Analysis of Parameters Affecting Costs of Horizontal Directional Drilling Projects in the United States for Municipal Infrastructure

by

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ABSTRACT

Horizontal Directional Drilling (HDD) is a growing and expanding trenchless method utilized to install pipelines from 2 to 60 inch diameters for lengths over 10,000 foot. To date, there are not many public documents where direct costs and bid prices incurred by HDD installations are available and analyzed. The objective is to provide a better understanding of the factors affecting the bid prices of these projects. The first section of the thesis analyzes how project parameters such as product diameter, bore length and soil conditions affect the bid price of water and wastewater pipeline installations using HDD. Through multiple linear regressions, the effect of project parameters on bid prices of small, medium and large rigs projects is extracted. The results were further investigated to gain a better understanding of bid factors that influence the relationship between total cost and the project parameters. The second section uses unit cost, based on bid prices, to compare the costs incurred by defined categories. Parameters such as community type, product type, soil conditions, and geographical region were used in the analysis. Furthermore, using average unit cost from 2001 to 2009, HDD project cost trends are briefly analyzed against the main variations of the US economy from the same time horizon by using economic indicators. It was determined that project geometric factors influence more the bid price of small rig projects than large rig projects because external factors including market rates and economic situation have an increasing impact on bid prices when rig size increases. It was observed that bid price variation of HDD projects over years

followed the same trend as the US economic variation described by economic indicators.

DEDICATION

This thesis is dedicated primarily to my dear parents, Jean-Claude and Jocelyne Vilfrant whom had always put all their love, wealth, time and commitment in my personal and professional education. I want to thank my three brothers for their immense contribution to my life, my extended family for their support; my best friends who had always loved and supported me in all that I was doing. A special dedication is made to my home country HAITI, which had suffered so much from the lack of good construction and infrastructure, after the earthquake of January 12th, 2010.

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CHAPTER 1 – INTRODUCTION

1.1 Background

Open-trenching construction has been for a long time, the single conventional method used to install, repair and remove underground utilities and pipelines. This method involves the installation of utility by performing excavations and removing soil to obtain an underground area open to the sky. It requires digging a trench along the alignment of the proposed pipeline, placing the pipe in the trench on an adequate bedding material and then backfilling (Najafi 2005). Often, the construction effort is concentrated on activities like: detour roads, traffic flows management, trench excavation and shoring, dewatering, backfilling and many other operations that are not adding value to the job but are actually increasing construction and social costs. Because of the drawbacks of open-cut methods, new technologies allowing underground utilities and pipeline installation without digging have been investigated and developed. These technologies are mostly known as "Trenchless Technologies", and there are different types of methods available for a wide range of applications. One of these methods is "Horizontal Directional Drilling".

Horizontal Directional Drilling is defined as a steerable system for the installation of pipes, conduits and cables using a surface launched drilling rig. This method usually involves 2 or 3 stages: Pilot hole drilling, prereaming and pullback. The pilot hole is drilled along the centerline of the proposed pipeline alignment. This is one of the most important phases in the process, since it fixes the ultimate position of the pipeline. The drill starts by penetrating the ground, at a specific position, with a small diameter (1 to 5 inches) drilling string. The entry angle is usually between 8 to 18 degrees. The drilling continues under and across obstacles along the design profile; and is performed by rotating a drill bit and thrusting force from the drill string, and by using a mechanical cutting method. A fluid is injected by small amount with high pressure and high velocity, creating a space for the drill string to proceed. The fluid is usually composed of bentonite, or polymer based slurry. The drill path is monitored by a bore tracking system. Two categories of them, walkover and non-walkover systems are used in HDD. These systems perform better in interference-free environment, because interference can modify the signal between the downhole transmitter and the receiver (Bennett and Ariaratnam 2008). The prereaming is performed to enlarge the pilot hole to a diameter 50% or more, larger than the outside diameter (OD) of the product pipe. The oversize is necessary to create an annular void for the return of drilling fluids and spoils and to allow enough space to accommodate the bend radius of the pipe. Upon completion of prereaming, the pipe is pulled back into the enlarged hole filled of fluid. A swivel is attached to the pipe, and blocks it from rotating. Depending on material, it can be necessary to place on rollers to protect its coating and reduce friction. Reducing friction forces prevent from unnecessary and hazardous increase of pullback forces. Often, pullback is done concurrently with prereaming by attaching a reamer head between the drill string and the pipe (Najafi 2005).

The most important equipment utilized during an HDD installation is the HDD rig necessary to perform thrusting and pullback. The scope of work, job specifications and contractor decision determine the characteristics of equipment used for an HDD project. Table 1.1 presents information about rig size and Figures 1.1, 1.2, 1.3 and 1.4 present a model for each type as currently used in the industry.

Table 1.1 Rig Size Information

Rig size	**Thrust / Pullback capacity (lbs)**
Small	less than 40,000
Medium	40,000 – 100,000
Light large	100,000 – 300,000
Heavy large	greater than 300,000

Figure 1.1 Small Rig (Vermeer 24x40)

Figure 1.2 Medium Rig (Ditchwitch 8020)

Figure 1.3 Light Large Rig (Vermeer 200x300)

Figure 1.4 Heavy Large Rig (AA660)

Pipe diameter usually ranges from 2 to 60 inches for lengths up to 10,000 foot, mostly using HDPE, PVC, Steel and Ductile Iron pipes. HDD has many advantages over open-cut and other trenchless methods; it requires minimum excavation and restoration, results in lower social and environmental costs, and has a shorter duration. It is used to install different types of utilities. In 2008 it was estimated that the market share was 19.6% for telecommunication, 15.8% for oil and gas transmission, 16.2% for gas distribution, 16.8% for water, 11.3 % for sewer and 12.6% for electric (Carpenter 2009). Numerous sectors are using this technology every day; while more and more research and investigations are being conducted to increase knowledge and experience about it.

