HDD user interface as a planning tool for prereaming operation. This tool will enable contractors and consultants to develop similar user interfaces to prepare work plans for their HDD operations. This user interface was developed using Java language, but other software, such as Microsoft Excel, can be used as well. The user interface can be expanded to describe, design, and plan HDD operations in more details.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

8.1 Introduction

HDD operation has grown exponentially compared to other trenchless technologies in installation of underground utilities, especially in crossing rivers, lakes, highways, and airports. There is a need for a model to predict productivity of operations and to estimate project duration, and resource needs. HDD prediction model provides contractors design engineers a way to improve bidding process and project planning and construction.

8.2 Conclusions

The conclusions of the current research indicate that ANOVA model is applicable in studying productivity of HDD and other trenchless technologies as well as other construction operations. Conclusions of this research are divided into four main areas: 1) HDD pilot project, 2) testing significance of HDD subconditions, 3) modeling of HDD productivity, and 4) HDD modified productivity and HDD user interface.

HDD Pilot Project

1. A HDD pilot project was selected to study the variations in HDD productivity through prereaming in different soil conditions. This study showed that HDD productivity is highly affected by encountered soil conditions. Although the general description of the soil condition at the pilot project site was described to be clayey conditions, some minor contents of sand, shale, and silt provided different HDD productivity values. The HDD productivity in shaly clay averaged 84 and 60 ft/hr, while in sandy clay averaged 54 ft/hr, and in silty clay it averaged 114 ft/hr. ANOVA model analysis showed that there is no difference in HDD productivity between shaly clay and sandy clay conditions.

2. The effects of depth, length, and depth-length interactions on HDD productivity in the pilot project was negligible as the 2^2 *ANOVA factorial design* results showed that these factors have calculated F_0-*Value* less than tabulated *F-Value* and have *P-Values* greater than α = 0.05.
3. The analysis of variance (ANOVA) model can be utilized successfully as a primary guide for modeling HDD productivity, since the SPSS model results confirmed ANOVA results about depth, length, and length-depth interaction effects on HDD productivity in pilot project.

Testing the Significance of HDD Subconditions through Data Questionnaire

4. By conducting statistical analysis using ANOVA model, significant subconditions in HDD operation were determined. It was concluded that prereaming diameter, borehole depth, thrust force, torque force, and drilling rod length are significant subconditions and should be included in the productivity model as $F_0 > F_\alpha$ and *P-Value* < α. Also, it was concluded that soil type, diameter, and depth of borehole are the most significant factors in HDD operations. These subconditions have the largest F_0 values and the lowest *P-Value* which is less than the significance level that was stated in the test α and equals to 0.05.
5. Significant subconditions including soil type, prereaming diameter, and depth of borehole can determine the size of HDD machine, type of reamer and size, and quantity of drilling fluid.

Modeling of HDD Productivity

6. HDD productivity is decreased by the increase of diameter of prereaming in clayey, rocky, and sandy conditions.
7. HDD productivity is increased by the increase of depth of borehole in clayey conditions. While in rocky conditions, the effects of depth were not clear because collected data showed similar depth that ranged from 25 to 30 ft.
8. HDD productivity is increased by the increase of drilling rod length specially in clayey conditions as the prereaming time is shorter compared to the time for adding or removing drilling rods. HDD crew used three to four rods per one hour during prereaming in clayey conditions. The HDD crew used only one drilling rod per hour during prereaming in rocky conditions.

9. HDD productivity is increased by the increase in machine force, specially thrust force, as contractors usually use the maximum thrust force to drill in the hardest soil conditions.
10. The average reported productivity in clayey conditions was 75 ft/hr, while the average modeled productivity equaled 77 with a validation factor of 117%. In rocky conditions, the average reported productivity was 34 ft/hr, while the average modeled productivity equaled 33 with a validation factor of 105%. In sandy conditions, the average reported productivity was 100 ft/hr. There were not enough observations for productivity in sandy conditions to develop a model.

HDD Modified Productivity

11. HDD modified productivity is a measurement of efficiency of operation as the percent of non-productive time is included as a reduction factor for HDD model productivity. It was found that percent of non-productive time averages 10% in rocky conditions, 13% in clayey conditions, and 15% in sandy conditions.

HDD User Interface

12. A user interface was developed as a planning tool that can be used by contractors, consultants, and engineers to plan for HDD projects.

8.3 Research Contributions

This research contributed in the following areas:

- Identifying the most significant factors that affect HDD productivity.
- Developing the analysis of significant subconditions by utilizing ANOVA model.
- Developing HDD productivity prediction models in clayey and rocky conditions as well as in mixed soils conditions.
- Developing HDD modified productivity by considering efficiency of HDD subconditions.
- Developing descriptive statistics necessary for HDD operational conditions, and market share.
- Developing HDD user interface as a planning tool for HDD operation that can be expanded for similar conditions.

8.4 Research Limitations

This research faced the following limitations:

- Limited data was available in soil conditions encountered.
- Reporting working days and working hours, may not have been accurate as some contractors work different hours per day and in different shifts.
- The developed model is limited to certain soil conditions as it was developed for predicting productivity in clayey and rocky conditions. Due to lack of enough data, an average value was developed for HDD productivity in sandy conditions.

8.5 Recommendations for Future Work

The comprehensive and integrated management of HDD projects has an important role in construction and installation of underground pipelines and utilities. This research can be expanded in the following areas:

- Research is needed on HDD productivity modeling for pipe diameter relationships with reaming requirements.
- The hydro-fractout in certain soil conditions requires drilling fluids improvements specially for large HDD projects in gravelly unstable and soft soil.
- Surface heave and settlements during and after construction needs more research.
- Zone of influence of drilling operations into different soil materials and conditions needs to be investigated.

APPENDIX A

HDD QUESTIONNAIRE

A-1

HDD QUESTIONNAIRE INTRODUCTION

Horizontal Directional Drilling Project Information Edit

Design Survey | Collect Responses | Analyze Results

Edit Survey
Survey Options
Print Survey
Restore Questions
Page Randomization

Edit Survey

Preview Survey | Send Survey »

To change the **look** of your survey, select a theme below.

Blue Ice | Create Custom Theme

+ Add Page

PAGE 1 | Edit Page Options ▼ | Add Page Logic | Move | Copy | Delete | Show this page only

Page (1/10) Horizontal Directional Drilling Survey Welcoming and Work Description

Greetings!

This questionnaire is a study to model Horizontal Directional Drilling (HDD) operation. Your responses will help us to better understand HDD process.

This study is being conducted by Mohmd Sarireh, Ph.D. student under direction of Dr. Mohammad Najafi, P.E. Professor of Civil Engineering at The University of Texas at Arlington.

To show our appreciation, we will email you a copy of the survey results after its expected completion in May 2011.

The questionnaire asks you to provide information for one HDD project you have implemented, involved, or supervised and then to rate factors that are related to HDD process.

This survey contains 8 questions and is expected to take about 20 minutes. Your answers are voluntary. You are free to answer any question or to stop participating at any time.

Your information will be strictly confidential to the maximum extent allowable by law and your responses will be used in aggregate for the purpose of this research.

We do not track or record the IP address from which you are responding.

Thank you in advance for your help, we do appreciate your time to respond to our survey.

Warm regards,

Mohmd Sarireh, Ph.D. Student
Department of Civil Engineering
Cell Phone: (817) 716-5839
Email: mohmd.sarireh@mavs.uta.edu

Dr. Mohammad Najafi, P.E.
Professor of Construction Engineering & Management
Phone: (817) 272-0507
E-mail: najafi@uta.edu

Center of Underground Infrastructure Research and Education (CUIRE)
College of Engineering, The University of Texas at Arlington
428 Nedderman Hall, Arlington, TX 76019-0308

The University of Texas ARLINGTON™ CUIRE

A-2

HDD QUESTIONNAIRE EXPLANATIONS

PAGE 2 Edit Page Options ▼ Add Page Logic Move Copy Delete Show this page only

Page (2/10) Explanations

1- Horizontal Directional Drilling (HDD): a trenchless technology method that is steerable in installation of pipes, conduits, and cables, starts with the drilling of pilot hole, then enlarging by reaming and backreaming, and finishes with the pulling back of the product pipe.

2-HDD machines (rigs) can be classified into three main types: Maxi-HDD, Midi-HDD, and Mini-HDD, depending on the diameter of hole, depth, and length, and every type has a minimum and maximum limits for these parameters.

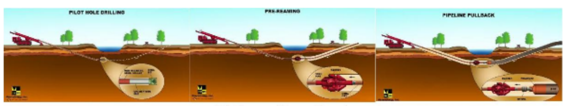
3-HDD technology uses suitable tools for drilling, depending on soil type we decide the type of drilling bit or the type of reamer to be used, in addition to drilling fluid type used, mixing ratio (lbs./100 gal), and fluid pumping rate (gpm).

4- If answer is "not applicable," please insert "NA." If "other," please explain in the appropriate comment box.

+ Add Question ▼

Edit Question ▼ Move Copy Delete

HDD Process



HDD Process (Source: Mears)

A-3

HDD PERSONAL AND PROJECT INFORMATION

PAGE 3 Edit Page Options ▼ Add Page Logic Move Copy Delete Show this page only

Page (3/10) Individual / Company Information

+ Add Question ▼

Q1 Edit Question ▼ Move Copy Delete

*Please complete your information and the company information.

First Name

Last Name

Position

Role in The Project

Email Address

Phone Number

Experience in HDD Work (yr)

Q2 Edit Question ▼ Move Copy Delete

*Company Information

Name of Company

Type of Company, such as contractor, consultant, owner, or agency, etc.

Number of Years Company in HDD Work (Yr)

Q3 Edit Question ▼ Move Copy Delete

In this question, we are asking you about a specific project your company / organization had implemented,involved, or supervised.

Name of Project

Location of project

Company Experience in HDD Work (yr)

Approximate Budget of Project ($)

Pipeline Outside Diameter (in.)

Depth of Installation at mid crossing (ft)

Total Length (ft)

Average Groundwater Depth (ft)

A-4

PROJECT DATES AND CURVE INFORMATION

Q4 Edit Question ▼ Move Copy Delete

Project Arch (Curve) Information

Entry Angle (Degree)

Exit Angle (Degree)

+ Add Question ▼ Split Page Here

Q5 Edit Question ▼ Move Copy Delete

Project Dates

	MM	DD	YYYY
Project Start Date	/	/	
Project Completion Date	/	/	

Q6 Edit Question ▼ Move Copy Delete

Project Details

	Pipeline Material	Pipeline Usage or Application	Soil Type
HDD Project Data			

+ Add Question ▼ Split Page Here

Q7 Edit Question ▼ Move Copy Delete

If "other," please explain in the appropriate comment box.

Pipe Material

Pipe Usage

Soil Type

A-5

HDD STAGES INFORMATION

Page (5/10) Project Durations Details

Q8 Edit Question ▼ Move Copy Delete

Please insert durations for project stages in hour (hr). If in days, please specify unit as day (d).

Durations of Stages

Project Preparation (hr)

Pilot Hole Duration (hr)

1st Back Reaming Duration (hr)

2nd Back Reaming Duration (hr)

3rd Back Reaming Duration (hr)

4th Back Reaming Duration (hr)

5th Back Reaming Duration (hr)

Swapping Duration (hr)

Pullback Duration (hr)

Q9 Edit Question ▼ Move Copy Delete

Please, insert diameter (in.) of each stage if applicable. If "not applicable," please insert "NA."

Pilot Hole Diameter (in.)

1st Back Reaming Diameter (in.)

2nd Back Reaming Diameter (in.)

3rd Back Reaming Diameter (in.)

4th Back Reaming Diameter (in.)

5th Back Reaming Diameter (in.)

Swapping Diameter (in.)

Final Pullback Diameter (in.)

Q10 Edit Question ▼ Move Copy Delete

Please, insert the maximum, minimum, and average rotational speed (rpm) for Pilot Hole, Back Reaming, and Pull back if applicable. If "not applicable," please insert "NA."

Min. Rotational Speed (rpm) in Pilot Hole

Max. Rotational Speed (rpm) in Pilot Hole

Average Rotational Speed (rpm) in Pilot Hole

Min. Rotational Speed (rpm) in Back Reaming

Max. Speed (rpm) in Back Reaming

Average Rotational Speed (rpm) in Back Reaming

Min. Rotational Speed (rpm) in Pullback

Max. Rotational Speed (rpm) in Pullback

Average Rotational Speed (rpm) in Pullback

A-6

HDD CREW DETAILS

PAGE 6 Edit Page Options ▼ | Add Page Logic | Move | Copy | Delete — Show this page only

Page (6/10) HDD Crew Details

Q11 Edit Question ▼ | Move | Copy | Delete

Please insert information for HDD operator and other crew.

	HDD Operator Type	HDD Operator Experience (yr)	Worker's Job
HDD Crew			

+ Add Question ▼ | Split Page Here

PAGE 7 Edit Page Options ▼ | Add Page Logic | Move | Copy | Delete — Show this page only

Page (7/10) HDD Rig Details

+ Add Question ▼

Q13 Edit Question ▼ | Move | Copy | Delete

Please, insert information for HDD Rig.

	Rig Size	HDD Rig Type	Machine Pull/Thrust (lbs)	Machine Torque (ft-lbs.)	Drill Bit Type	Reamer Type	Drilling Rod Length (ft)
HDD Rig							

Q14 Edit Question ▼ | Move | Copy | Delete

If "other," please explain in the appropriate comment box.

HDD Rig Type
Machine Pull/Thrust (lbs.)
Machine Torque (ft-lbs.)
Drilling Bit Type
Reamer Type
Drilling Rod Length (ft)

A-7

PILOT STAGE

PAGE 8 Edit Page Options ▼ | Add Page Logic | Move | Copy | Delete — Show this page only

Page (8/10) Drilling Stages' Details - Pilot Hole

+ Add Question ▼

Q15 Edit Question ▼ | Move | Copy | Delete

Please, insert information for Pilot Hole Stage if applicable.

	Drilling Fluid Used	Drilling Fluid Pumping Rate (gpm)	Bentonite Mixing Ratio (lb/100 gal)	Polymer Mixing Ratio (lb./100 gal)	Problem Type (Obstructions)	Problem Solving Time (hr)	Tracking System Used	% of Nonproductive Time (Average)	% of Solid Removal in Slurry
Pilot Hole									

Q16 Edit Question ▼ | Move | Copy | Delete

If "other," please explain in the appropriate comment box.

Drilling Fluid Used
Drilling Fluid Pumping Rate (gpm)
Bentonite Mixing Ratio (lb/100 GAL)
Polymer Mixing Ratio (gpm)
Problem Type (Obstructions)
Problem Solving Time (hr)
% of Nonproductive Time (Average)
% of Solid Removal in Slurry

A-8

HDD PILOT HOLE DETAILS

Page (9/10) Drilling Stages' Details - Reaming

+ Add Question ▼

Q17 Edit Question ▼ Move Copy Delete

Please, insert information for Reaming Stage if applicable.

	Drilling Fluid Used	Drilling Fluid Pumping Rate (gpm)	Bentonite Mixing Ratio (lb/100 gal)	Polymer Mixing Ratio (lb./100 gal)	Problem Type (Obstructions)	Problem Solving Time (hr)	% of Nonproductive Time (Average)	% of Solid Removal in Slurry
Reaming Stage								

A-9

PULL BACK STAGE

Page (10/10) Drilling Stages' Details - Pullback

+ Add Question ▼

Q19 Edit Question ▼ Move Copy Delete

Please, insert information for Pulling Back Stage if applicable.

	Drilling Fluid Used	Drilling Fluid Pumping Rate (gpm)	Bentonite Mixing Ratio (lb/100 gal)	Polymer Mixing Ratio (lb/100 gal)	Problem Type (Obstructions)	Problem Solving Time (hr)	% of Nonproductive Time (Average)	% of Solid Removal in Slurry
Pulling Back Stage	▼	▼	▼	▼	▼	▼	▼	▼

APPENDIX B

HDD RAW DATA RESPONSE

B-1

PERSONAL INFORMATION AND PROJECT INFORMATION

1. Please complete your information and the company information.

First Name - Bradley

Last Name - King

Position - Construction Manager

Role in The Project - Construction Management (Pipeline)

Email Address - bking@ugsi.us

Phone Number - 832-385-5979

Experience in HDD Work (yr) - 15

2. Company Information

Name of Company - Kinsel Industries

Type of Company, such as contractor, consultant, owner, or agency, etc. - Contractor

Number of Years Company in HDD Work (Yr) - 5

B-2

CONTRACTOR INFORMATION

1. In this question, we are asking you about a specific project your company / organization had implemented,involved, or supervised.

Name of Project - Bellaire Waterline

Location of project - Bellaire, TX

Company Experience in HDD Work (yr) - 5

Approximate Budget of Project ($) - 750,000.00

Pipeline Outside Diameter (in.) - 20.00

Depth of Installation at mid crossing (ft) - 22

Total Length (ft) - 2700

Average Groundwater Depth (ft) - 16

2. Project Arch (Curve) Information

Entry Angle (Degree) - 10

Exit Angle (Degree) - 10

3. Project Dates

Project Start Date - 07/01/2003

Project Completion Date - 10/01/2003

4. Project Details

	Pipeline Material	Pipeline Usage or Application	Soil Type
HDD Project Data	HDPE	Water Force Main	Silty Clay

5. If "other," please explain in the appropriate comment box.

No Response

B-3

DURATIONS, DIAMETERS, AND ROTATIONAL SPEED INFORMATION

1. Please insert durations for project stages in hour (hr). If in days, please specify unit as day (d). Durations of Stages

Project Preparation (hr) - 50

Pilot Hole Duration (hr) - 20

1st Back Reaming Duration (hr) - 35

2nd Back Reaming Duration (hr) - 34

3rd Back Reaming Duration (hr) - NA

4th Back Reaming Duration (hr) - NA

5th Back Reaming Duration (hr) - NA

Swapping Duration (hr) - 13

Pullback Duration (hr) - 8

2. Please, insert diameter (in.) of each stage if applicable. If "not applicable," please insert "NA."

Pilot Hole Diameter (in.) - 6

1st Back Reaming Diameter (in.) - 20

2nd Back Reaming Diameter (in.) - 28

3rd Back Reaming Diameter (in.) - NA

4th Back Reaming Diameter (in.) - NA

5th Back Reaming Diameter (in.) - NA

Swapping Diameter (in.) - 24

Final Pullback Diameter (in.) - 20

3. Please, insert the maximum, minimum, and average rotational speed (rpm) for Pilot Hole, Back Reaming, and Pull back if applicable. If "not applicable," please insert "NA."

Min. Rotational Speed (rpm) in Pilot Hole - NA

Max. Rotational Speed (rpm) in Pilot Hole - NA

B-4

HDD RIG AND CREW INFORMATION

1. Please insert information for HDD operator and other crew.

	HDD Operator Type	HDD Operator Experience (yr)	Worker's Job
HDD Crew	In-house Operator	8 - 10	One Job Specified

2. If "other," please explain in the appropriate comment box.

No Response

1. Please, insert information for HDD Rig.

	Rig Size	HDD Rig Type	Machine Pull/Thrust (lbs)	Machine Torque (ft-lbs.)	Drill Bit Type	Reamer Type	Drilling Rod Length (ft)
HDD Rig	Maxi-HDD	American Auger DD	200,001 - 220,000	20,001 - 30,000	Carbide Button Slant-face	Blade Reamer	30

2. If "other," please explain in the appropriate comment box.

No Response

B-5

HDD STAGES INFORMATION

1. Please, insert information for Pilot Hole Stage if applicable.

	Drilling Fluid Used	Drilling Fluid Pumping Rate (gpm)	Bentonite Mixing Ratio (lb/100 gal)	Polymer Mixing Ratio (lb./100 gal)	Problem Type (Obstructions)	Problem Solving Time (hr)	Tracking System Used	% of Nonproductive Time (Average)	% of Solid Removal in Slurry
Pilot Hole	Bentonite and Polymers	75.01 - 100	25.01 - 35	1.51 - 2	Losing Tracking Signal	2-3	Walkover Tracking System	5-10	Other

2. If "other," please explain in the appropriate comment box.

% of Solid Removal in Slurry - Not Tracked on pilot

1. Please, insert information for Reaming Stage if applicable.

	Drilling Fluid Used	Drilling Fluid Pumping Rate (gpm)	Bentonite Mixing Ratio (lb/100 gal)	Polymer Mixing Ratio (lb./100 gal)	Problem Type (Obstructions)	Problem Solving Time (hr)	% of Nonproductive Time (Average)	% of Solid Removal in Slurry
Reaming Stage	Bentonite and Polymers	75.01 -100	25.01 - 35	1.51 - 2	Machine Breakdown	1-2	< 5	30-40

2. If "other," please explain in the appropriate comment box.

No Response

1. Please, insert information for Pulling Back Stage if applicable.

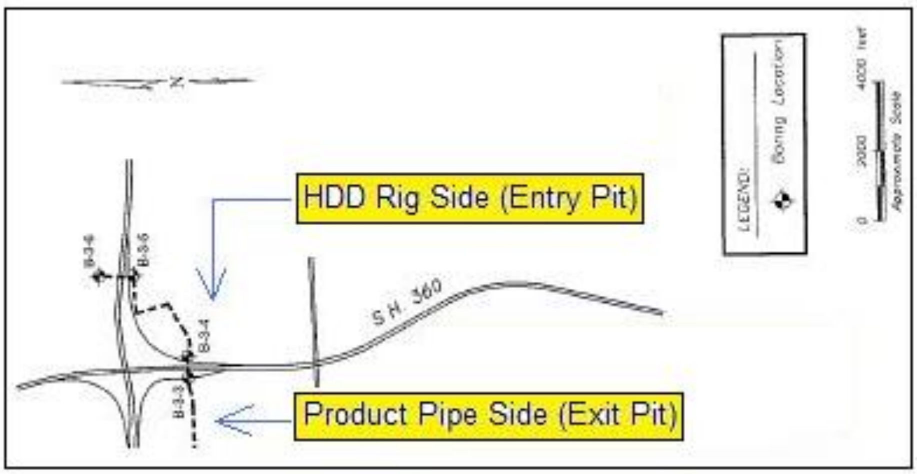
	Drilling Fluid Used	Drilling Fluid Pumping Rate (gpm)	Bentonite Mixing Ratio (lb/100 gal)	Polymer Mixing Ratio (lb/100 gal)	Problem Type (Obstructions)	Problem Solving Time (hr)	% of Nonproductive Time (Average)	% of Solid Removal in Slurry
Pulling Back	Bentonite and	50.01 - 75	25.01 - 35	1.51 - 2	Machine Breakdown	1-2	10-20	Other

APPENDIX C

HDD PILOT PROJECT DOCUMENT

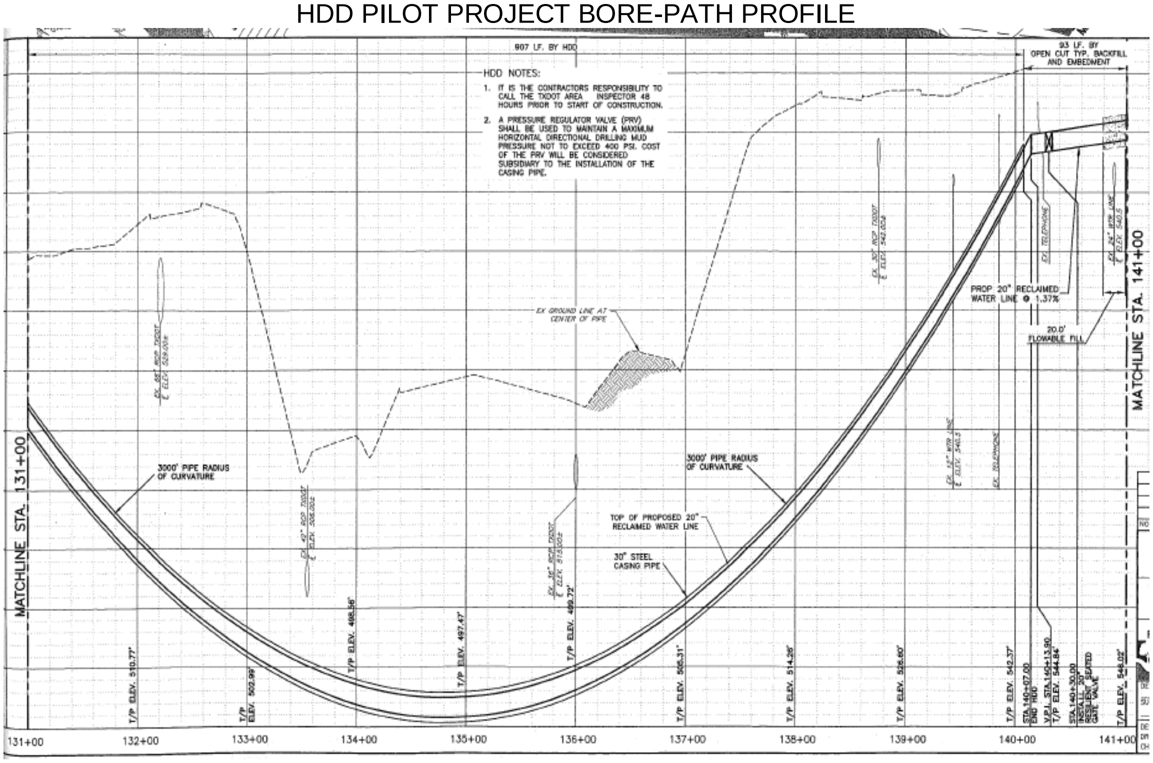
C-1

LOCATIONS OF BORE TEST IN HDD PILOT PROJECT



C-2

HDD PILOT PROJECT BORE-PATH PROFILE



GEOTECHNICAL BORE INFORMATION FOR HDD PILOT PROJECT AT EXIT SIDE

CMJ ENGINEERING INC

Project No	Boring No	Project	
425-09-15	B-3-3	Village Creek Reclaimed Water System Fort Worth, Texas	
Location: See Plate A.1		Water Observations: Seepage at 8' during drilling; water at 8' at completion	
Completion Depth: 45.0'	Completion Date: 2-25-09		
Surface Elevation: 537.6		Type: B-53-CFA	

Elevation	Stratum Description	REC %	RQD %	Blows/Ft. or Pen Reading, T.S.F.	Passing No 200 Sieve, %	Liquid Limit, %	Plastic Limit, %	Plasticity Index	Moisture Content, %	Unit Dry Wt. Lbs./Cu. Ft.	Unconfined Compression Pounds/Sq. Ft.
	SILTY CLAY, tan and brown w/ ironstone nodules firm to stiff			3.5					19		
				3.0					19		
534.6				2.5					20		
	CLAYEY SAND, dark brown - tan and brown, 4' - 8.5'			2.0					13		
				2.0					19		
				4.0					18		
529.1	**SANDSTONE**, tan and gray, very hard			100/0.5"							
526.1	**CLAYEY SHALE**, brown and gray, soft			4.5+		52	20	32	19		
521.6	**CLAYEY SANDY SHALE**, gray, w/ clayey sand seams, soft			1.5					22	100	1040
515.6	**SANDY SHALE**, gray, moderately hard to hard			100/2"							
				100/1.5"							
				100/2"							
				100/1.5"							
492.6				100/1"							

Depth, Ft.: 5, 10, 15, 20, 25, 30, 35, 40, 45

LOG OF BORING 425-09-15.GPJ CMJ.GDT 3/9/09

LOG OF BORING NO. **B-3-3** **PLATE A.19**

C-4

GEOTECHNICAL BORE INFORMATION FOR HDD PILOT PROJECT AT ENTRY SIDE

CMJ ENGINEERING INC

Project No. 425-09-15	Boring No. B-3-4	Project: Village Creek Reclaimed Water System, Fort Worth, Texas
Location: See Plate A.1		Water Observations: Seepage at 23' furing drilling; water at 18' at completion
Completion Depth: 60.0'	Completion Date: 2-11-09	
Surface Elevation: 550.3	Type: CME55-CFA	

Elevation	Stratum Description
	SILTY CLAY, dark brown and brown w/ calcareous nodules and ironstone nodules very stiff to hard, fill
541.8	**SILTY CLAY**, brown and reddish-brown, w/ calcareous nodules, hard
537.8	**SHALY CLAY**, light reddish-brown and gray, w/ ironstains and silt seams, hard
532.3	**SAND**, light reddish-brown to tan, w/ cemented sand seams dense to very dense
525.3	**SANDSTONE**, tan, extremely hard
522.8	**SHALY CLAY**, light brown and gray, w/ cemented sand and sand seams, hard
517.3	**SHALY CLAY**, dark gray, sandy w/ occasional sand seams, hard - firm to stiff 44' - 50'
500.3	**SANDY SHALE**, dark gray, w/ occasional sand and sandstone seams moderately hard to hard
490.3	

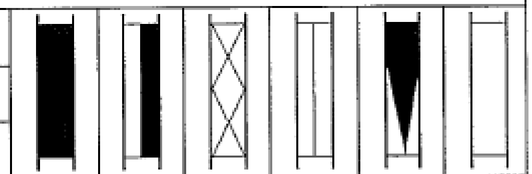
REC %	RQD %	Blows/Ft. or Pen Reading, T.S.F.	Passing No 200 Sieve, %	Liquid Limit, %	Plastic Limit, %	Plasticity Index	Moisture Content, %	Unit Dry Wt. Lbs./Cu. Ft.	Unconfined Compression Pounds/Sq. Ft.
		3.25					20		
		4.5+					23		
		4.5+					15		
		4.5+					15		
		4.5+		61	23	38	17		
		4.5+					18		
		4.5+					19		
		2.75					26	99	2950
		30					10		
		58					23		
		3.5					23		
		4.5+					18		
		4.5+		60	22	38	27		
		2.0					21		
		2.5					22	104	3460
		100/2.75"							
		100/2.5"							

LOG OF BORING NO. **B-3-4** **PLATE A.20**

SOIL GUIDES AND STANDARDS

SOIL OR ROCK TYPES

GRAVEL	LEAN CLAY	LIMESTONE
SAND	SANDY	SHALE
SILT	SILTY	SANDSTONE
HIGHLY PLASTIC CLAY	CLAYEY	CONGLOMERATE



Shelby Tube	Auger	Split Spoon	Rock Core	Cone Pen	No Recovery

TERMS DESCRIBING CONSISTENCY, CONDITION, AND STRUCTURE OF SOIL

Fine Grained Soils (More than 50% Passing No. 200 Sieve)

Descriptive Item	Penetrometer Reading, (tsf)
Soft	0.0 to 1.0
Firm	1.0 to 1.5
Stiff	1.5 to 3.0
Very Stiff	3.0 to 4.5
Hard	4.5+

Coarse Grained Soils (More than 50% Retained on No. 200 Sieve)

Penetration Resistance (blows/foot)	Descriptive Item	Relative Density
0 to 4	Very Loose	0 to 20%
4 to 10	Loose	20 to 40%
10 to 30	Medium Dense	40 to 70%
30 to 50	Dense	70 to 90%
Over 50	Very Dense	90 to 100%

Soil Structure

Calcareous	Contains appreciable deposits of calcium carbonate; generally nodular
Slickensided	Having inclined planes of weakness that are slick and glossy in appearance
Laminated	Composed of thin layers of varying color or texture
Fissured	Containing cracks, sometimes filled with fine sand or silt
Interbedded	Composed of alternate layers of different soil types, usually in approximately equal proportions

APPENDIX D

PILOT PROJECT SITE VISITS PHOTOES

D-1

SITE PREPARATION

Entry Pit

Exit Pit

Recycling System Preparation

Bentonite Storage at Site

Slurry Return Pump

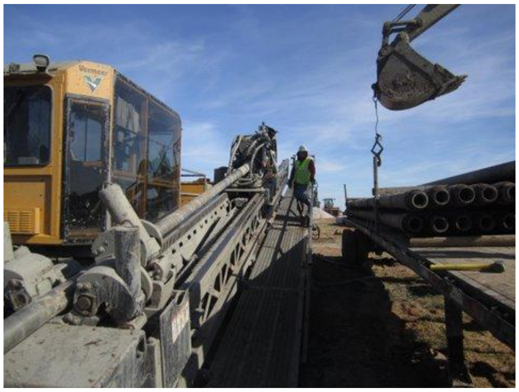
Fuel Storage for Use

D-2

DRILLING IN PILOT PROJECT

Start of Pilot Hole Drilling

Walk Over Tracking System



Handling of Drilling Rod

Drilling Activity

Prereaming/Reaming of Borehole

Locating Underground Utilities

D-3

WELDING OF STEEL PIPE

Service Truck

Welding Machine

Welding Preparation

Welding Operation

D-4

PULLING BACK OF STEEL PIPE

Trenching for Steel Pipe

Pushing Back Reamer

Connecting Swivel to Reamer

Testing of Reamer

Connecting Steel Pipe

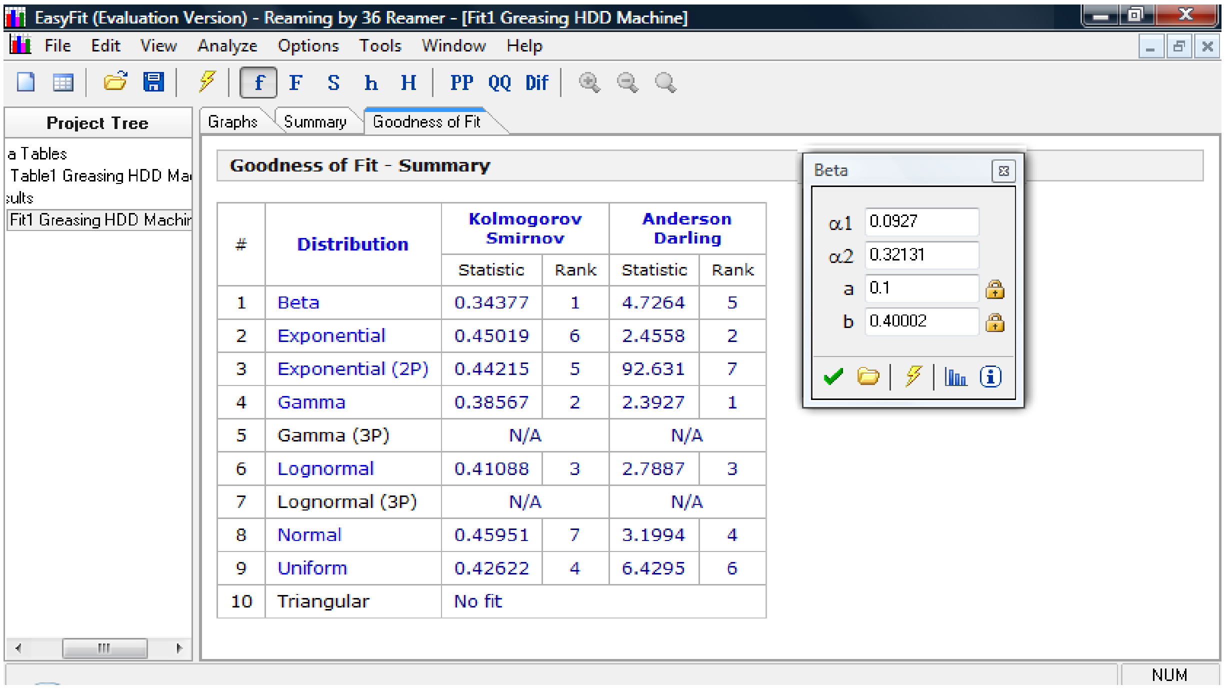
Hoisting Steel Pipe

APPENDIX E

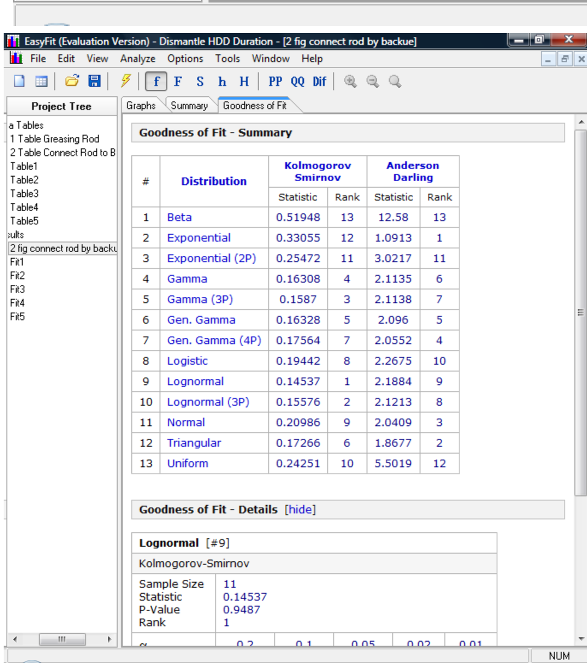
MICROCYCLONE ANALYSIS FOR PILOT PROJECT

E-1

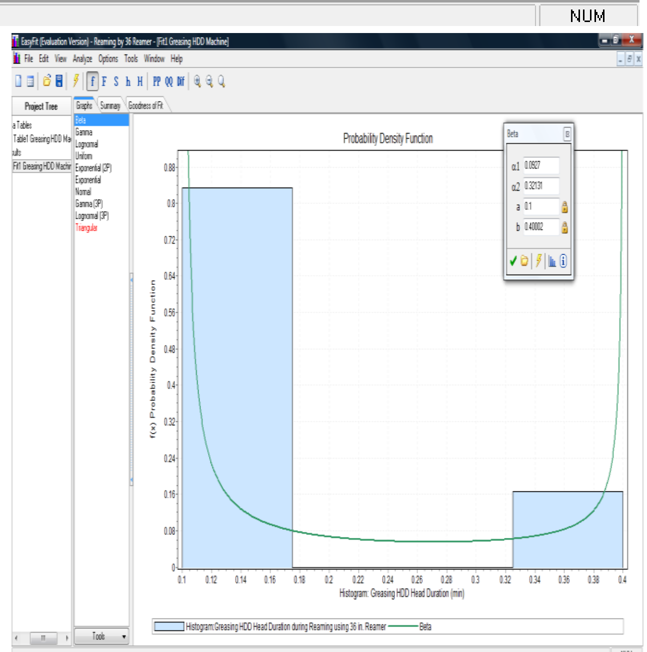
ACTIVITY DURATION DISTRIBUTION – GREASING HDD MACHINE



#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Beta	0.34377	1	4.7264	5
2	Exponential	0.45019	6	2.4558	2
3	Exponential (2P)	0.44215	5	92.631	7
4	Gamma	0.38567	2	2.3927	1
5	Gamma (3P)	N/A		N/A	
6	Lognormal	0.41088	3	2.7887	3
7	Lognormal (3P)	N/A		N/A	
8	Normal	0.45951	7	3.1994	4
9	Uniform	0.42622	4	6.4295	6
10	Triangular	No fit			