1.2 Objectives of the Thesis

The primary objective of the research presented in this thesis is to develop a better understanding of the parameters affecting the direct costs of HDD projects in the United States, installing water and wastewater pipelines. To date, there are not many detailed studies related to HDD project costs, and it is important for the industry to have a summary of the main practices related to bid prices and cost calculation in the US market. The facts presented here are based on work performed by municipalities and contractors all over the United States. Bid prices are investigated using two different approaches. The first approach studies how project geometry affects the bid price of water and wastewater projects and determines the share that these parameters represent in the bid price. It provides information for municipalities on how their project costs are calculated, based on project scope, contractor experience and market situation. It relates different aspects of HDD to price calculation and is developed to provide a new way to look at project prices and give insight for future projects planning.

The second approach compares projects bid prices obtained in different situations, and analyze the main causes of these differences. In addition, external factors affecting projects costs are investigated. The variations of the average bid prices over years are studied in comparison to the fluctuations of the US economy, by looking at key economic indicators related to the construction industry.

This research is a start for the Horizontal Directional Drilling industry, because it provides new information about bid price composition of HDD projects. It quantifies the effect of project geometry on bid prices and gives an overview of industry practices. It compares values of bid prices resulting from different construction specifications or situations. This research is a new way to look at HDD construction bid prices and the preliminary step to the development of specific models to estimate them.

It will be profitable for different sectors of the trenchless industry, particularly HDD users. It will help them during their decision processes while allowing them to understand the trends prevailing in the industry. It will allow them to compare HDD to other installation alternatives, on a financial matter. Information in this research will also benefit contractors by first providing them information about other contractors' practices; and second by informing them about potential areas for new business based on company definition and expertise, and by looking at price comparisons and associations investigated in the research.

1.3 Organization of the Thesis

This thesis is divided into 5 chapters. The first chapter introduces the context of the research and why it is conducted. A quick definition of the method being investigated is provided and the need of an analysis of HDD cost is explained. Chapter 2 presents a literature review of the main and most important research being done in different aspects of trenchless projects cost and productivity, and provides evidence of the lack of information about the current topic. These main areas, related to cost of trenchless projects being investigated are project productivity, studies related to direct and indirect costs of projects, and a cost comparison using open-cut versus trenchless. Chapter 3 defines the data collection methodology, and presents the outline of the analysis. The different data sources are presented and described, data modifications are explained and the general approach to the problem is presented. Chapter 4 is the analysis itself describing and explaining calculations to develop forecasting models using regression analysis, analyzing the differences between bid prices of projects of different nature and also investigating external factors that impact these bid prices. Chapter 5 presents the final thoughts about the research, its extent and limitations, and recommendation for future and deeper investigations about the topic.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

General economics of construction projects involve the study of costs, expenses and profit related to the project. Cost estimation, cost control and productivity are important aspects of construction project success and construction company development for the long term. Trenchless technology research conducted to date in North America have considered construction aspects including productivity, comparison between open-cut project cost and trenchless projects cost, and analyses of indirect costs associated with the use of trenchless technology. These aspects are affected by a great number of parameters, which impact project success and determine project spending, costs and profit. Horizontal Directional Drilling (HDD) is a fast growing industry in North America and it is important that owners and contractors are equipped with tools and models permitting them to evaluate the impact of projects parameters on project costs. Regarding HDD, not much work has been done to modelize project cost using main project parameters. This study presents an analysis of bid prices for direct costs of HDD projects in North America, related to important factors impacting project expenditures, for example, rig size, bore length, location, and soil conditions; and provides useful information to the HDD industry about project bid prices. This literature review presents previous studies of the past ten years analyzing important parameters impacting trenchless pipeline installation related to productivity of trenchless methods and analysis of direct or indirect cost associated to the use of these technologies.

2.2 Productivity Analysis of Trenchless Technology Methods

Productivity has been a constant subject of study in the trenchless industry for years, since it is an important determinant of project quantity and quality. Hegab and Salem (2010), presented a study where they ranked the factors affecting the productivity of microtunneling projects. Using data from literature reviews and surveys from experts in the microtunneling industry, they come up with 20 factors, of which 3 were the most important: underground conditions, operator's experience and mechanics of the system. The paper provides information about the dependencies between all these 20 factors and how they are involved in projects by increasing or reducing productivity. These dependencies include for example: the effect of soil condition and slurry flow rate on the cutting head shape, the effect of technical support on the operator's experience, the selection of pipe section length is affected by the shaft dimensions, pipe material and existence of curves during tunneling. These factors were used to develop a productivity model presented in another pending publication of ASCE. Even though, one finds good information about many factors affecting trenchless projects, the study does not link these factors to project costs and does not go further than the microtunnelling method.