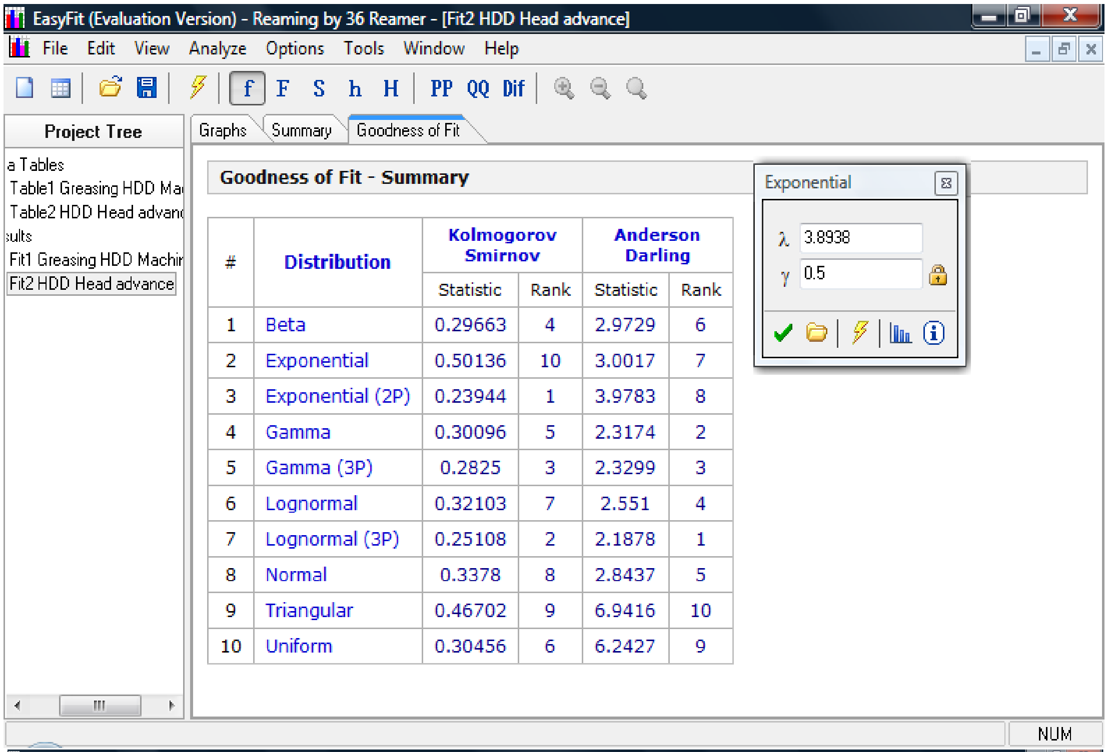


#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Beta	0.51948	13	12.58	13
2	Exponential	0.33055	12	1.0913	1
3	Exponential (2P)	0.25472	11	3.0217	11
4	Gamma	0.16308	4	2.1135	6
5	Gamma (3P)	0.1587	3	2.1138	7
6	Gen. Gamma	0.16328	5	2.096	5
7	Gen. Gamma (4P)	0.17564	7	2.0552	4
8	Logistic	0.19442	8	2.2675	10
9	Lognormal	0.14537	1	2.1884	9
10	Lognormal (3P)	0.15576	2	2.1213	8
11	Normal	0.20986	9	2.0409	3
12	Triangular	0.17266	6	1.8677	2
13	Uniform	0.24251	10	5.5019	12



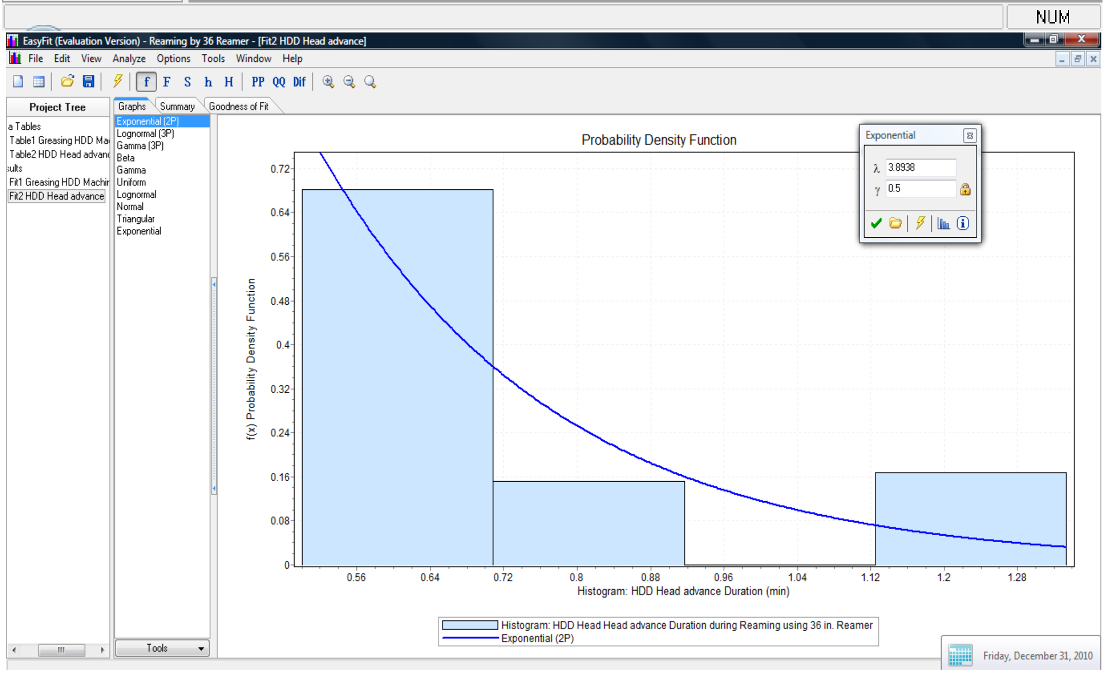
E-2

HDD MACHINE DURATION – ADVANCING HDD MACHINE



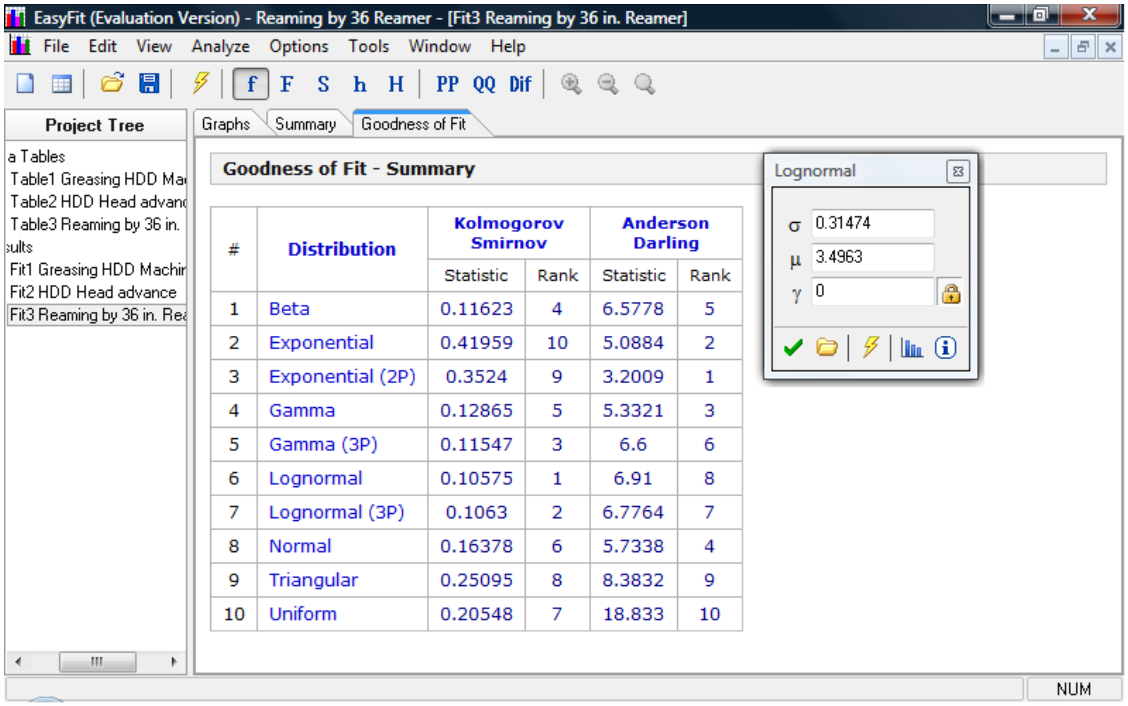
Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Beta	0.29663	4	2.9729	6
2	Exponential	0.50136	10	3.0017	7
3	Exponential (2P)	0.23944	1	3.9783	8
4	Gamma	0.30096	5	2.3174	2
5	Gamma (3P)	0.2825	3	2.3299	3
6	Lognormal	0.32103	7	2.551	4
7	Lognormal (3P)	0.25108	2	2.1878	1
8	Normal	0.3378	8	2.8437	5
9	Triangular	0.46702	9	6.9416	10
10	Uniform	0.30456	6	6.2427	9

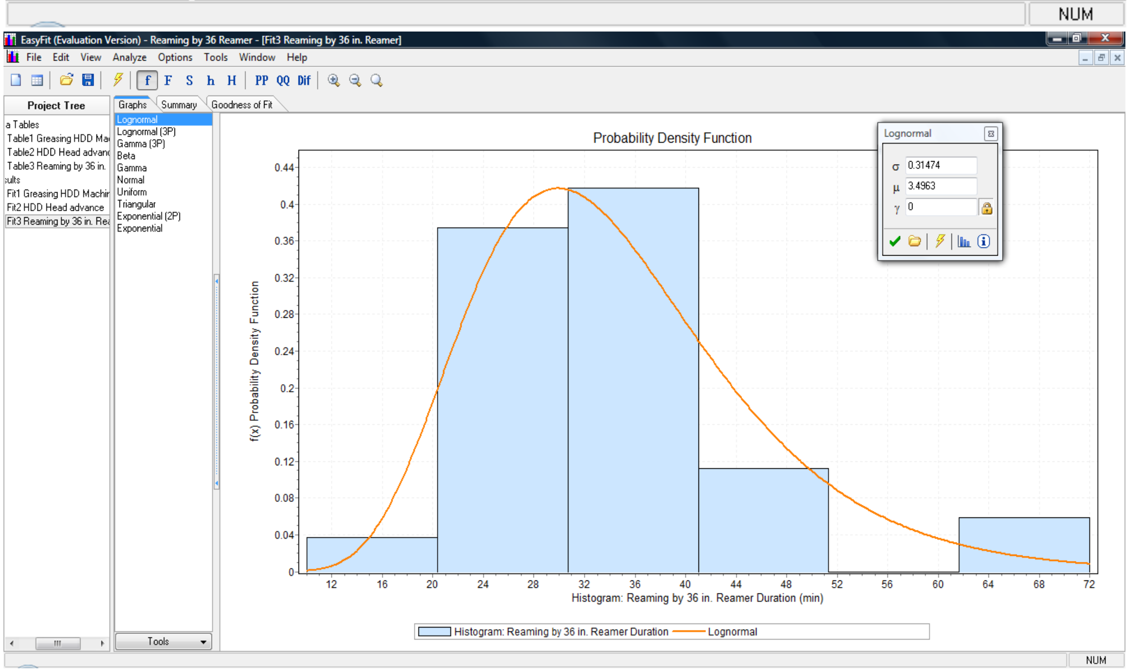


E-3

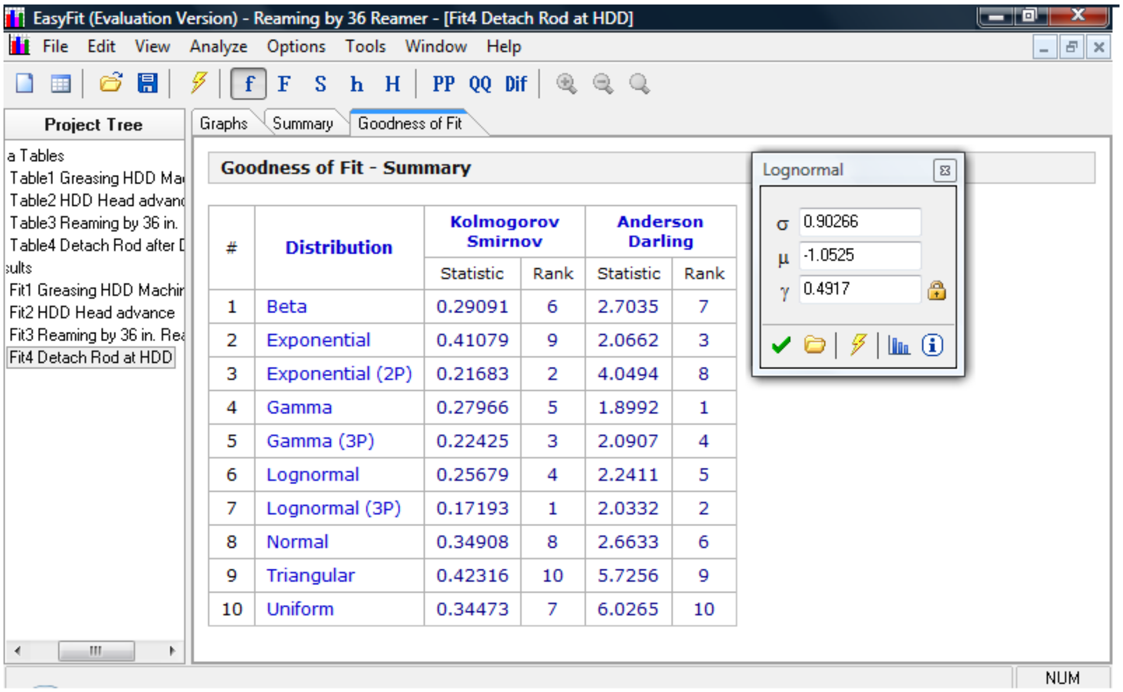
HDD MACHINE DURATION – PREREAMING USING 36 IN. REAMER



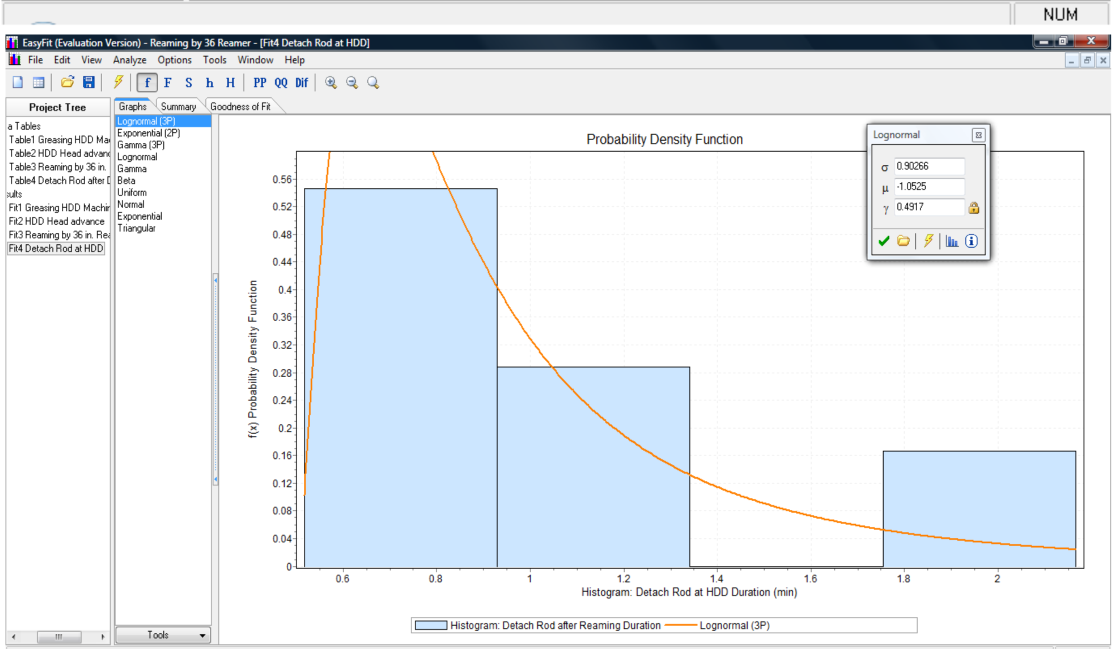
#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Beta	0.11623	4	6.5778	5
2	Exponential	0.41959	10	5.0884	2
3	Exponential (2P)	0.3524	9	3.2009	1
4	Gamma	0.12865	5	5.3321	3
5	Gamma (3P)	0.11547	3	6.6	6
6	Lognormal	0.10575	1	6.91	8
7	Lognormal (3P)	0.1063	2	6.7764	7
8	Normal	0.16378	6	5.7338	4
9	Triangular	0.25095	8	8.3832	9
10	Uniform	0.20548	7	18.833	10



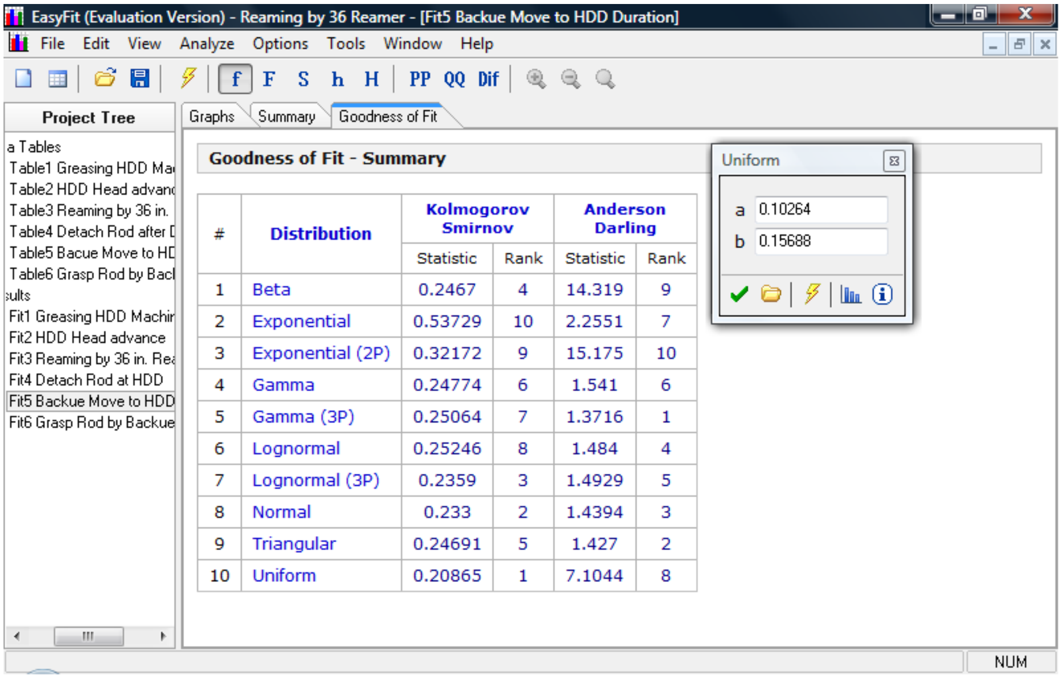
HDD MACHINE DURATION – DETACH DRILLING ROD BY HDD MACHINE



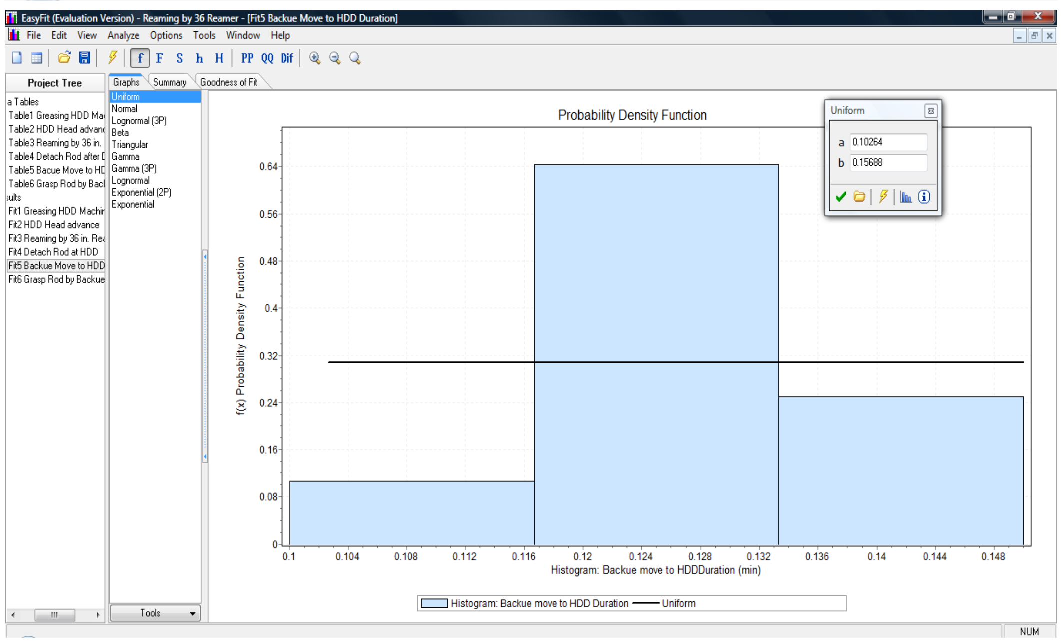
#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Beta	0.29091	6	2.7035	7
2	Exponential	0.41079	9	2.0662	3
3	Exponential (2P)	0.21683	2	4.0494	8
4	Gamma	0.27966	5	1.8992	1
5	Gamma (3P)	0.22425	3	2.0907	4
6	Lognormal	0.25679	4	2.2411	5
7	Lognormal (3P)	0.17193	1	2.0332	2
8	Normal	0.34908	8	2.6633	6
9	Triangular	0.42316	10	5.7256	9
10	Uniform	0.34473	7	6.0265	10



HDD MACHINE DURATION – BACKUE ADVANCING TO TRAILER DECK

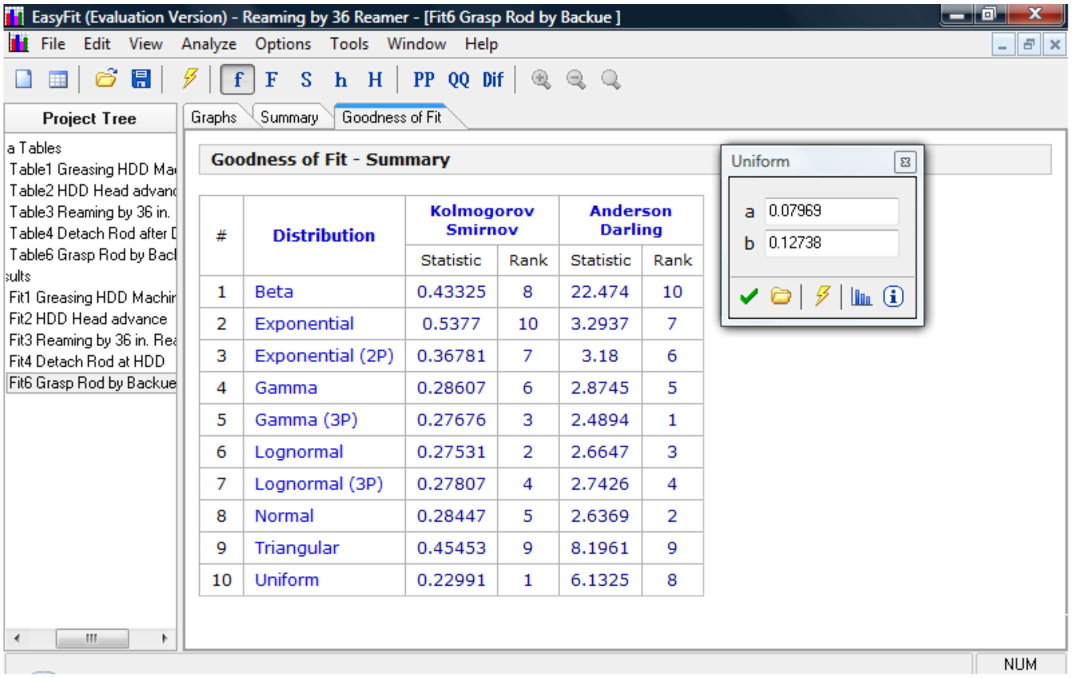


#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Beta	0.2467	4	14.319	9
2	Exponential	0.53729	10	2.2551	7
3	Exponential (2P)	0.32172	9	15.175	10
4	Gamma	0.24774	6	1.541	6
5	Gamma (3P)	0.25064	7	1.3716	1
6	Lognormal	0.25246	8	1.484	4
7	Lognormal (3P)	0.2359	3	1.4929	5
8	Normal	0.233	2	1.4394	3
9	Triangular	0.24691	5	1.427	2
10	Uniform	0.20865	1	7.1044	8



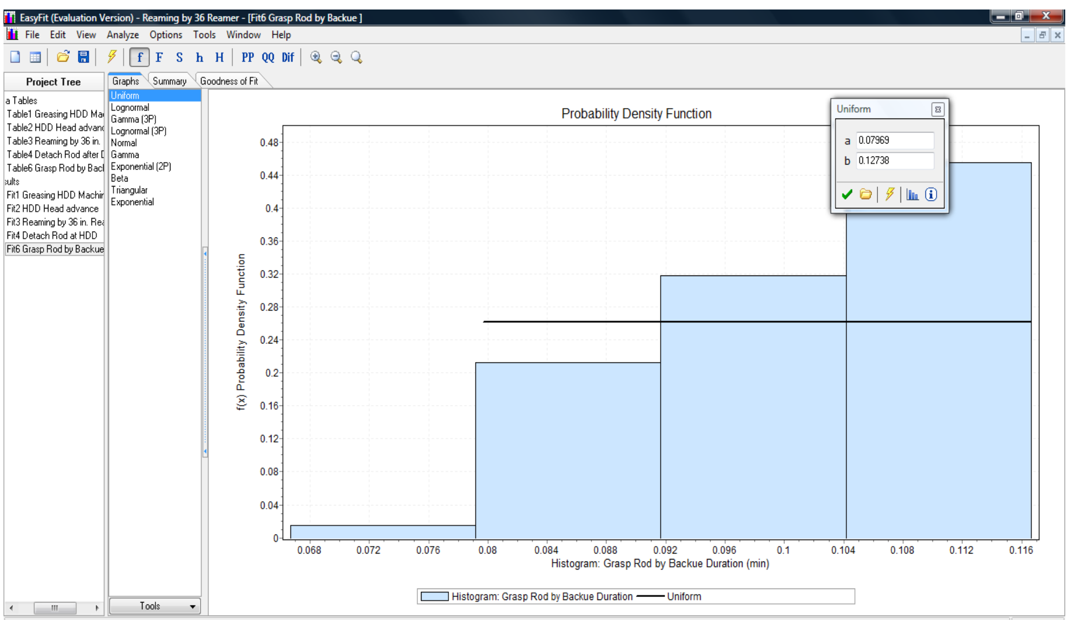
E-5

HDD MACHINE DURATION – ATTACH DRILLING ROD BY BACKUE



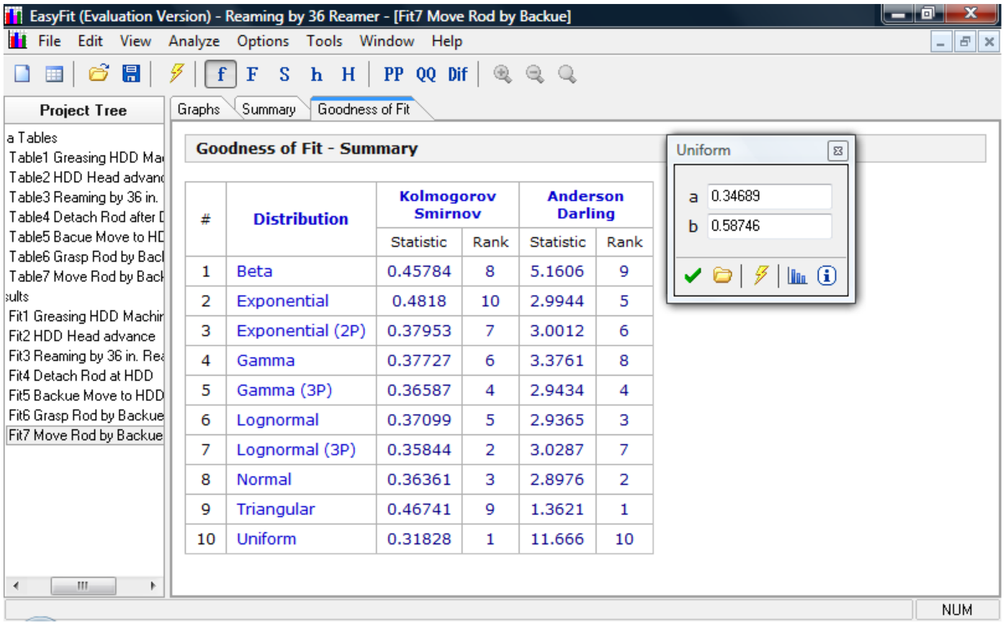
Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov Statistic	Kolmogorov Smirnov Rank	Anderson Darling Statistic	Anderson Darling Rank
1	Beta	0.43325	8	22.474	10
2	Exponential	0.5377	10	3.2937	7
3	Exponential (2P)	0.36781	7	3.18	6
4	Gamma	0.28607	6	2.8745	5
5	Gamma (3P)	0.27676	3	2.4894	1
6	Lognormal	0.27531	2	2.6647	3
7	Lognormal (3P)	0.27807	4	2.7426	4
8	Normal	0.28447	5	2.6369	2
9	Triangular	0.45453	9	8.1961	9
10	Uniform	0.22991	1	6.1325	8

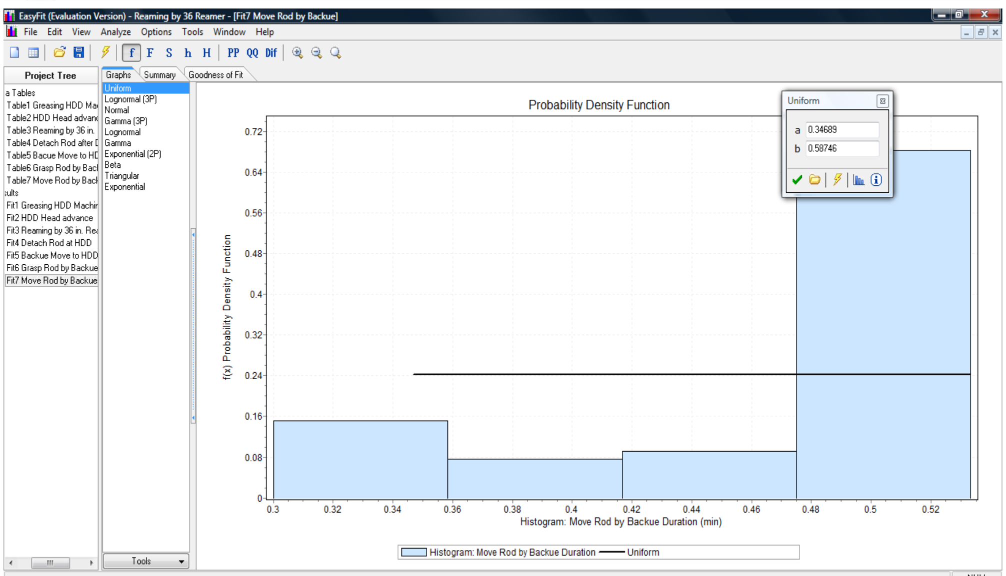


E-6

HDD MACHINE DURATION – MOVING DRILLING ROD TOWARD MACHINE



#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Beta	0.45784	8	5.1606	9
2	Exponential	0.4818	10	2.9944	5
3	Exponential (2P)	0.37953	7	3.0012	6
4	Gamma	0.37727	6	3.3761	8
5	Gamma (3P)	0.36587	4	2.9434	4
6	Lognormal	0.37099	5	2.9365	3
7	Lognormal (3P)	0.35844	2	3.0287	7
8	Normal	0.36361	3	2.8976	2
9	Triangular	0.46741	9	1.3621	1
10	Uniform	0.31828	1	11.666	10



E-7

HDD MACHINE DURATION – MICROCYCLONE PROGRAM SIMULATION

NAME REAMING 36 in. LENGTH 1040 CYCLES 31

NETWORK INPUT

1 QUE 'Rod WT'

2 QUE 'HDD MACH WT'

3 QUE 'BACKUE WT'

4 COM 'GREASE HDD HEAD' SET 4 PRE 1 2 3 FOL 6

6 NOR 'ADVANCE HDD HEAD AND CONNECT' SET 6 PRE 4 FOL 7

7 NOR 'REAMING' SET 7 PRE 6 FOL 8

8 NOR 'DETACH ROD' SET 8 PRE 3 7 FOL 9

9 NOR 'BACKUE ADVANCE TO HDD' SET 9 PRE 3 8 FOL 16 17

16 QUE 'HDD WT'

17 QUE 'BACKUE WT'

10 COM 'GRASP ROD BY BACKUE' SET 10 PRE 16 17 FOL 11

11 NOR 'MOVE ROD BY BACKUE' SET 11 PRE 10 FOL 1 2 3 12

12 FUN COU FOL 3 QUA 31

DURATION INPUT

SET 4 BETA 0.1 0.4002 0.0927 0.32131

SET 6 BETA 0.5 1.333 0.40384 0.75547

SET 7 NOR 34.704 143.73612

SET 8 BETA 0.51667 2.1667 0.38428 0.72756

SET 9 UNI 0.10264 0.15688

SET 10 UNI 0.07969 0.12738

SET 11 UNI 0.34689 0.58746

RESOURCE INPUT

1 'HOE' AT 1 FIX 60

1 'HDD' AT 2 FIX 25

1 'FOREMAN' AT 3 FIX 30

HDD MACHINE DURATION – SENSITIVITY ANALYSIS

cyclone ecn purdue web... | Purdue CEM Web Cyclon...

cyclone.ecn.purdue.edu:8080/WebCYCLONE/Cyclone.jsp

Results:

REAMING 36 in.		
PRODUCTIVITY INFORMATION		
Total Sim. Time Unit	Cycle No.	Productivity (per time unit)
1035.3	25	0.7485928412541027

REAMING 36 in.						
CYCLONE ACTIVE ELEMENTS STATISTICS INFORMATION						
Activity Type	No.	Name	Access Counts	Average Duration	Maximum Duration	Minimum Duration
COMBI	4	GREASE HDD HEAD	26	0.2	0.4	0.1
NORMAL	6	ADVANCE HDD HEAD AND CONNECT	26	0.8	1.3	0.5
NORMAL	7	REAMING	25	38.9	63.8	10.6
NORMAL	8	DETACH ROD	25	1.1	2.2	0.5
NORMAL	9	BACKUE ADVANCE TO HDD	25	0.1	0.2	0.1
COMBI	10	GRASP ROD BY BACKUE	25	0.1	0.1	0.1
NORMAL	11	MOVE ROD BY BACKUE	25	0.4	0.6	0.3

REAMING 36 in.									
CYCLONE PASSIVE ELEMENTS STATISTICS INFORMATION									
Type	No.	Name	Average Units Idle	Max. Idle Units	Times not empty	% Idle	Total Sim Time	Average Wt Time	Units at end