Adel and Zayed (2009) identified the main factors affecting productivity of Horizontal Directional Drilling and developed a neurofuzzy productivity prediction model for pipe installation in clay soils. According to their investigation, the most significant factors affecting productivity are: operation/crew skills, safety regulations, rig size, machine condition, slurry flow rate, steering problems, soil types, unseen obstacles, site/weather condition, pipe diameter, pipe length, pipe depth and pipe type. These factors are subdivided in four main categories: management, mechanical, environmental and pipe condition. Their study focused only on eight of these parameters (operation/crew skills, pipe diameter, rig size, machine condition, unseen obstacles, pipe length and site/ weather condition) due to data limitation, and studied the relationship between activities cycle time and these parameters. Model inputs represent a set of data collected beforehand, related to the parameters cited above: cycle time and productivity measures from real HDD projects. It determines relationships between these parameters and overall productivity, and therefore; can predict the productivity of a given HDD project, with an effective error percent. Tested data compared to real time productivity measures yields an average validation of 96%. Many of the parameters used in their paper, are also important to cost estimation; and this research is analyzing their effect on HDD project cost.

Ali, Zayed and Hegab (2007) developed a model capable of quantifying and measuring the effect of subjective factors on productivity of trenchless construction methods. These factors are: managerial skills, machine operator, safety regulations, mechanical condition, unseen soil obstacles, ground water table, soil condition, site condition, pipe material, pipe length, pipe usage, pipe ground depth. They are grouped into three main categories similar to those presented in the research conducted by Adel and Zayed (2009) cited previously and they are: management, environmental and physical conditions. An integrated AHP/FL (Analytical Hierarchy Process and Fuzzy Logic) technique is used to assess them. This model called the SFE (subjective factor effect model), evaluated the effect of twelve parameters, falling under the three categories cited above, on productivity. The SFE model uses these twelve productivity factors, where the overall contribution for each factor is given by its effect value $E_i(x_i)$ multiplied by its decomposed weight W_i. The term x_i is added to the model, in order to allow inclusion of any extended future work using sub factors. A performance scale, from 1 to 9, is used to determine the $E_i(x_i)$ for each productivity factor. The factor's relative weight W_i is determined by using the AHP algorithm. SFE = $\sum_{i=1}^{n} W_i E_i(x_i)$.

The productivity index (PI) represents the reverse of non-productive time. This reverse is the subjective factor effect model (SFE) which represents the effect of these factors on productivity of a specific Trenchless Technology project. PI = 1- SFE

The PI is a decision support tool that supports contractors in their scheduling and bidding process. Tested, the reliability of the tool, for measuring the PI value for both microtunneling and HDD, was of 95.10 and 87.36% respectively. By identifying the factors affecting productivity of TT project, this study gives insight to further research where they can be used to assess project cost models for different methods, particularly HDD.

Zayed, et al. (2007) discussed the most important factors affecting productivity of HDD projects: job and management conditions, rig capabilities, pipe material and diameter, soil type, operator experience and weather conditions. They use three of these factors (operator experience, job and management conditions, and weather conditions) to develop a deterministic productivity assessment model for HDD. This preliminary study calls attention on the many factors influencing HDD project success, but it only considers a few of the factors affecting the project and eventually its costs. The current study means to analyze the effects of other factors, not included in the discussion cited above, on cost estimation.

Salem, et al. (2003) investigated productivity of Auger Boring trenchless pipe installation, where they assessed the construction factors affecting this type of project. Two simulation models developed, using MicroCYCLONE and Arena, were used to simulate the installation process. Based on surveys among contractors, it is concluded that most factors affecting auger boring productivity are similar to those affecting microtunneling as cited in previous papers. These factors are: cutter head, boring machine and equipment, crew and operator experience, soil conditions, drive length, diameter of borehole and casing, pipe section length, quality of geotechnical investigations, installation depth, ground water conditions, effectiveness of the method, obstruction, restriction to working hours, accuracy of line and grade, existing utilities, and pipe alignment. Dependencies exist between these factors; for example, the choice of equipment and auger boring machine depends on soil conditions, underground obstruction and bore length. One of the focuses of this study was on the effect of bore length on costs and productivity. Simulation results show that productivity increases with bore length, because cycle time increases and therefore the amount of time to build shafts and blocks are reduced when compared to the total system time. Unit costs decrease when length increases, because the total cost of making shafts decreases comparing to total project cost. These simulation models show a minor difference with actual projects, where it predicts a higher cost and a lower productivity than those of the real project situation. This paper is a useful tool for planning an auger boring installation. These models are effective for only one method, and they focus on just parameters related to length.

2.3 Studies on Direct and Indirect Costs Associated with Trenchless Technology

Many researchers have worked on establishing surveys, models and software to evaluate direct and indirect costs of Trenchless Technology projects.

Matthews and Allouche (2009) presented an update to the software TTWorld, a decision support tool to which a social cost calculator was added. The software was first developed to assist decision makers in choosing the best method to install pipelines, when project parameters are defined. Later, a social cost calculator was added to this software allowing users to estimate the cost of their project based on historical data. It compiled previous algorithms coming from different researchers, in a single one, and combined the following costs: traffic delay, vehicle operating, pedestrian delay, dust and dirt control, air pollution, noise pollution, loss of parking revenue, reduced service life of pavement structures and associated restoration. Using these data, the calculator compiled a database of unit cost ranges that can be used to estimate social costs of underground construction projects, for either open-cut or trenchless construction. This software is useful not only to have an estimate of the social cost of projects, but also to contrast the social cost of trenchless and open-cut construction. However, the software use historical data to make this cost evaluation and does not determine a direct relationship between project parameters and its costs.