APPENDIX F

HDD PRODUCTIVITY ANALYSIS – PILOT PROJECT

F-1

HDD DATA FOR WHOLE BORE-PATH IN PILOT PROJECT

36' Reaming Table whole path.sav [DataSet1] - SPSS Data Editor

File Edit View Data Transform Analyze Graphs Utilities Add-ons Window Help

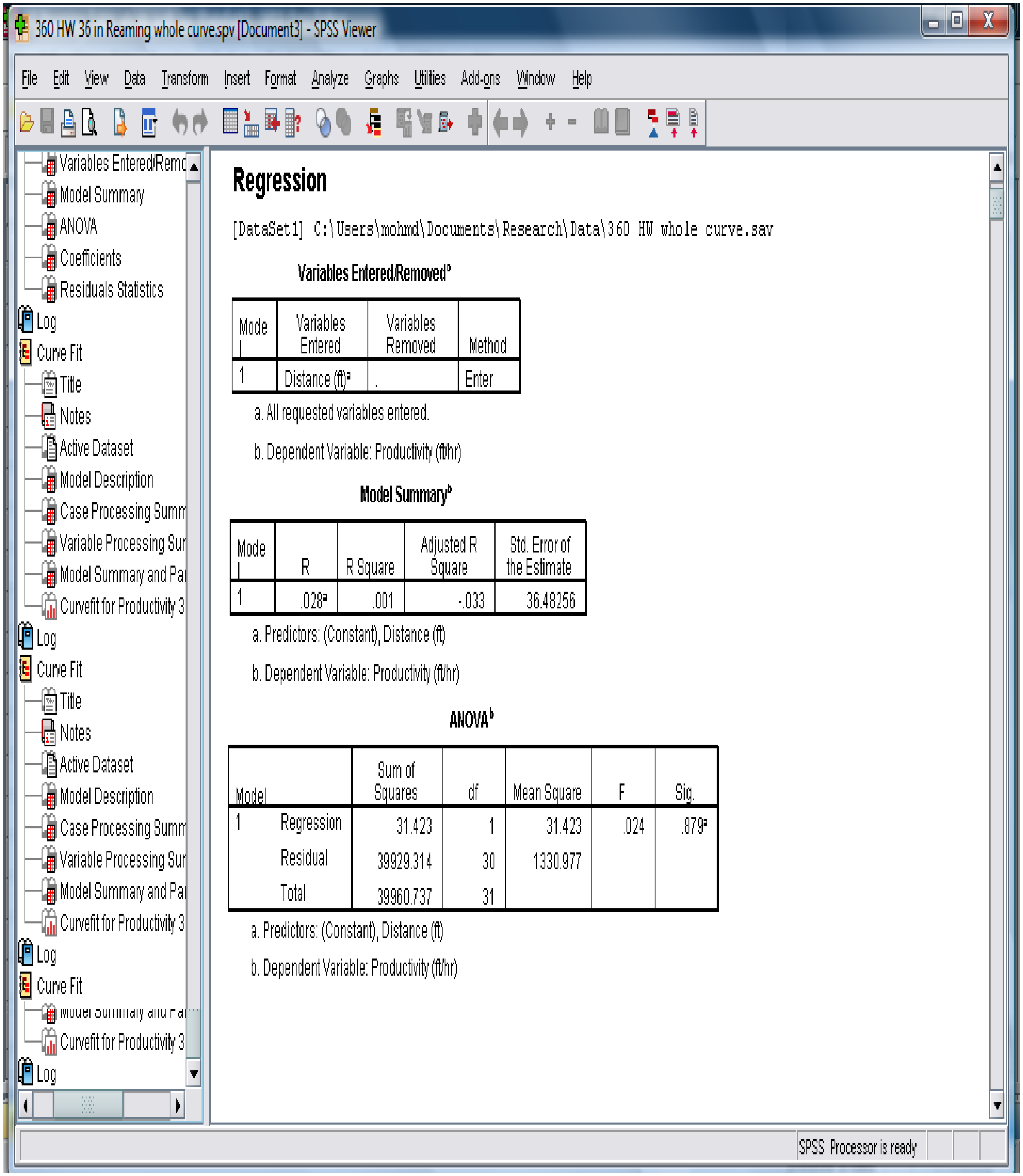
1 : VAR00001 1 Visible: 9 of 9 Variables

	VAR00001	VAR00002	PRE_1	RES_1	ZRE_1	LMCI_1	UMCI_1	LICI_1	UICI_1	var	var	var
1	1.00	150.00	72.69951	77.30049	2.11981	47.86628	97.53275	-5.80486	151.20389			
2	30.00	150.00	72.83257	77.16743	2.11616	49.00923	96.65591	-5.35821	151.02335			
3	60.00	90.00	72.97021	17.02979	0.46701	50.17207	95.76836	-4.91433	150.85476			
4	90.00	64.29	73.10786	-8.82215	-0.24193	51.31229	94.90343	-4.48914	150.70486			
5	120.00	75.00	73.24550	1.75450	0.04811	52.42662	94.06439	-4.08284	150.57385			
6	150.00	81.82	73.38315	8.43503	0.23131	53.51125	93.25505	-3.69564	150.46194			
7	180.00	52.94	73.52079	-20.57962	-0.56435	54.56172	92.47987	-3.32772	150.36930			
8	210.00	46.15	73.65844	-27.50459	-0.75426	55.57286	91.74402	-2.97925	150.29613			
9	240.00	62.07	73.79608	-11.72712	-0.32159	56.53870	91.05347	-2.65040	150.24257			
10	270.00	64.29	73.93373	-9.64802	-0.26458	57.45240	90.41506	-2.34131	150.20877			
11	300.00	60.00	74.07138	-14.07138	-0.38588	58.30627	89.83648	-2.05211	150.19486			
12	330.00	75.00	74.20902	0.79098	0.02169	59.09180	89.32624	-1.78294	150.20098			
13	360.00	75.00	74.34667	0.65333	0.01792	59.79985	88.89348	-1.53388	150.22721			
14	390.00	64.29	74.48431	-10.19860	-0.27968	60.42099	88.54763	-1.30503	150.27365			
15	420.00	60.00	74.62196	-14.62196	-0.40098	60.94601	88.29790	-1.09646	150.34037			
16	450.00	38.30	74.75960	-36.46173	-0.99989	61.36655	88.15265	-0.90823	150.42743			
17	480.00	25.00	74.89725	-49.89725	-1.36833	61.67592	88.11857	-0.74038	150.53487			
18	610.00	43.90	75.49371	-31.59127	-0.86633	61.68510	89.30232	-0.24878	151.23620			
19	640.00	51.43	75.63135	-24.20278	-0.66371	61.39849	89.86422	-0.18963	151.45234			
20	670.00	81.82	75.76900	6.04918	0.16589	61.01912	90.51887	-0.15074	151.68873			
21	700.00	75.00	75.90664	-0.90664	-0.02486	60.55638	91.25691	-0.13202	151.94530			
22	730.00	51.43	76.04429	-24.61572	-0.67504	60.01961	92.06896	-0.13338	152.22196			
23	760.00	48.65	76.18193	-27.53328	-0.75504	59.41777	92.94610	-0.15472	152.51858			
24	790.00	42.86	76.31958	-33.46244	-0.91764	58.75906	93.88010	-0.19590	152.83506			
25	810.00	58.06	76.41134	-18.34683	-0.50312	58.29201	94.53068	-0.23432	153.05700			

Data View Variable View

F-2

RESULTS OF MODELING HDD PRODUCTIVITY ON LENGTH OF WHOLE BORE-PATH



Regression

[DataSet1] C:\Users\mohmd\Documents\Research\Data\360 HW whole curve.sav

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Distance (ft)[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Productivity (ft/hr)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.028[a]	.001	-.033	36.48256

a. Predictors: (Constant), Distance (ft)

b. Dependent Variable: Productivity (ft/hr)

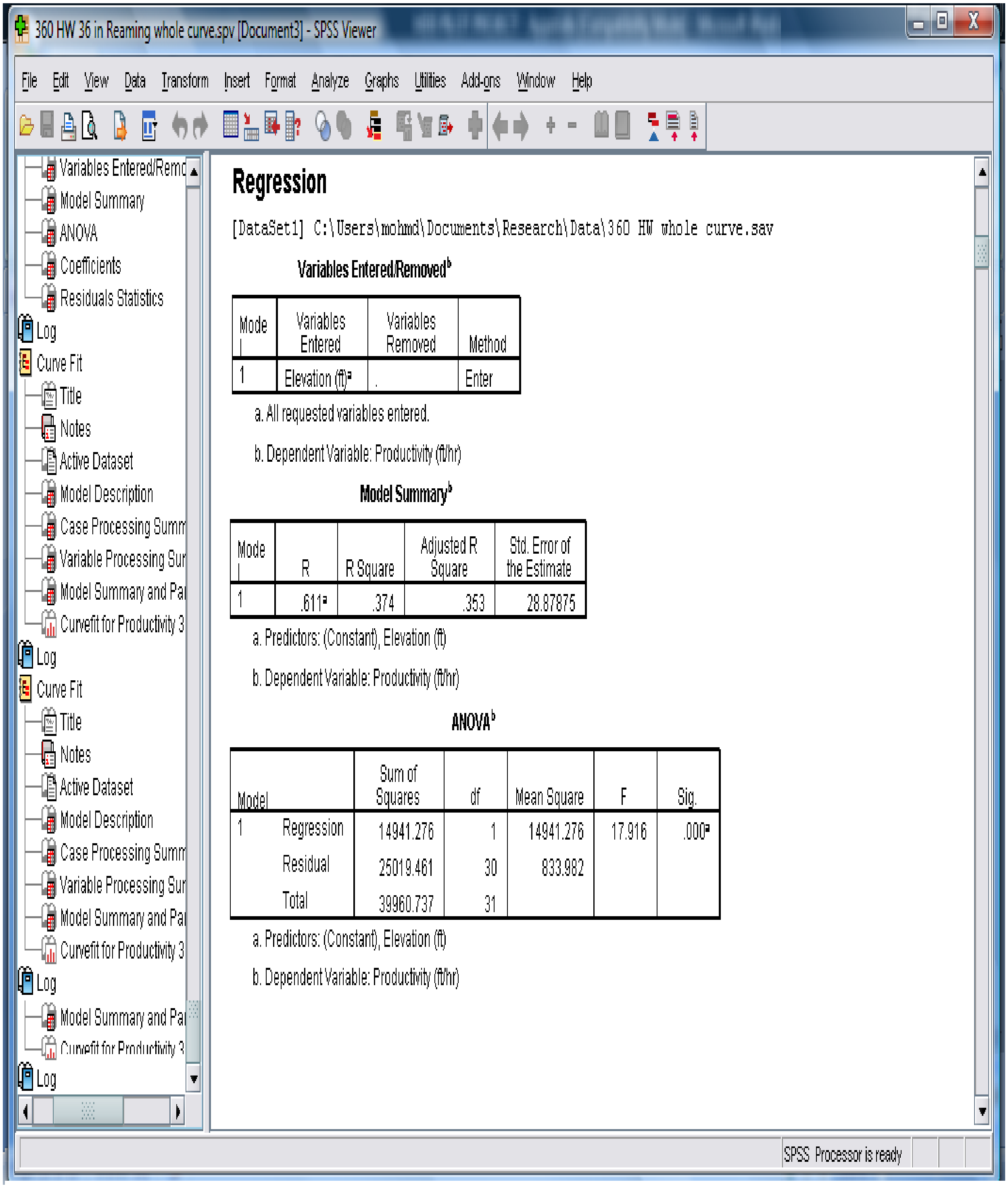
ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	31.423	1	31.423	.024	.879[a]
	Residual	39929.314	30	1330.977		
	Total	39960.737	31			

a. Predictors: (Constant), Distance (ft)

b. Dependent Variable: Productivity (ft/hr)

RESULTS OF MODELING HDD PRODUCTIVITY ON DEPTH OF WHOLE BORE-PATH



Regression

[DataSet1] C:\Users\mohmd\Documents\Research\Data\360 HW whole curve.sav

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Elevation (ft)[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Productivity (ft/hr)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.611[a]	.374	.353	28.87875

a. Predictors: (Constant), Elevation (ft)

b. Dependent Variable: Productivity (ft/hr)

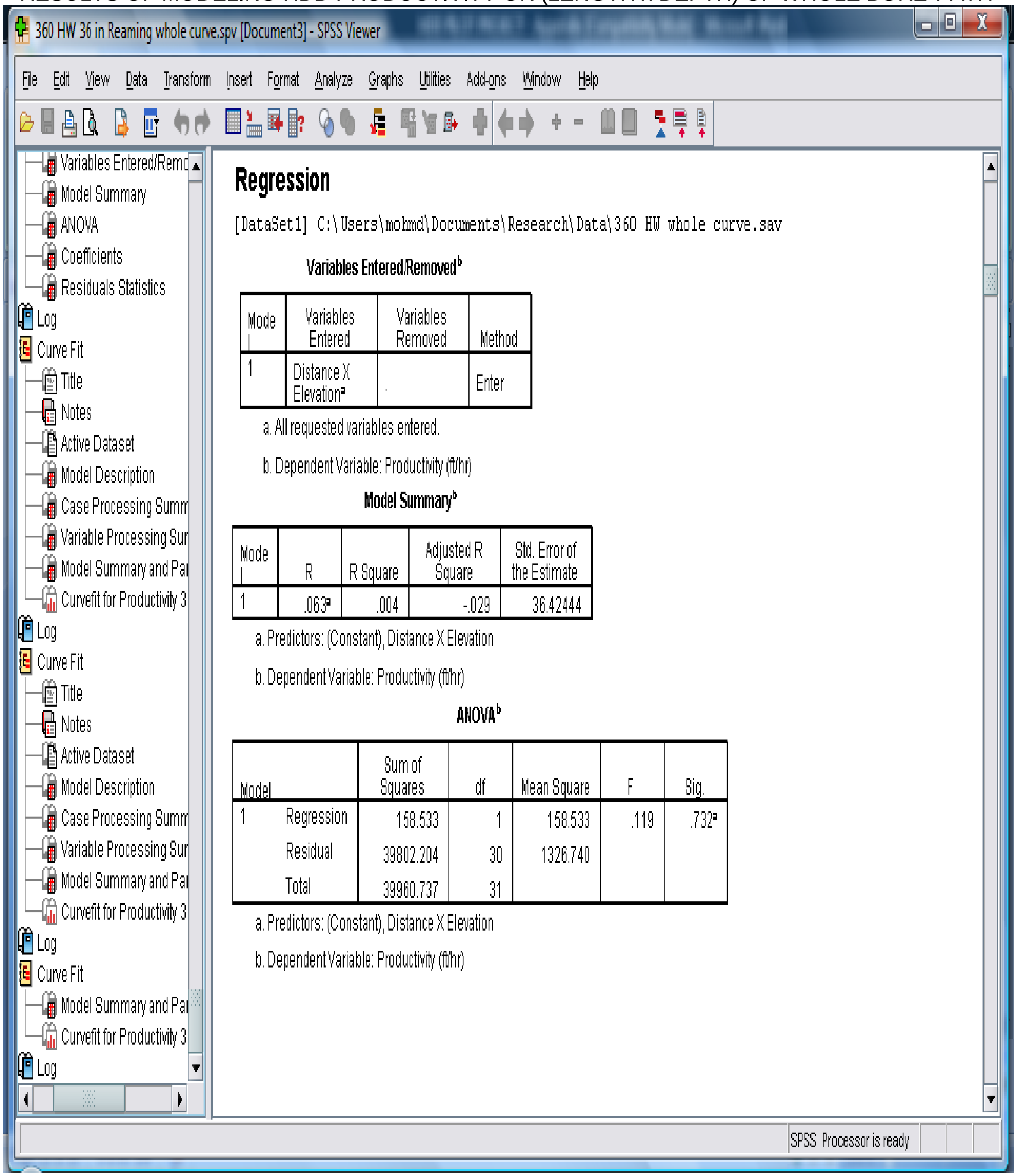
ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	14941.276	1	14941.276	17.916	.000[a]
	Residual	25019.461	30	833.982		
	Total	39960.737	31			

a. Predictors: (Constant), Elevation (ft)

b. Dependent Variable: Productivity (ft/hr)

RESULTS OF MODELING HDD PRODUCTIVITY ON (LENGTH x DEPTH) OF WHOLE BORE-PATH



Regression

[DataSet1] C:\Users\mohmd\Documents\Research\Data\360 HW whole curve.sav

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Distance X Elevation[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Productivity (ft/hr)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.063[a]	.004	-.029	36.42444

a. Predictors: (Constant), Distance X Elevation

b. Dependent Variable: Productivity (ft/hr)

ANOVA[b]

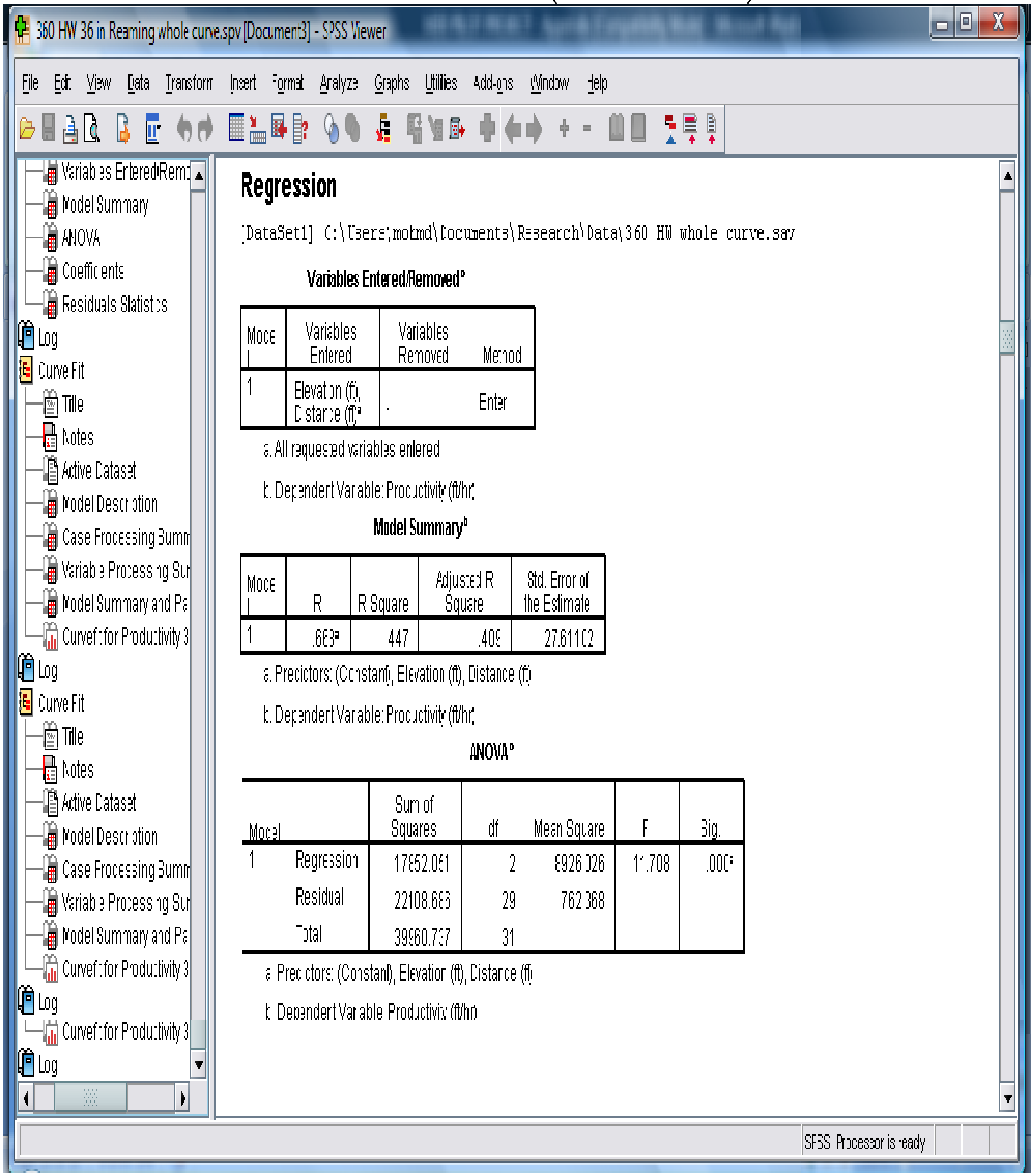
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	158.533	1	158.533	.119	.732[a]
	Residual	39802.204	30	1326.740		
	Total	39960.737	31			

a. Predictors: (Constant), Distance X Elevation

b. Dependent Variable: Productivity (ft/hr)

F-5

RESULTS OF MODELING HDD PRODUCTIVITY ON (LENGTH + DEPTH) OF WHOLE BORE-PATH



Regression

[DataSet1] C:\Users\mohmd\Documents\Research\Data\360 HW whole curve.sav

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Elevation (ft), Distance (ft)[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Productivity (ft/hr)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.668[a]	.447	.409	27.61102

a. Predictors: (Constant), Elevation (ft), Distance (ft)

b. Dependent Variable: Productivity (ft/hr)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	17852.051	2	8926.026	11.708	.000[a]
	Residual	22108.686	29	762.368		
	Total	39960.737	31			

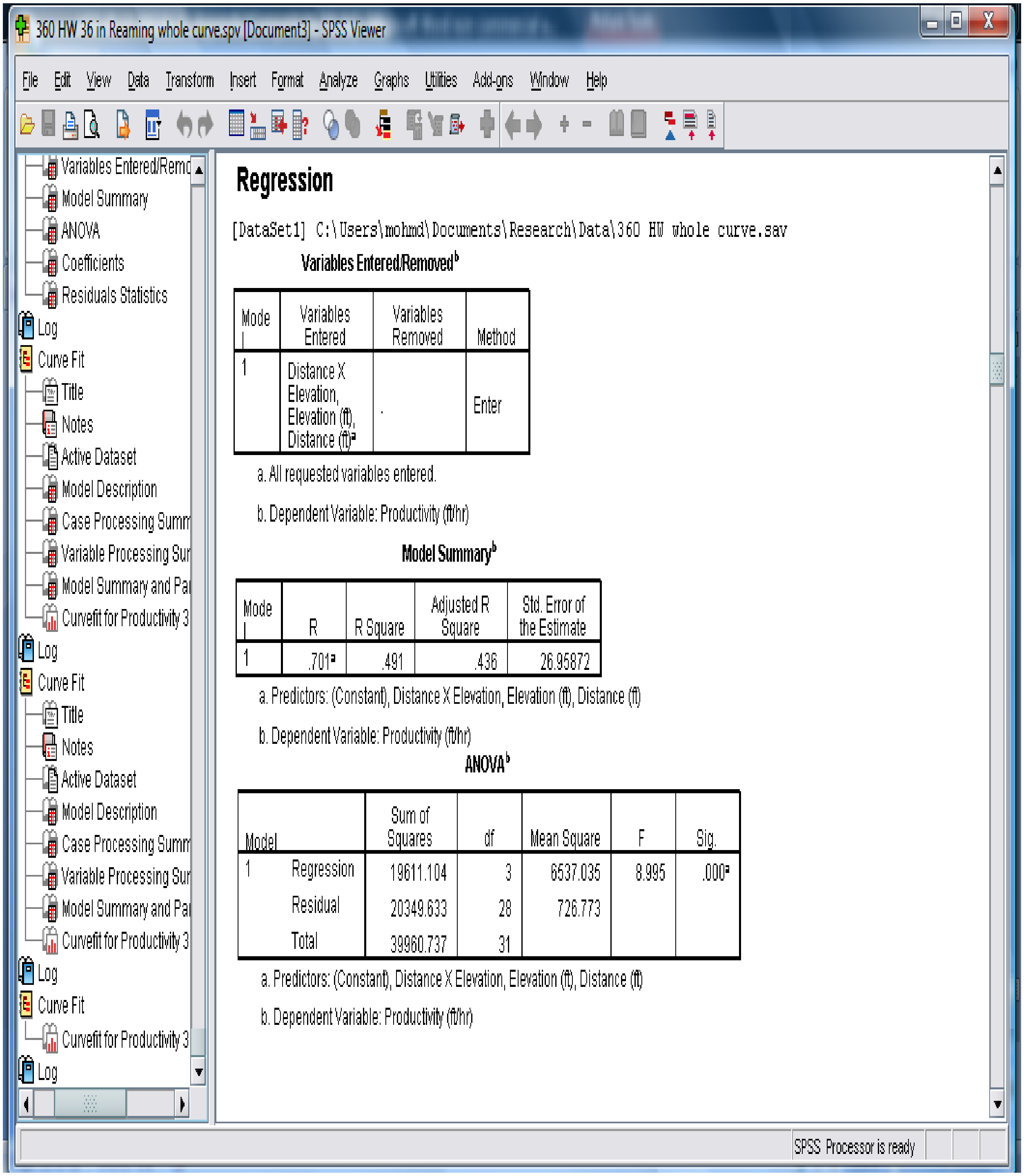
a. Predictors: (Constant), Elevation (ft), Distance (ft)

b. Dependent Variable: Productivity (ft/hr)

F-6

RESULTS OF MODELING HDD PRODUCTIVITY ON (LENGTH + DEPTH + LENGTH x DEPTH)

WHOLE BORE-PATH



Regression

[DataSet1] C:\Users\mohmd\Documents\Research\Data\360 HW whole curve.sav

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Distance X Elevation, Elevation (ft), Distance (ft)[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Productivity (ft/hr)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.701[a]	.491	.436	26.95872

a. Predictors: (Constant), Distance X Elevation, Elevation (ft), Distance (ft)

b. Dependent Variable: Productivity (ft/hr)

ANOVA[b]

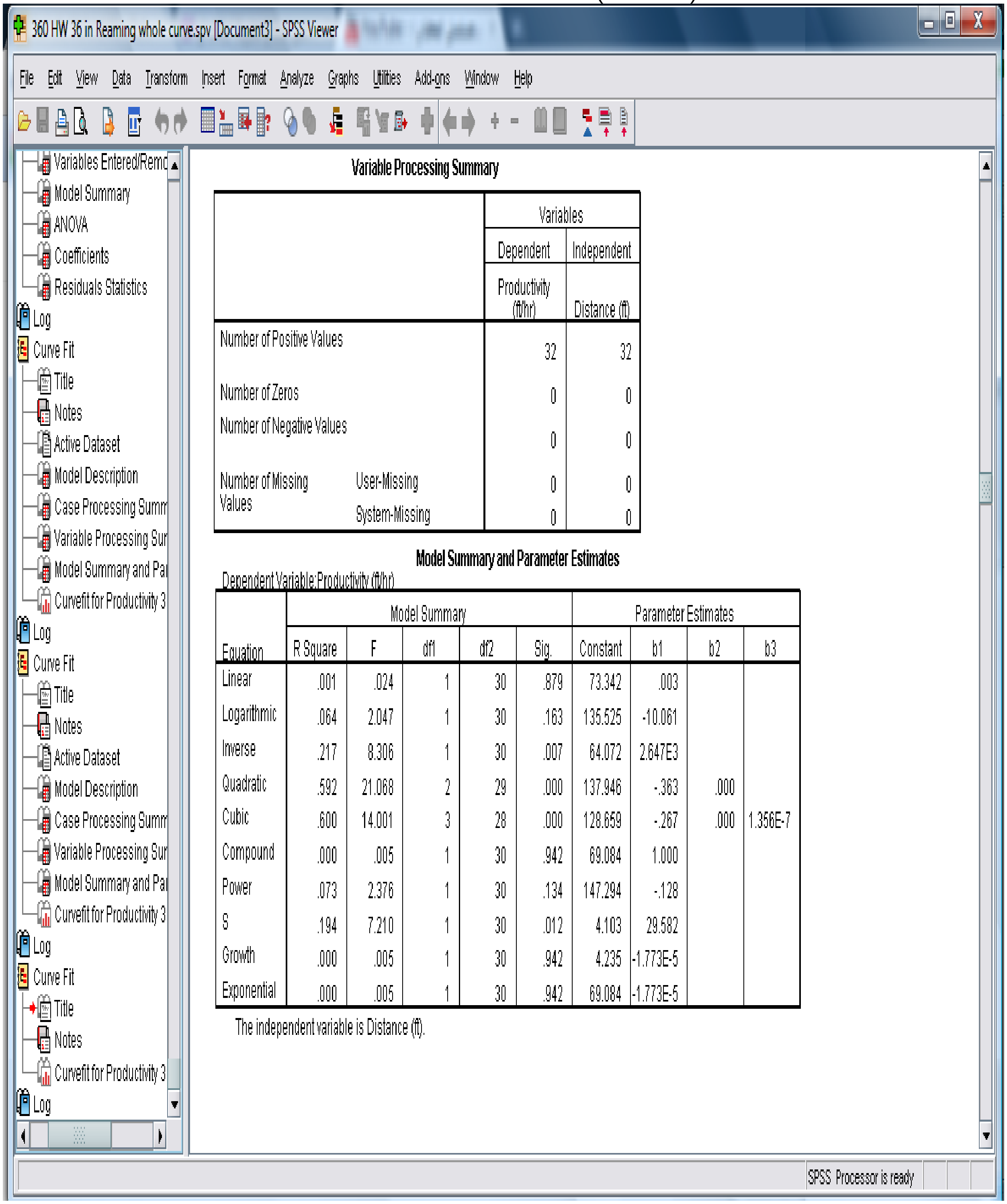
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	19611.104	3	6537.035	8.995	.000[a]
	Residual	20349.633	28	726.773		
	Total	39960.737	31			

a. Predictors: (Constant), Distance X Elevation, Elevation (ft), Distance (ft)

b. Dependent Variable: Productivity (ft/hr)

F-7

NONLINEAR MODELING OF HDD PRODUCTIVITY ON (LENGTH) OF WHOLE BORE-PATH



Variable Processing Summary

		Variables	
		Dependent	Independent
		Productivity (ft/hr)	Distance (ft)
Number of Positive Values		32	32
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

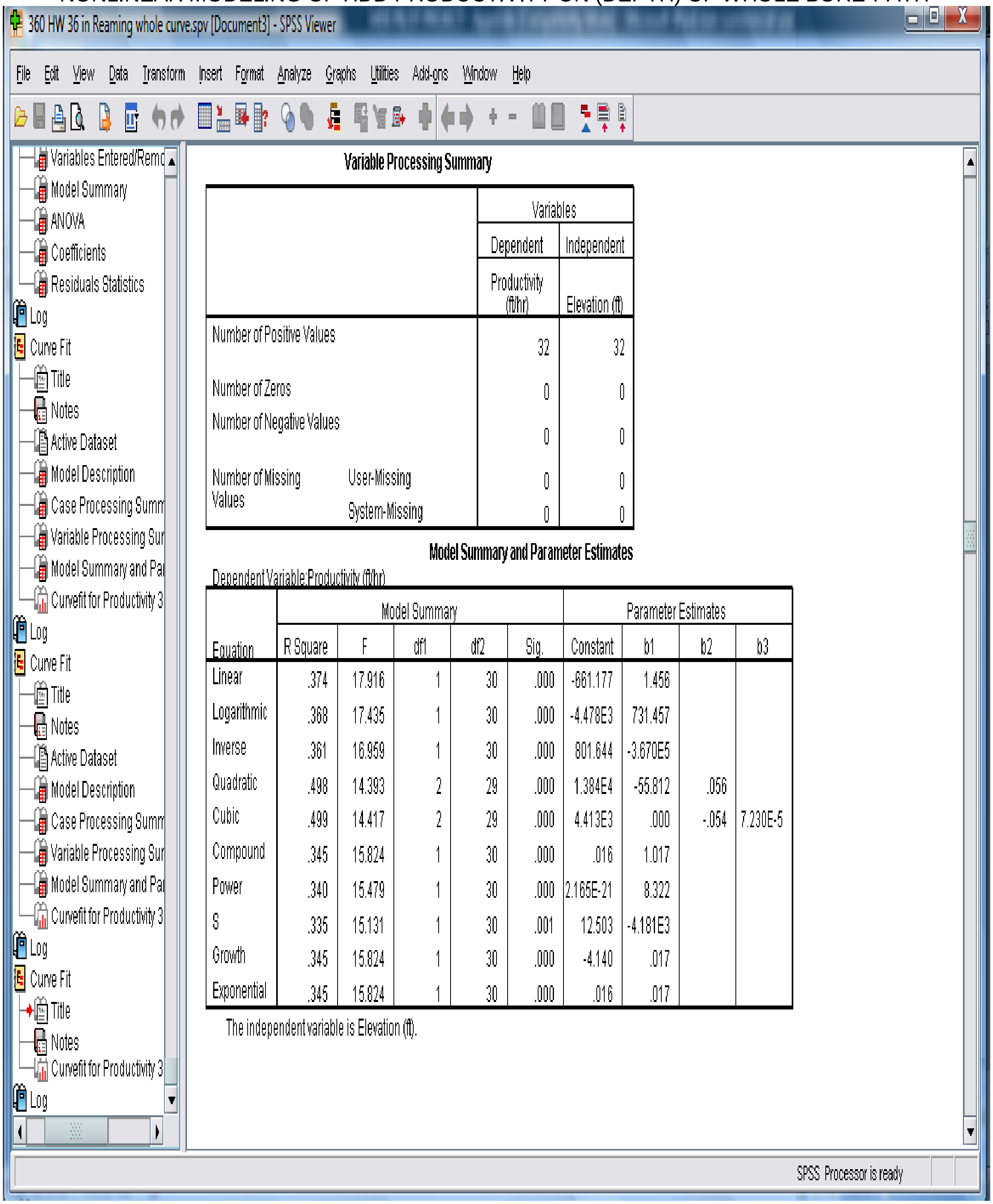
Model Summary and Parameter Estimates

Dependent Variable:Productivity (ft/hr)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.001	.024	1	30	.879	73.342	.003		
Logarithmic	.064	2.047	1	30	.163	135.525	-10.061		
Inverse	.217	8.306	1	30	.007	64.072	2.647E3		
Quadratic	.592	21.068	2	29	.000	137.946	-.363	.000	
Cubic	.600	14.001	3	28	.000	128.659	-.267	.000	1.356E-7
Compound	.000	.005	1	30	.942	69.084	1.000		
Power	.073	2.376	1	30	.134	147.294	-.128		
S	.194	7.210	1	30	.012	4.103	29.582		
Growth	.000	.005	1	30	.942	4.235	-1.773E-5		
Exponential	.000	.005	1	30	.942	69.084	-1.773E-5		

The independent variable is Distance (ft).

NONLINEAR MODELING OF HDD PRODUCTIVITY ON (DEPTH) OF WHOLE BORE-PATH



Variable Processing Summary

		Variables	
		Dependent	Independent
		Productivity (ft/hr)	Elevation (ft)
Number of Positive Values		32	32
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

Model Summary and Parameter Estimates

Dependent Variable:Productivity (ft/hr)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.374	17.916	1	30	.000	-661.177	1.456		
Logarithmic	.368	17.435	1	30	.000	-4.478E3	731.457		
Inverse	.361	16.959	1	30	.000	801.644	-3.670E5		
Quadratic	.498	14.393	2	29	.000	1.384E4	-55.812	.056	
Cubic	.499	14.417	2	29	.000	4.413E3	.000	-.054	7.230E-5
Compound	.345	15.824	1	30	.000	.016	1.017		
Power	.340	15.479	1	30	.000	2.165E-21	8.322		
S	.335	15.131	1	30	.001	12.503	-4.181E3		
Growth	.345	15.824	1	30	.000	-4.140	.017		
Exponential	.345	15.824	1	30	.000	.016	.017		

The independent variable is Elevation (ft).