Orton (2009) determined the cost- generating elements, which intervene in the calculation of operating costs related to HDD projects; then used them in an operating cost model that can be used on any given HDD project to evaluate profit. These factors considered parameters regarding equipment and crew working on the project, and some assumptions are made in order to choose them. Factors to be included in operating costs calculations: number of work-hours per year for the HDD crew, the useful life of equipment, the number of actual hours of work per day for the drill, the expected average income per foot over equipment's lifespan, crew size to monitor equipment, and the average daily productive capability of the equipment in feet of product installed. Only equipment directly involved in the HDD process should be considered; for example: drill system, vehicles used during the process, vacuum excavation equipment, air compressors, pneumatic pavement breaking tools, and pneumatic digging tools. The acquisition costs of this equipment were an important input. Miscellaneous costs should also be involved in these calculations. For each of these cost-generating elements, an individual hourly operating cost was calculated, then the operating cost per hour for the entire HDD project was calculated by adding the hourly cost of each item one to each other. One can calculate the average production per hour by dividing the daily production by the average hours worked per day. Finally, knowing the estimated cost and revenue per foot, one can calculate the estimated profit per foot. Orton's research focuses more on criteria affecting profit or loss faced by a contractor during a project. It is only about operating costs, not total cost, and considers factors related to equipment use and crew composition.

Allouche, Ariaratnam and MacLeod (2003) conducted a survey to demonstrate the need of HDD industry for a cost estimating software. They developed two computerized applications. The first one allows the HDD contractor to track the operating cost per meter of product pipe, for each rig operated; and monitor maintenance and repair costs associated to their equipments, this is the "Integrated Management System for Trenchless Contractors (IMS-TC). The second one is a decision support tool, which simulates the interactions between the different equipments used in an HDD operation and helps determine the optimum combination of equipment considering project inputs; this is the "Simulation Modeling of Directional Drilling Installations (SIMDDI). The paper also highlights the lack of utilization of computerized software in cost tracking and cost estimation in the HDD industry. Useful, it provides a mean for contractors to track their expenditures and operating costs, however it does not analyze all parameters involved in this type of projects, and the models do not provide a way to estimate project total cost.

Paris and Hampson (2007), in a study conducted in 17 cities around the Dallas Forth-Worth (DFW) Metroplex, analyzed the trends and differences of pipeline construction costs in this area. They presented the main factors that impacted the significant cost increase observed, in water and wastewater pipeline installation. Using bids tabulation data for 8 to 18 inch pipelines installation projects, from 2000 to 2006; a cost assessment for Cured-in-Place Pipe, Directional Drilling and Pipe Bursting is realized. Additionally, a cost comparison between trenchless methods and open-cut was made from 1998 to 2007. These evaluations depended on pipe size and type of installation (open-cut or trenchless). The last comparison, from 1998 to 2007, was based on city population, where 3 categories were defined: less than 50,000 residents; between 50,000 and 100,000 residents; and greater than 100,000 residents. This study determined that factors influencing water and wastewater pipeline cost in DFW Metroplex can be divided into 3 categories: local conditions (project length, depth, adjacent and crossing utilities, service connections, pavement replacement, traffic control, backfill, trench excavation material, municipal bureaucracy, disadvantaged and minority owned business participation goals), market conditions (cost of material, cost of petroleum, labor costs, workforce supply, and overall U.S. economy), external conditions (natural disasters, terrorist activity, political actions). This paper evaluated yearly, existing projects costs for open-cut or trenchless method in order to find the main factors affecting their increase. It represents general information about parameters to look closely when estimating a project cost, but does not provide information about how these factors affect the cost and how to come up with cost estimation when parameters are defined.

Tighe, et al. (1999) researched on the savings associated with trenchless construction by elimination of social costs due to traffic disruption. They developed a method to evaluate the typical traffic delay associated with underground utility construction. These equations quantify the disruption, associated to 3 different common traffic control plans. They have considered different type of delays: user delay, speed delay, queuing delay and detour delay. From this, the total delay is determined and the cost associated to it can be assessed. Once a decision maker knows the direct cost of different methods for installing an underground utility, these equations became useful to rank and choose the most suitable method, based on social cost due to traffic disruption. They analyze indirect costs of a method, but do not provide a mean to evaluate the direct cost of a project in order to have an estimate of the total cost.

2.4 Chapter 2 Summary

Factors affecting productivity and costs of underground infrastructure installation projects can be classified in many different groups. Previous research has assessed them and determined the most important affecting productivity of trenchless construction projects, the following groups of parameters are cited by almost all writers as important: ground conditions, company management and operator's experience, and mechanics of the equipment systems. Investigations show that the most important parameters influencing trenchless project total cost are: project length, depth, soil conditions, type of equipment, type of material, social and environmental costs, and costs associated to general construction factors. Some of these parameters were used in different models and software to develop cost estimating tools for trenchless construction methods; however, most of them are based on comparisons with historic data, do not use all important parameters determining project costs, evaluate only indirect costs, and are not related to HDD.

Estimation of direct costs in an HDD project is important for construction projects. Having a preliminary evaluation of your direct costs, while predicting the social and environmental costs, is necessary information for owners in determining the most suitable method for their projects. In addition, a cost estimation model is an important decision tool for contractors trying to optimize their portfolios and their profit; because it will allow them to have a general idea of the costs associated with the project before preparing their bids. This study aims to determine a relation between important factors impacting the cost of HDD projects and the bid prices of projects. It will provide an adequate formula related to pipe diameter and pipe length, where the direct cost of the project will be quickly determined.

CHAPTER 3 - METHODOLOGY

3.1 Introduction

This chapter reviews the methodology chosen to develop the research from data collection to research findings. It explains the selections of methods used to collect data and analyze parameters for developing a technical analysis necessary to understand the trends of Horizontal Directional Drilling (HDD) costs projects based on analysis of project bid prices previously collected.

This research has three key stages: The first one is the data collection where information on 106 projects was gathered from different regions of the United States, Hawaii and Canada. Among these 106 projects, only 63 were used to investigate costs because bid prices could not be collected for all of them. Many of the projects were not awarded publicly and some of them were negotiated bids; therefore, it was not possible to find prices even when all other project information was available. However, the totality of projects was used to analyze rig utilization and to compare the dominant design conditions (length, diameter and soil characteristics) between rig sizes. The second stage is the process of modifying the collected data. Data was reclassified in groups for further analysis. Rig size was collected as ratio variables, for example a numerical value for each project; but the level of measurement was reduced to ordinal variables, because they have been reclassified by ranges. Soil classification and pipe material are nominal variables and they were recoded into a ratio variable to be used in regression calculations. The third stage involved analysis of projects bid prices using comparison between different categories.

The remainder of this chapter discusses data collection methods and data modifications, presents the general approach of the study where hypotheses are defined and explained, and analysis steps (developed further in Chapter 4) are introduced.

3.2 Data Collection

This research was based on conceptual investigation because the analysis depended on parameters that impact Horizontal Directional Drilling projects and not on current project designs and specifications. Consequently, data used were historical and real information was gathered from past and successfully completed projects. Finding information was a long task necessitating identification of official and certified sources. The following sections present the different data sources used in this research.

1.2.1 Principal Sources

The main sources of HDD projects executed in the US and used in this study were primarily found in:

- North American Society of Trenchless Technology (NASTT) No-Dig Conference Proceedings. NASTT is a non-profit society, assuring the promotion of the benefits of trenchless technology for public awareness through technical education, training and research. Since 1992, No-Dig Conference provides attendees with a quality technical paper program. The most instructive and interesting papers are presented after a careful and detailed peer-review, and make a long lasting contribution to the state-of-the-art of trenchless technologies(Trenchless Times 2007). Information about NASTT can be found at: (North American Society of Trenchless Technology 2010) http://www.nastt.org/

- American Society of Civil Engineers (ASCE) Pipeline Conference proceedings. ASCE is a society representing more than 144,000 members of the civil engineering profession worldwide and is the oldest national engineering society in America. ASCE Pipeline Conference publishes books and CD-ROM s containing papers from the most prestigious professional meetings of leading civil engineers from around the globe regarding underground utilities construction. Information about ASCE can be found at:http://www.asce.org/
- Underground Construction Technology (UCT) Conference proceedings. Since 1995, Underground Construction Technology International Conference & Exhibition has been one of the meeting places for the underground utility construction and rehabilitation market. Through this conference, engineers are able to stay connected in all things underground in both trenchless and conventional methods. Information about UCT can be found at: http://uctonline.com/
- Trenchless Technology Magazine is one of the primary magazines providing, since 1993, information about the trenchless technology industry worldwide and particularly the US. It is one of the premier

communications vehicles for the promotion and the development of the global trenchless industry. Each issue usually describes a featured trenchless project using one of these methods, and is a relevant source to find project historical data.

- Directional Drilling Magazine is an archived magazine on Directional Drilling projects, which merged with Trenchless Technology magazine in the early 2000s.
- Underground Construction Magazine publishes information related to buried infrastructure, including: equipment, methods, contractors and projects.

1.2.2 Additional Sources

Data collection for this research also included input from practicing professionals in the HDD industry. Their primary objectives are not to provide data about HDD projects; however, because they have worked or used the technology, they are able to provide important and useful data for the advancement of the research.

Oftentimes, it was necessary to contact owners or contractors in order to confirm project information. Some of them provided data about different parameters affecting bid prices, some about just one and some others could not provide any due to privacy terms related to their company. Most municipalities and public agencies provided bid price information easily. It was more difficult to obtain it from the private sector; which is understandable because contractors are cautious about disclosing their prices due to competition.

HDD equipment manufacturers were consulted to gather technical specification about equipment, when it was not available on the main project description.

Because this study focused only on water and wastewater infrastructure, for which owners are municipalities, it was possible to find some particular information on the Online Government Information and Services in US. Some public agencies provide clear details about the projects of the year, and their infrastructure rehabilitation projects often represent an important percentage of their yearly objectives; therefore, financial details about these projects are located on their websites.

1.2.3 Sources for Specific Data

While most parameters are presented in a paper or an article, they are rarely provided in the same format. This is the case for soil conditions and project cost. Soil conditions description varies from one paper to another or from one writer to another. It was also important to compare bid prices from different years based on year 2009, and all prices for projects before 2009 were actualized using the Consumer Price Index.

In order to had a uniform soil description for the 106 projects analyzed, this research used soil type information found directly on the United States Department of Agriculture (USDA) website, where different ground conditions are classified and provided by states and counties. The Unified Soil Classification System (USCS) is used because it better standardized the many different ways ground conditions are described in papers. USCS is also one soil classification method recommended by the HDD Good Practices Guidelines(Bennett and Ariaratnam 2008).