APPENDIX G

HDD PRODUCTIVITY SEPARATE MODELS – PILOT PROJECT

G-1

HDD PRODUCTIVITY DATA AMONG SOIL TYPES PROFILE – PILOT PROJECT

*NEW NEW HDD PRODUCTIVITY 360 HW DATA.sav [DataSet4] - SPSS Data Editor

File Edit View Data Transform Analyze Graphs Utilities Add-ons Window Help

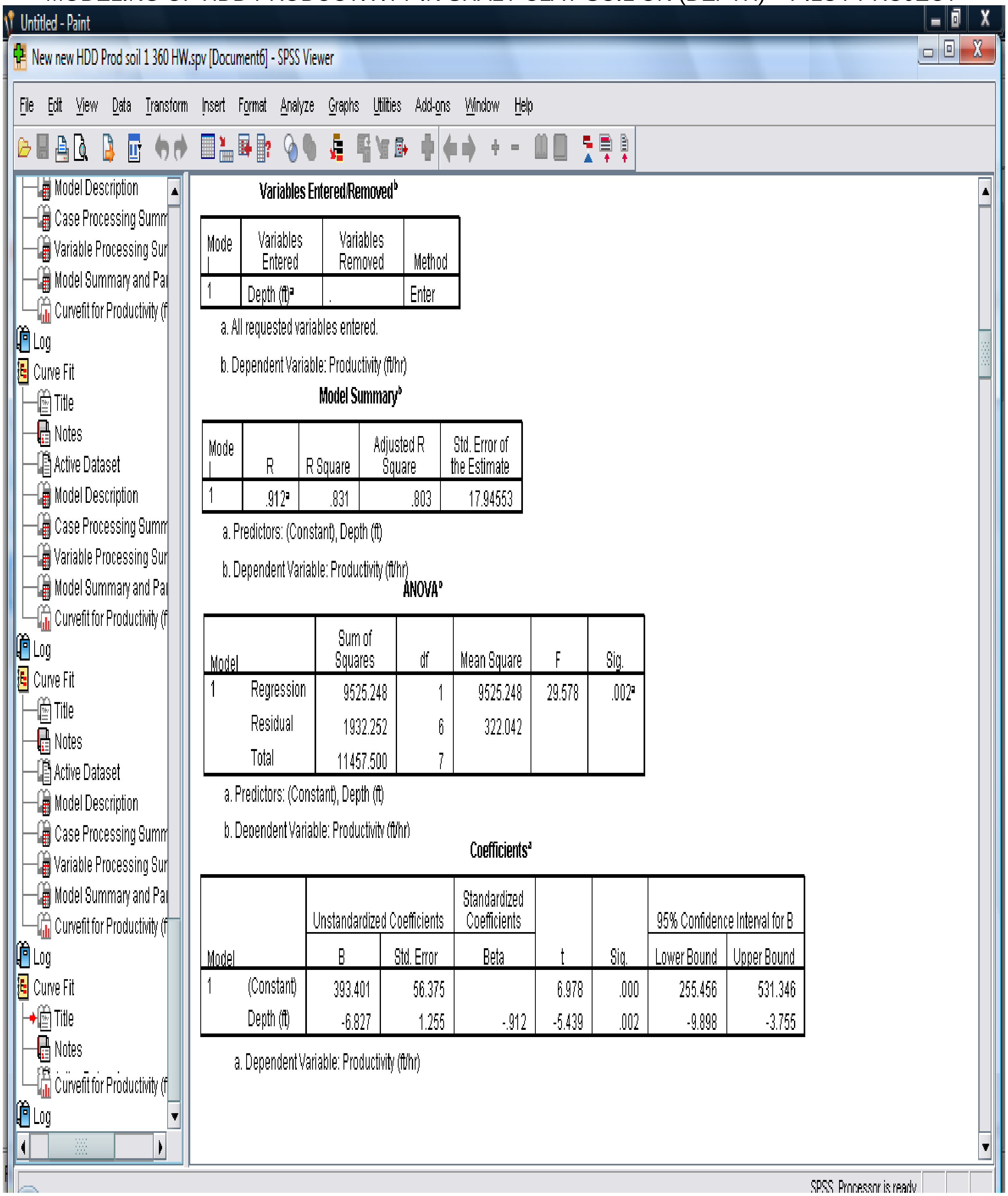
5 : VAR00016

Visible: 845 of 845 Variables

	VAR00001	VAR00002	VAR00003	VAR00004	VAR00005	VAR00006	VAR00007	VAR00008	VAR00009	VAR00010	VAR00011	VAR00012	VAR00013	VAR00014	VAR00015	VAR00016
1	60.00	36.00	2160.00	150.00	30.00	53.50	1605.00	75.00	30.00	45.50	1365.00	82.00	30.00	19.00	570.00	106.00
2	90.00	39.00	3510.00	150.00	60.00	53.50	3210.00	75.00	60.00	43.50	2610.00	75.00	60.00	14.00	840.00	67.00
3	120.00	42.00	5040.00	90.00	90.00	53.00	4770.00	64.00	90.00	40.50	3645.00	51.00	90.00	9.00	810.00	69.00
4	150.00	44.00	6600.00	64.00	120.00	52.50	6300.00	60.00	120.00	37.50	4500.00	49.00	120.00	7.00	840.00	150.00
5	180.00	46.50	7560.00	75.00	150.00	51.50	7725.00	38.00	150.00	34.50	5175.00	43.00	.	.	.	.
6	210.00	48.00	9240.00	82.00	180.00	50.50	9090.00	25.00	180.00	31.00	5580.00	58.00	.	.	.	.
7	240.00	50.00	11160.00	53.00	.	.	.	.	.	.	.	.	.	.	.	.
8	270.00	51.50	12960.00	46.00	.	.	.	.	.	.	.	.	.	.	.	.
9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Data View Variable View

MODELING OF HDD PRODUCTIVITY IN SHALY CLAY SOIL ON (DEPTH) – PILOT PROJECT



Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Depth (ft)[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Productivity (ft/hr)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.912[a]	.831	.803	17.94553

a. Predictors: (Constant), Depth (ft)

b. Dependent Variable: Productivity (ft/hr)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	9525.248	1	9525.248	29.578	.002[a]
	Residual	1932.252	6	322.042		
	Total	11457.500	7			

a. Predictors: (Constant), Depth (ft)

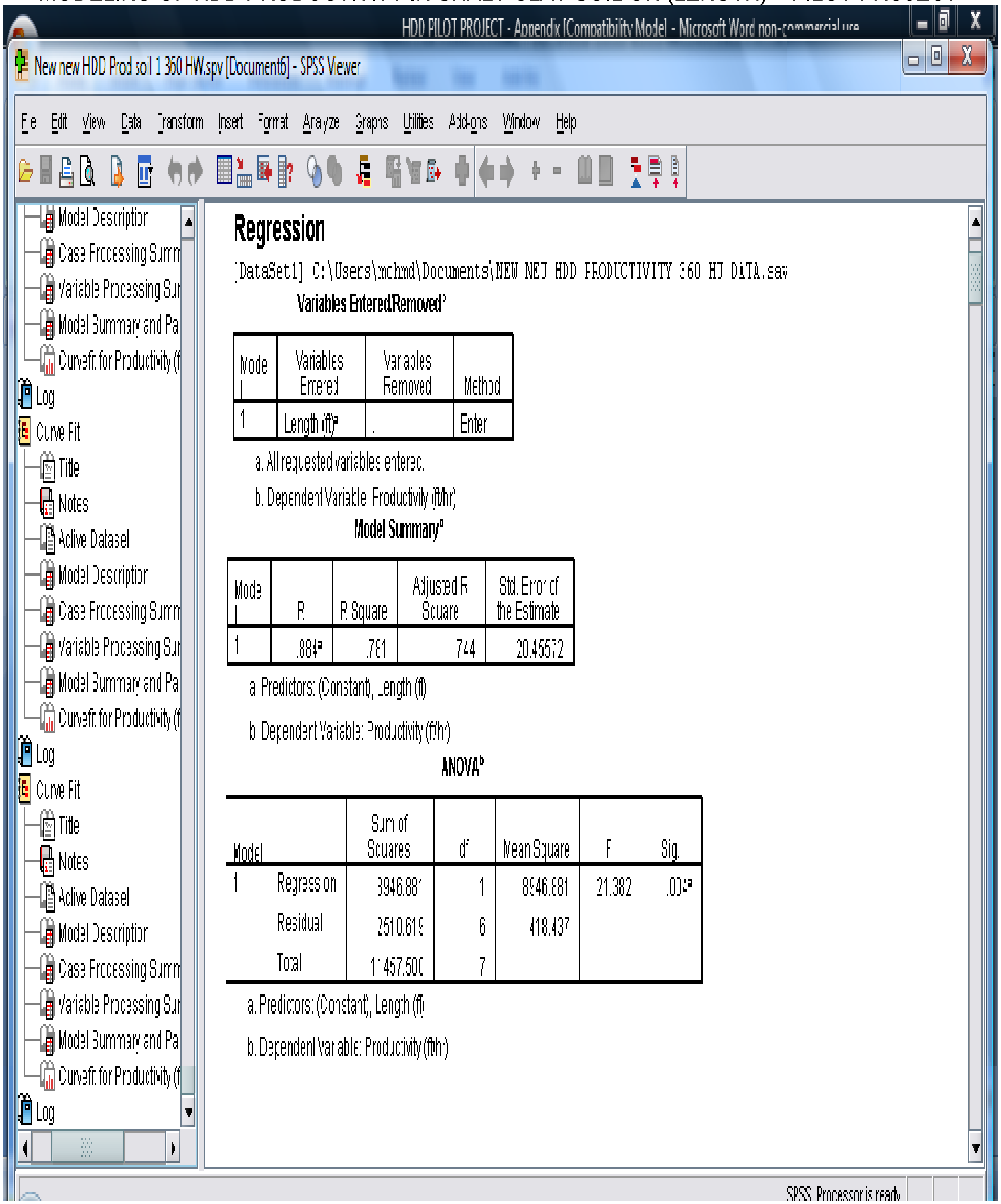
b. Dependent Variable: Productivity (ft/hr)

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	393.401	56.375		6.978	.000	255.456	531.346
	Depth (ft)	-6.827	1.255	-.912	-5.439	.002	-9.898	-3.755

a. Dependent Variable: Productivity (ft/hr)

MODELING OF HDD PRODUCTIVITY IN SHALY CLAY SOIL ON (LENGTH) – PILOT PROJECT



Regression

[DataSet1] C:\Users\mohmd\Documents\NEW NEW HDD PRODUCTIVITY 360 HW DATA.sav

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Length (ft)[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Productivity (ft/hr)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.884[a]	.781	.744	20.45572

a. Predictors: (Constant), Length (ft)

b. Dependent Variable: Productivity (ft/hr)

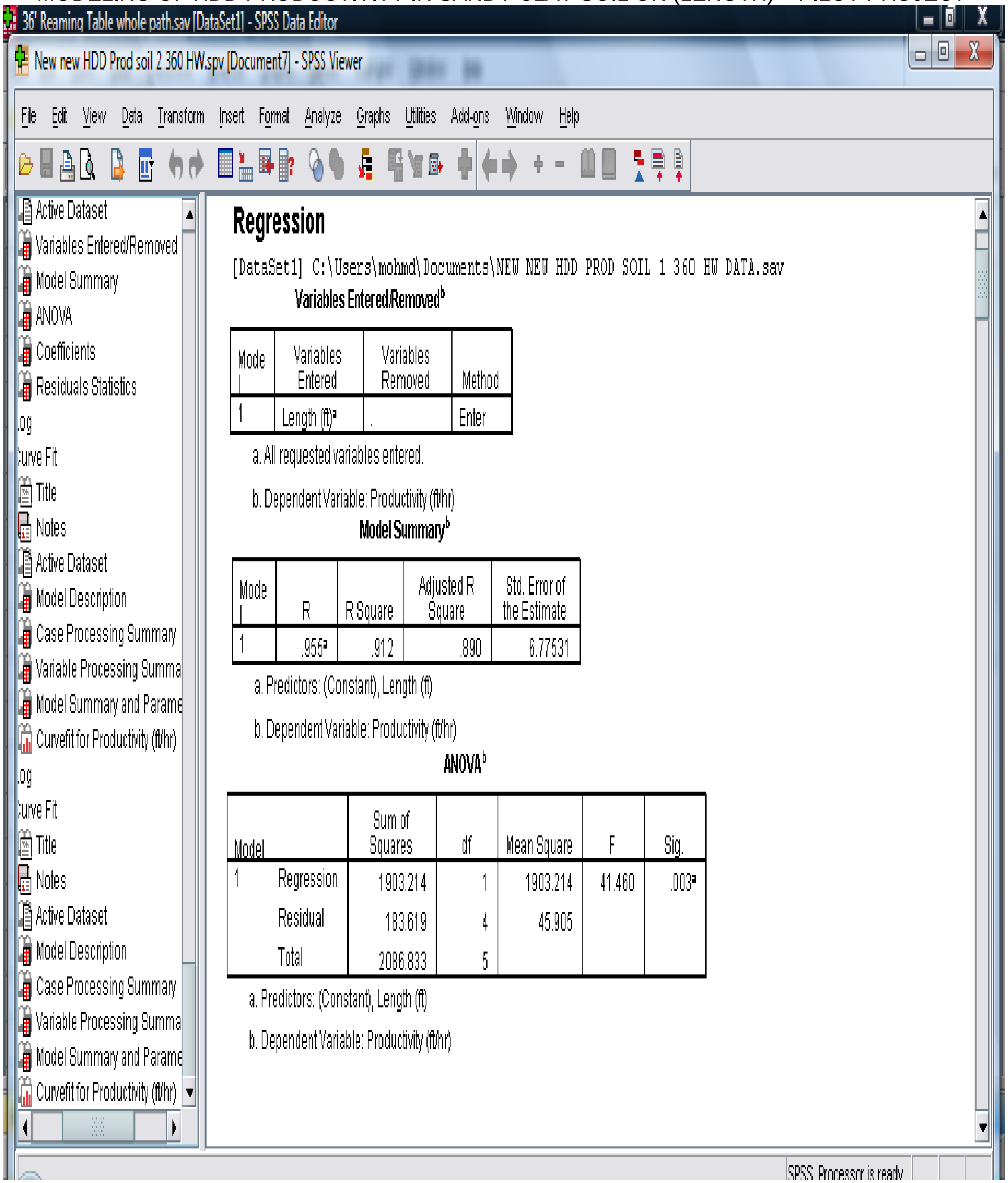
ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	8946.881	1	8946.881	21.382	.004[a]
	Residual	2510.619	6	418.437		
	Total	11457.500	7			

a. Predictors: (Constant), Length (ft)

b. Dependent Variable: Productivity (ft/hr)

MODELING OF HDD PRODUCTIVITY IN SANDY CLAY SOIL ON (LENGTH) – PILOT PROJECT



Regression

[DataSet1] C:\Users\mohmd\Documents\NEW NEW HDD PROD SOIL 1 360 HW DATA.sav

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Length (ft)[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Productivity (ft/hr)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.955[a]	.912	.890	6.77531

a. Predictors: (Constant), Length (ft)

b. Dependent Variable: Productivity (ft/hr)

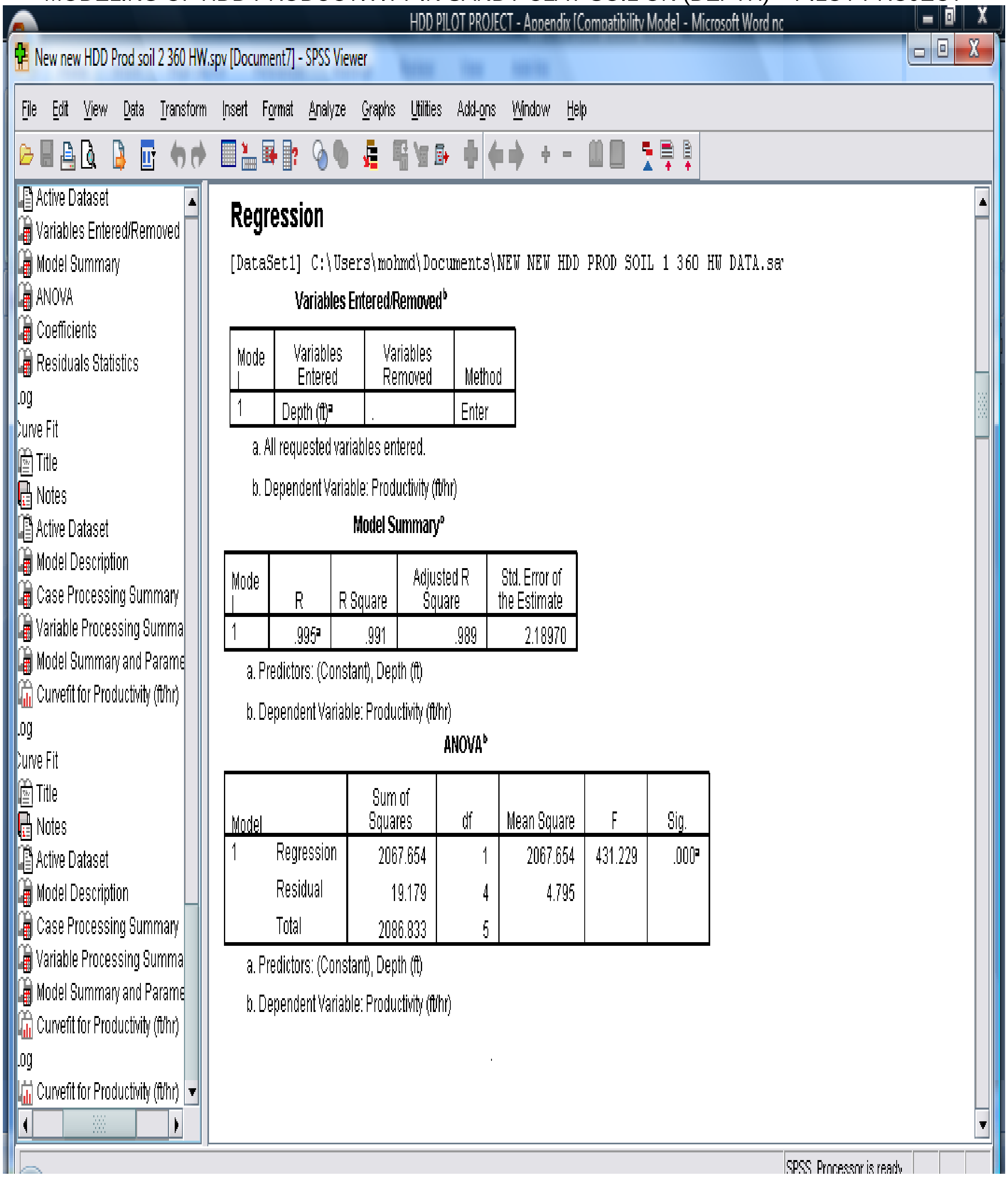
ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1903.214	1	1903.214	41.460	.003[a]
	Residual	183.619	4	45.905		
	Total	2086.833	5			

a. Predictors: (Constant), Length (ft)

b. Dependent Variable: Productivity (ft/hr)

MODELING OF HDD PRODUCTIVITY IN SANDY CLAY SOIL ON (DEPTH) – PILOT PROJECT



Regression

[DataSet1] C:\Users\mohmd\Documents\NEW NEW HDD PROD SOIL 1 360 HW DATA.sa

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Depth (ft)[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Productivity (ft/hr)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.995[a]	.991	.989	2.18970

a. Predictors: (Constant), Depth (ft)

b. Dependent Variable: Productivity (ft/hr)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2067.654	1	2067.654	431.229	.000[a]
	Residual	19.179	4	4.795		
	Total	2086.833	5			

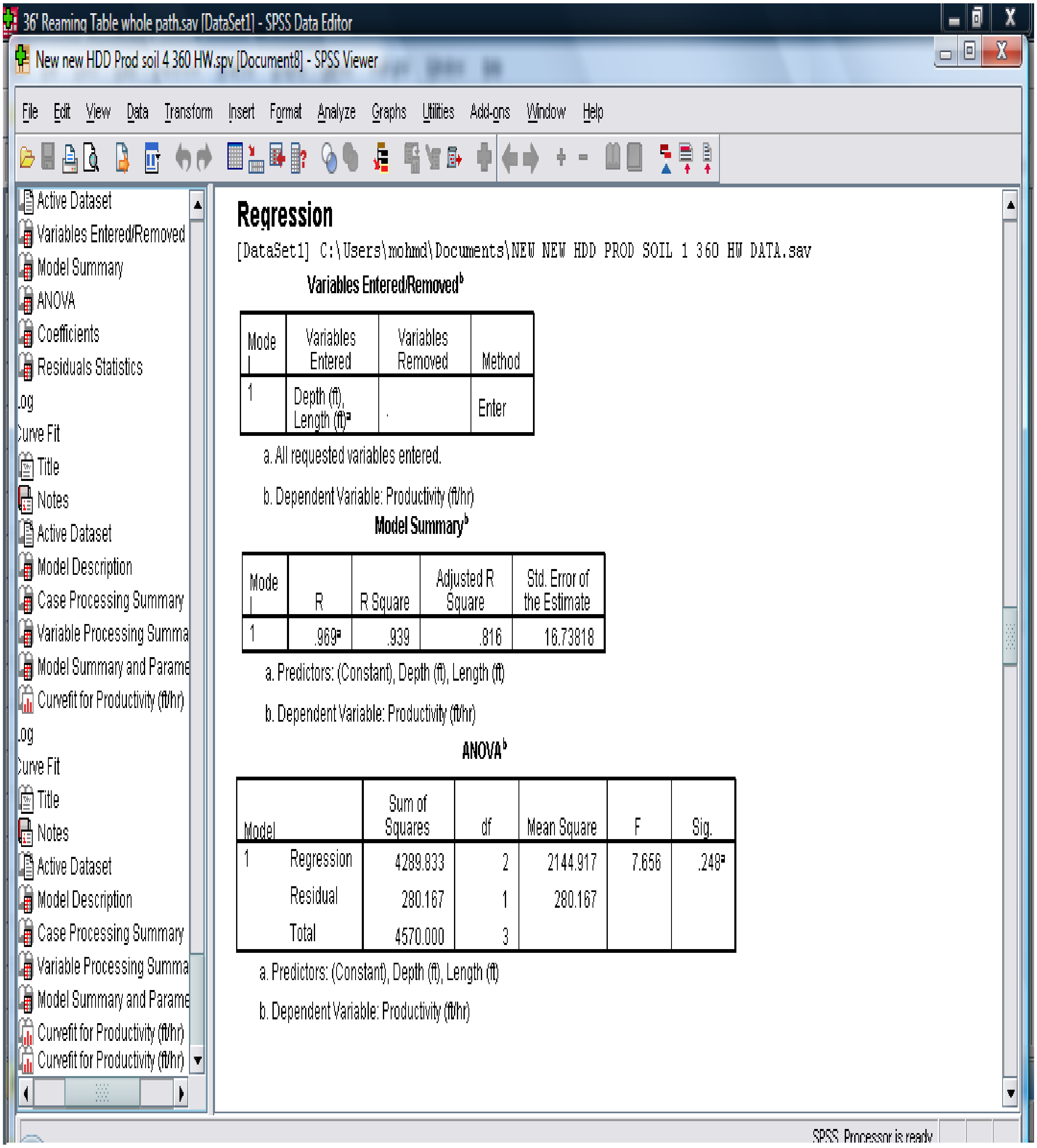
a. Predictors: (Constant), Depth (ft)

b. Dependent Variable: Productivity (ft/hr)