Because projects took place in different years, bid prices are modified to consider inflation rate to 2009. To transform these values a tool calculator, based on Consumer Price Index (CPI) rate from the Bureau of Labor Statistics (BLS), was used. This tool allows one to know the current value (as of 2009) of prices and monetary services from past years in the current year; using the CPI to evaluate changes in prices.

3.3 Classification

Raw data usually requires transformation and categorization, before insertion into calculations. According to the limits and constraints of the research, an adequate selection was of great importance. This data was classified into two types of variables: ratio variables and categorical variables. Ratio variables are: Length, depth, diameter, bid price and unit price, Categorical variables are: Community type (Urban or Rural), Soil type using the Unified Soil Classification System (USCS), location, year, pipe material, rig size and product type.

In order to compare the cost of projects based on regions, community type, product type and soil type, it was necessary to regroup the projects using this particular information. To differentiate regions, locations were categorized into five main regions: Northeast, South, Midwest, West and Non-continental US; Soil type was following the specifications of the USCS; community types were Urban and Rural, and product types were water and wastewater. Rig size primarily collected as ratio variables were recategorized into ordinal variables, using only three sizes ranges based on their maximum thrust/pullback force capability. They are: 1) small rigs (< 40,000 lbs); 2) medium rigs (between 40,000 lbs and 100,000 lbs) and 3) large rigs (> 100,000 lbs)(Bennett and Ariaratnam 2008).To analyze the utilization of different sizes of rigs, large rigs were further sub-classified as: 1) light large rigs (between 100,000 lbs and 300,000 lbs) and 2) heavy large rigs (> 300,000 lbs) because it was observed that costs incurred by heavy large rigs projects were clearly higher than cost incurred by light large rigs projects.

3.4 General Approach to the Problem

This research is divided into two sections. The first section analyzed how project parameters impact costs of HDD projects, and was based on investigation conducted on 63 water and wastewater projects because bid prices were not available for all 106 projects. This was the first step of understanding the effects of project variables on their costs and calculations were based on bid prices from real past HDD projects. The 63 projects were categorized by rig size; consequently, statistical analysis was conducted separately on three different datasets. The first calculation was a regular multiple regressions procedure using cost as response (dependent variable) and the following parameters as regressors (independent variables): length, diameter, soil classification, and pipe material. Based on the value of R-square and adjusted R-square (R_a^2) and on the significance of the regression, it was important to consider whether to go further in the analysis for each specific model. The second calculation involved a stepwise regression procedure to determine those among the parameters that could have an important significance and contribution to the model. The interaction between the remaining variables was assessed using the collinearity diagnostics, in order to avoid redundancy of parameters in case one of them is controlled by another one. The last calculation of the regression was to verify that the fitted model is effective and adequate to describe the variation of dependents variables, accordingly to those of independent variables. Using the results coming from the different regression procedures, a broad and deep technical analysis was conducted based on HDD practices, the type and amount of data collected and the limitations of the research; then it was determined whether a cost forecasting model (based on bid prices) could be deduced or whether the analysis represented only an insight for the trenchless industry, that will need a deeper investigation.

The second section of the research was intended to provide a relative comparison of the unit cost per foot per inch-diameter, based on community type (urban or rural), product type (Water or Wastewater), by US regions (Northeast, Midwest, South, West and Non-Continental US) and by soil type (GW-GC, SW-SC, MH-OH, ML-OL and PT). Figure 3.1 presents the regions according to the United States census.

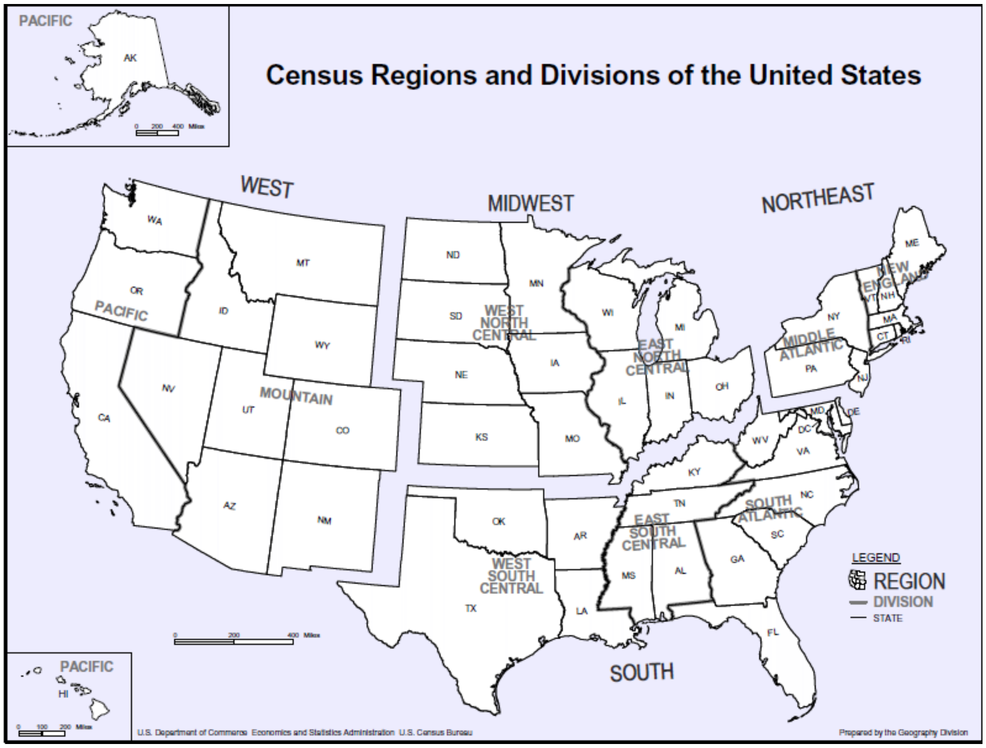


Figure 3.1 Census Regions and Divisions of the United States

Sixty-three water and wastewater projects were classified based on the categories cited above and the average unit cost per foot per inch-diameter for each category was calculated. These values were used to compare costs from one category to another. Municipalities will be able to use them in their preliminary estimation, based on both their location and technical information available in their area, to decide whether to adopt HDD prior to instigate further studies, or only to have a big picture for the cost of a future project. It can be useful for them if they need to split projects in different sub-projects or if a single project requires many different specifications, for example different soil characteristics or different product type. These values are also an insight for contractors looking for potential location for new businesses. Based on the identity of their company, they can decide to look for businesses in either low or high bid price locations.

This section also includes an investigation of the main design and projects characteristics affecting HDD drill rig size and is based on an analysis conducted on the 106 projects. Projects were categorized by rig size and diameter ranges. Information about diameter, length and soil type was then compared to determine the dominant conditions and characteristics for each rig size. Information is given about how drill rig are used, for example percentage of projects, for a specific diameter range. This information is important to compare theoretical data and recommendation to regular industry and contractors' practices and habits when facing a particular situation, and represents useful information for the industry in knowing the average number of projects using a particular rig size when design specifications are identified.

The primary hypothesis of this research is that HDD project cost significantly depends on project parameters, particularly length (L), and diameter (D), on soil conditions (USCS) and pipe material (PM); and that most of the other parameters are highly correlated to these two. Therefore, the first idea was to develop a cost model using the variables cited above, using multiple linear regression. The next chapter presents the many steps and calculations necessary to attain the research objectives described in this current chapter, and results are stated and interpreted to provide advice about HDD cost. Figure 3.2 presents a flowchart of the methodology for the regression analysis, and Figure 3.3 presents a flowchart of the methodology followed to conduct the average price comparison.