G-6

MODELING OF HDD PRODUCTIVITY IN SILTY CLAY SOIL ON (LENGTH + DEPTH)

PILOT PROJECT



Regression

[DataSet1] C:\Users\mohmd\Documents\NEW NEW HDD PROD SOIL 1 360 HW DATA.sav

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Depth (ft), Length (ft)[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Productivity (ft/hr)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.969[a]	.939	.816	16.73818

a. Predictors: (Constant), Depth (ft), Length (ft)

b. Dependent Variable: Productivity (ft/hr)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	4289.833	2	2144.917	7.656	.248[a]
	Residual	280.167	1	280.167		
	Total	4570.000	3			

a. Predictors: (Constant), Depth (ft), Length (ft)

b. Dependent Variable: Productivity (ft/hr)

APPENDIX H

HDD PRODUCTIVITY MODEL – CLAYEY CONDITIONS

HDD PRODUCTIVITY DATA – CLAYEY CONDITIONS

*HDD Clayey Model Data.sav [DataSet4] - SPSS Data Editor

File Edit View Data Transform Analyze Graphs Utilities Add-ons Window Help

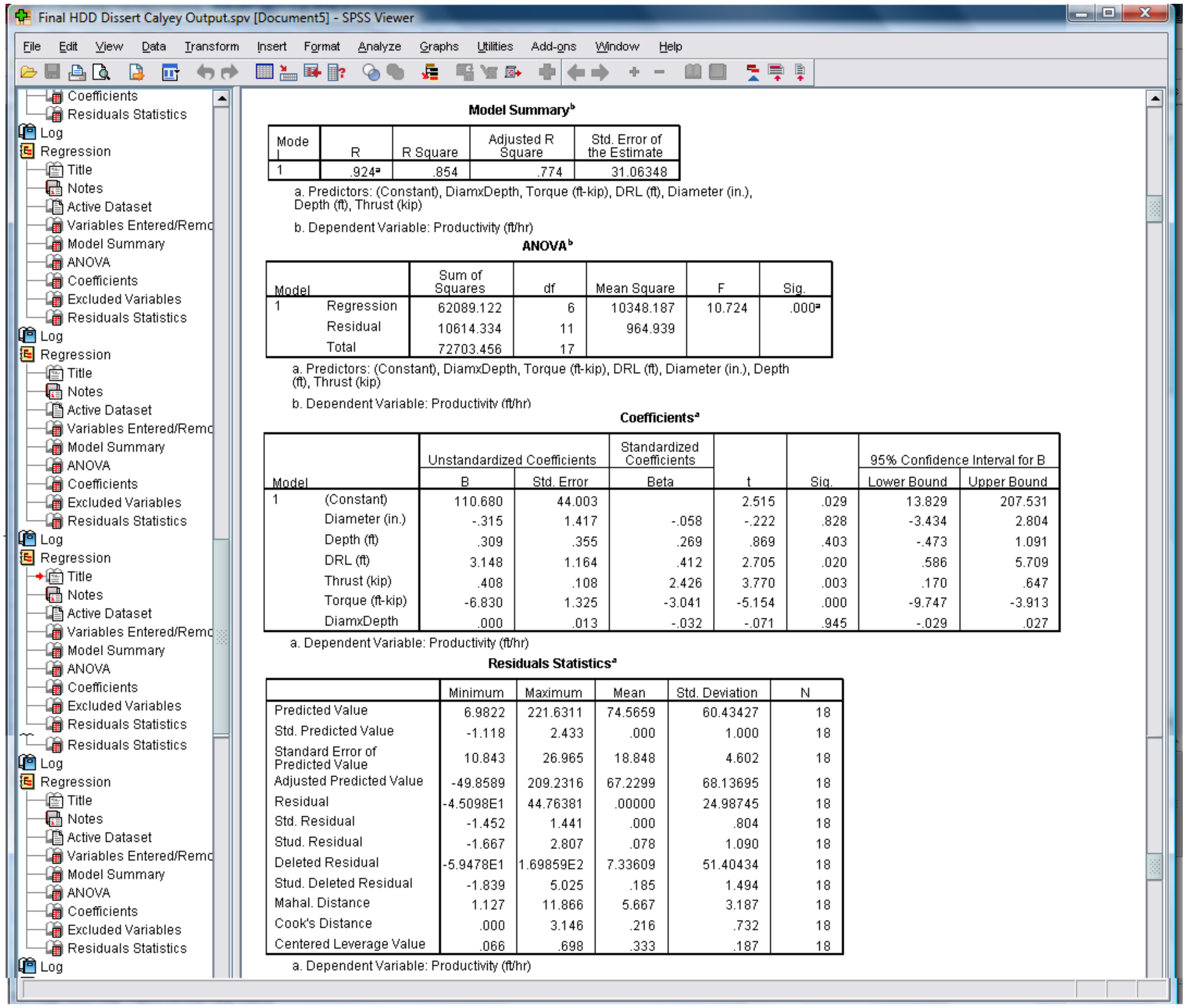
20 : VAR00001 | 82 of 82 Variables

	VAR00001	VAR00002	VAR00003	VAR00004	VAR00005	VAR00006	00015	VA
1	9.00	30.00	30.00	280.00	45.00	22.00	.	
2	9.88	150.00	30.00	1200.00	100.00	55.56	.	
3	12.00	6.00	10.00	25.00	11.00	120.00	.	
4	16.00	70.00	30.00	130.00	25.00	75.64	.	
5	20.00	22.00	30.00	215.00	25.00	77.14	.	
6	22.00	30.00	30.00	280.00	45.00	27.50	.	
7	24.00	120.00	30.00	230.00	25.00	183.33	.	
8	26.00	147.64	10.00	260.00	35.00	26.77	.	
9	26.00	125.00	30.00	40.00	4.00	238.10	.	
10	28.00	22.00	30.00	215.00	25.00	79.41	.	
11	28.00	70.00	30.00	130.00	25.00	75.64	.	
12	34.00	150.00	30.00	1200.00	100.00	41.67	.	
13	36.00	120.00	30.00	230.00	25.00	183.33	.	
14	36.00	30.00	30.00	280.00	45.00	27.50	.	
15	38.00	147.64	10.00	260.00	35.00	22.94	.	
16	42.00	30.00	30.00	280.00	45.00	23.91	.	
17	48.00	147.64	10.00	260.00	35.00	20.08	.	
18	48.00	150.00	30.00	1200.00	100.00	41.67	.	

Data View | Variable View

H-2

HDD PRODUCTIVITY MODEL – CLAYEY CONDITIONS



Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.924[a]	.854	.774	31.06348

a. Predictors: (Constant), DiamxDepth, Torque (ft-kip), DRL (ft), Diameter (in.), Depth (ft), Thrust (kip)

b. Dependent Variable: Productivity (ft/hr)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	62089.122	6	10348.187	10.724	.000[a]
	Residual	10614.334	11	964.939		
	Total	72703.456	17			

a. Predictors: (Constant), DiamxDepth, Torque (ft-kip), DRL (ft), Diameter (in.), Depth (ft), Thrust (kip)

b. Dependent Variable: Productivity (ft/hr)

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	110.680	44.003		2.515	.029	13.829	207.531
	Diameter (in.)	-.315	1.417	-.058	-.222	.828	-3.434	2.804
	Depth (ft)	.309	.355	.269	.869	.403	-.473	1.091
	DRL (ft)	3.148	1.164	.412	2.705	.020	.586	5.709
	Thrust (kip)	.408	.108	2.426	3.770	.003	.170	.647
	Torque (ft-kip)	-6.830	1.325	-3.041	-5.154	.000	-9.747	-3.913
	DiamxDepth	.000	.013	-.032	-.071	.945	-.029	.027

a. Dependent Variable: Productivity (ft/hr)

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	6.9822	221.6311	74.5659	60.43427	18
Std. Predicted Value	-1.118	2.433	.000	1.000	18
Standard Error of Predicted Value	10.843	26.965	18.848	4.602	18
Adjusted Predicted Value	-49.8589	209.2316	67.2299	68.13695	18
Residual	-4.5098E1	44.76381	.00000	24.98745	18
Std. Residual	-1.452	1.441	.000	.804	18
Stud. Residual	-1.667	2.807	.078	1.090	18
Deleted Residual	-5.9478E1	1.69859E2	7.33609	51.40434	18
Stud. Deleted Residual	-1.839	5.025	.185	1.494	18
Mahal. Distance	1.127	11.866	5.667	3.187	18
Cook's Distance	.000	3.146	.216	.732	18
Centered Leverage Value	.066	.698	.333	.187	18

a. Dependent Variable: Productivity (ft/hr)

APPENDIX I

HDD PRODUCTIVITY MODEL – ROCKY CONDITIONS

I-1

HDD PRODUCTIVITY DATA – ROCKY CONDITIONS

HDD Rocky Model Data.sav [DataSet2] - SPSS Data Editor

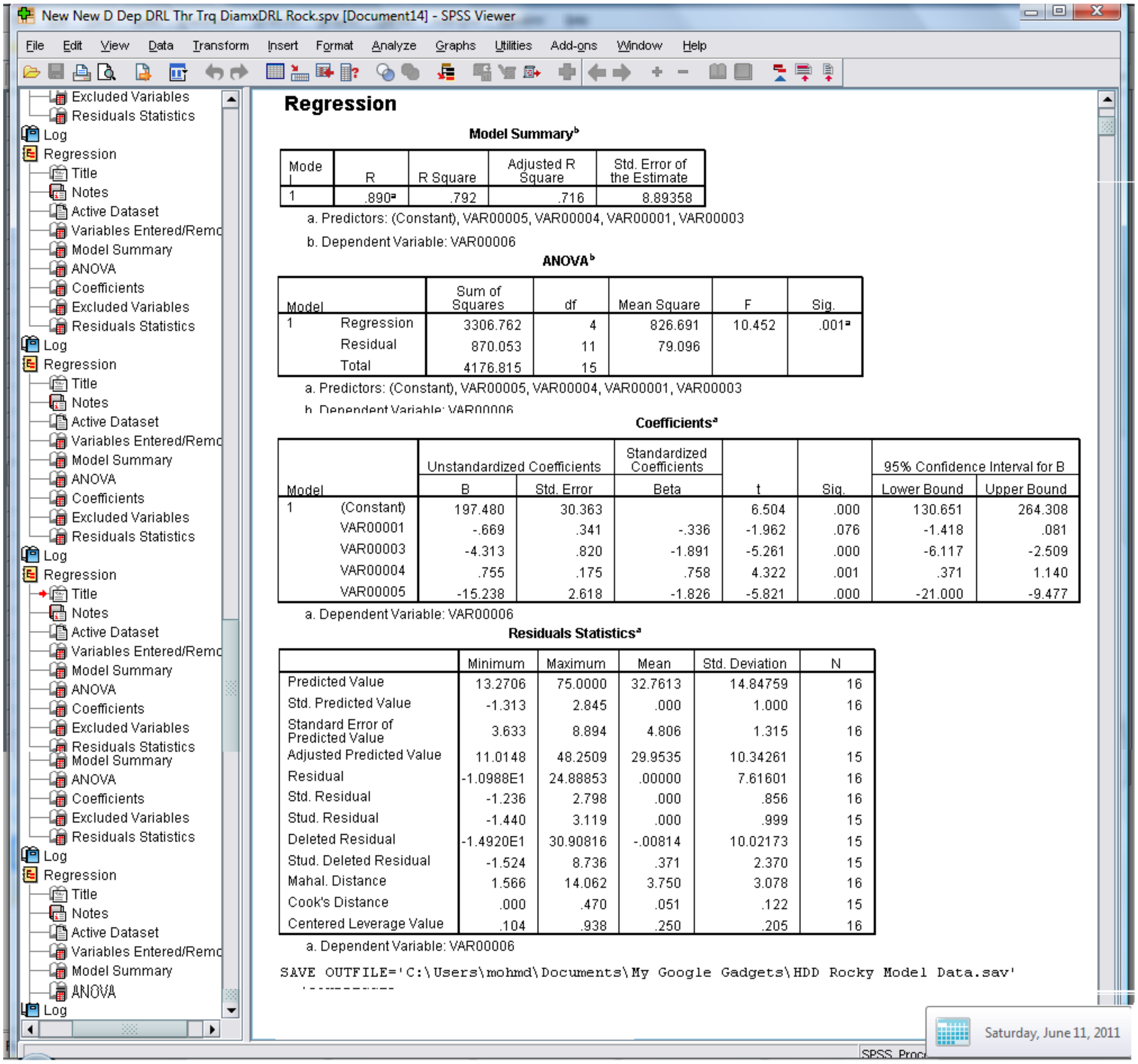
File Edit View Data Transform Analyze Graphs Utilities Add-ons Window Help

22 : VAR00001

	VAR00001	VAR00002	VAR00003	VAR00004	VAR00005	VAR00006
1	8.75	30.00	30.00	70.00	5.00	40.00
2	9.00	14.00	14.25	35.00	9.00	18.30
3	10.00	25.00	15.00	70.00	9.00	66.70
4	12.00	25.00	15.00	35.00	5.00	75.00
5	13.00	14.00	14.25	35.00	9.00	18.30
6	14.00	25.00	15.00	70.00	9.00	33.30
7	16.00	25.00	15.00	70.00	9.00	33.33
8	18.00	14.00	14.25	35.00	9.00	18.30
9	18.00	25.00	15.00	70.00	9.00	33.33
10	18.00	30.00	30.00	70.00	5.00	33.33
11	22.00	25.00	15.00	70.00	9.00	33.33
12	30.00	30.00	30.00	70.00	5.00	25.00
13	36.00	30.00	30.00	70.00	5.00	20.00
14	24.00	30.00	30.00	70.00	5.00	27.40

Data View | Variable View

MODELING HDD PRODUCTIVITY – ROCKY CONDITIONS



Regression

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.890[a]	.792	.716	8.89358

a. Predictors: (Constant), VAR00005, VAR00004, VAR00001, VAR00003

b. Dependent Variable: VAR00006

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3306.762	4	826.691	10.452	.001[a]
	Residual	870.053	11	79.096		
	Total	4176.815	15			

a. Predictors: (Constant), VAR00005, VAR00004, VAR00001, VAR00003

b. Dependent Variable: VAR00006

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients			95% Confidence Interval for B	
		B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound
1	(Constant)	197.480	30.363		6.504	.000	130.651	264.308
	VAR00001	-.669	.341	-.336	-1.962	.076	-1.418	.081
	VAR00003	-4.313	.820	-1.891	-5.261	.000	-6.117	-2.509
	VAR00004	.755	.175	.758	4.322	.001	.371	1.140
	VAR00005	-15.238	2.618	-1.826	-5.821	.000	-21.000	-9.477

a. Dependent Variable: VAR00006

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	13.2706	75.0000	32.7613	14.84759	16
Std. Predicted Value	-1.313	2.845	.000	1.000	16
Standard Error of Predicted Value	3.633	8.894	4.806	1.315	16
Adjusted Predicted Value	11.0148	48.2509	29.9535	10.34261	15
Residual	-1.0988E1	24.88853	.00000	7.61601	16
Std. Residual	-1.236	2.798	.000	.856	16
Stud. Residual	-1.440	3.119	.000	.999	15
Deleted Residual	-1.4920E1	30.90816	-.00814	10.02173	15
Stud. Deleted Residual	-1.524	8.736	.371	2.370	15
Mahal. Distance	1.566	14.062	3.750	3.078	16
Cook's Distance	.000	.470	.051	.122	15
Centered Leverage Value	.104	.938	.250	.205	16

a. Dependent Variable: VAR00006

```
SAVE OUTFILE='C:\Users\mohmd\Documents\My Google Gadgets\HDD Rocky Model Data.sav'
```

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BIOGRAPHICAL INFORMATION

Mohmd Khaleel Sarireh was born on August 10, 1974 at the City of South Al-Mazar, Jordan. He received his bachelor degree in Civil Engineering from Mu'tah University, Jordan in January 1997. After graduating, he worked as a civil engineer at Tahaineh Contraction Company and as a trainee engineer in Ministry of Public Works, Jordan. Then, during his work for Ministry of Municipalities he received his master degree in Civil Engineering (Environment and water resources) from The University of Jordan, Amman, Jordan in June 2002. Then he worked for Ministry of Planning and International Cooperation as projects' coordinator. After that he worked for Tafila Technical University, Jordan as a full-time lecturer. With the great motivation and enthusiasm for developing higher-level skills and knowledge in the area of civil engineering, he decided to pursue Ph.D. graduate studies majoring in construction engineering at The University of Texas at Arlington. In August 2008, he was admitted to the Department of Civil Engineering at The University of Texas at Arlington as a doctoral candidate. During his studies, he had the opportunity to work on his research with Dr. Mohammad Najafi. His research is focused on testing significance of conditions and subconditions involved in Horizontal Directional Drilling (HDD) for pipes and conduits installation utilizing the analysis of variance (ANOVA) model as well as modeling of HDD productivity using significant subconditions and developing of HDD user interface as a planning tool for operation.