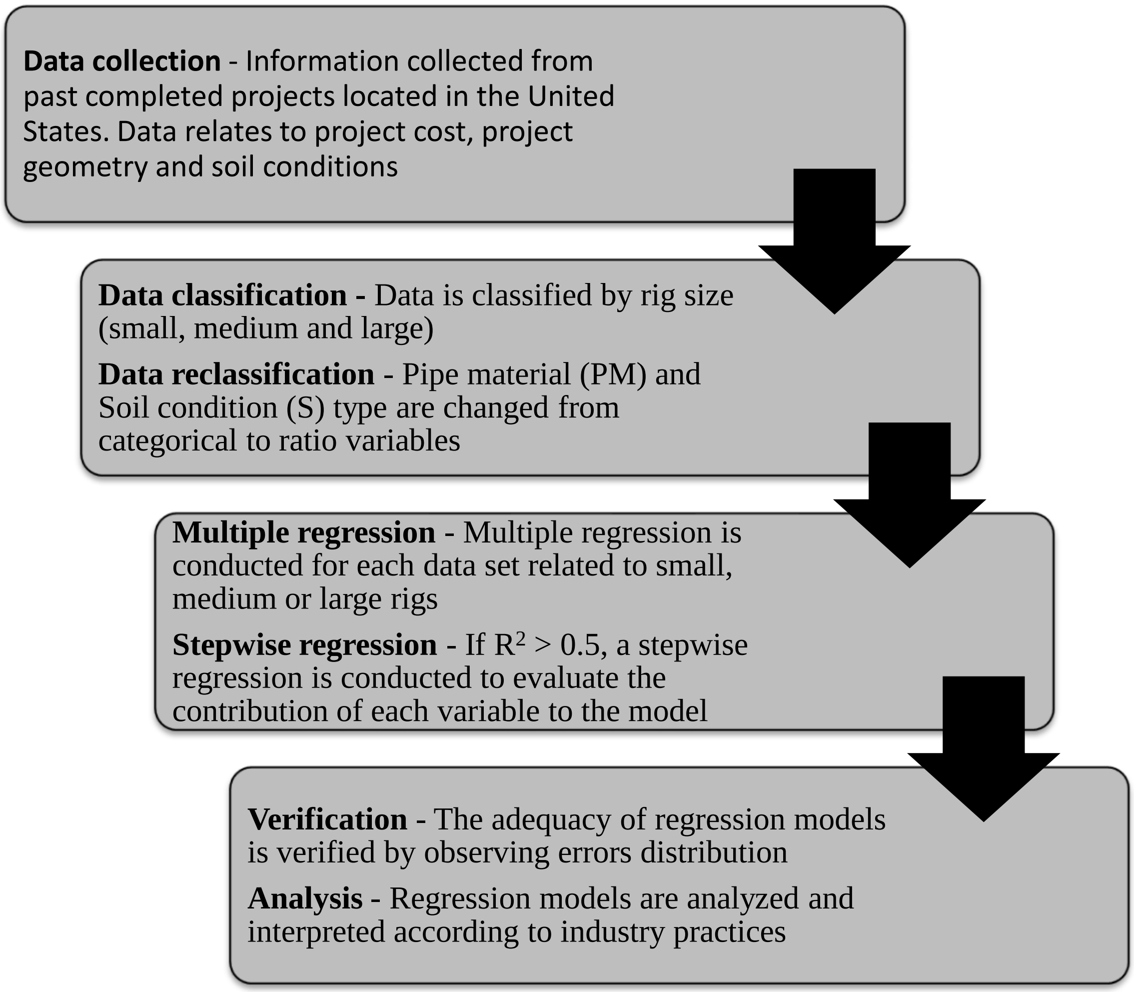


Figure 3.2 Methodology to Analyze the Effect of Project Geometry on Bid Prices

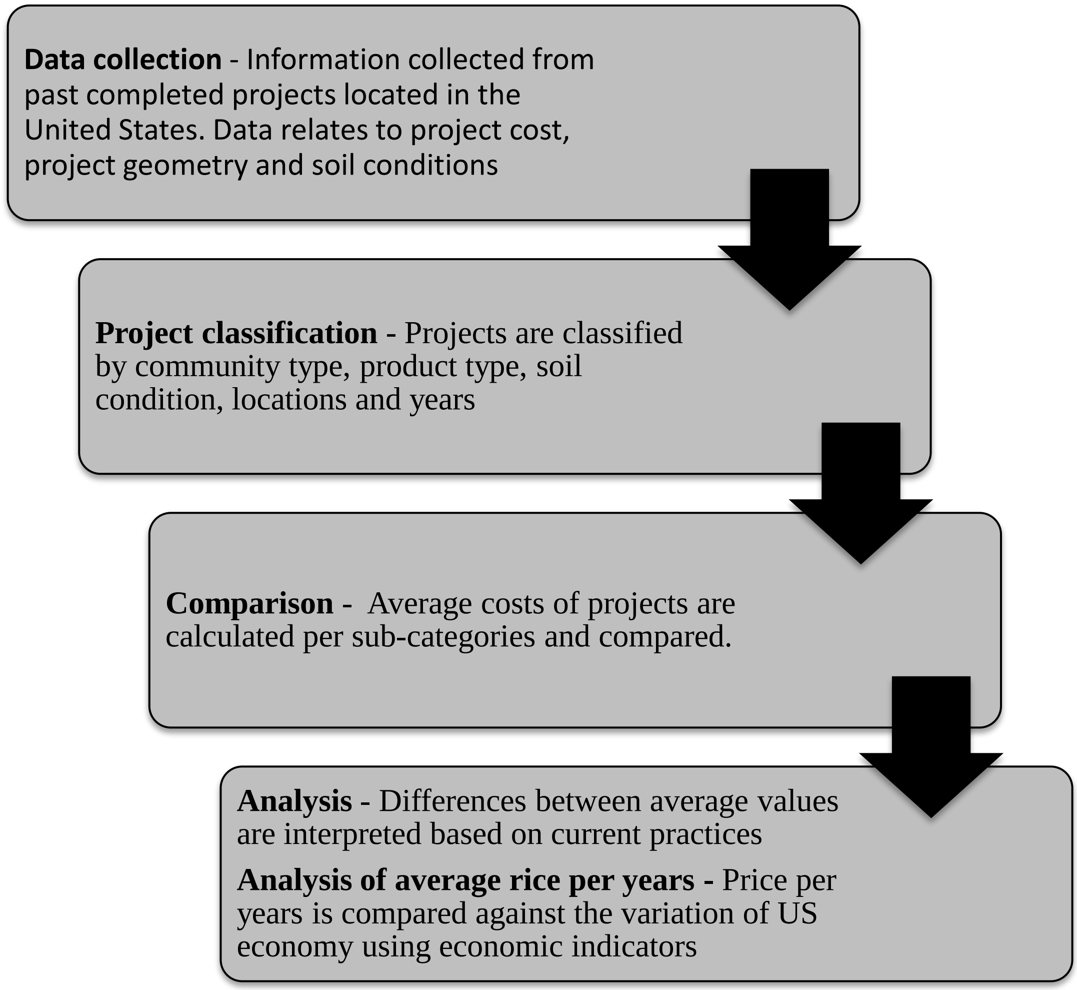


Figure 3.3 Methodology for Average Bid Price Comparison and Analysis

CHAPTER 4 - ANALYSIS

4.1 Introduction

This chapter specifies and describes the research process, calculations and results. Hypotheses are analyzed and verified, the steps of the investigation are implemented, and results are presented and evaluated. A technical interpretation, in accordance to HDD current practices and the actual state of the US economy, is provided in order to accurately understand the cost trends and the relative values obtained in calculations.

The first section of Chapter 4 is dedicated to the regression analysis executed on 63 projects, in order to understand how a number of project parameters involved in any HDD job affect the cost of the job, and determine their impact on a preliminary cost forecasting model. The cost values utilized comes from historical data for HDD project bid prices.

The second section presents different calculations and processes necessary to determine the unit cost per foot per inch for each category, provides a relative comparison between these categories, and tries to understand the reasons of the differences in cost. It also includes a summary of data collected for each rig size, where information about the most dominant conditions encountered on 106 projects from the North American trenchless market are analyzed and presented for information purpose.

4.2 Model Development (Regression Analysis)

Regression analysis is concerned with modeling the relationships among variables. It quantifies how a response (or dependent) variable is related to a set of explanatory (independent, predictor) variables (Abraham and Ledotler 1983). It is a quantitative forecast method, because it is based on mathematical/statistical models. These models can be linear or non-linear.

The conceptual framework of a forecast system consists of two major components: the model building stage and the forecasting stage. This research deals with the first stage: the model building. Figure 4.1 illustrates the phases of this stage.

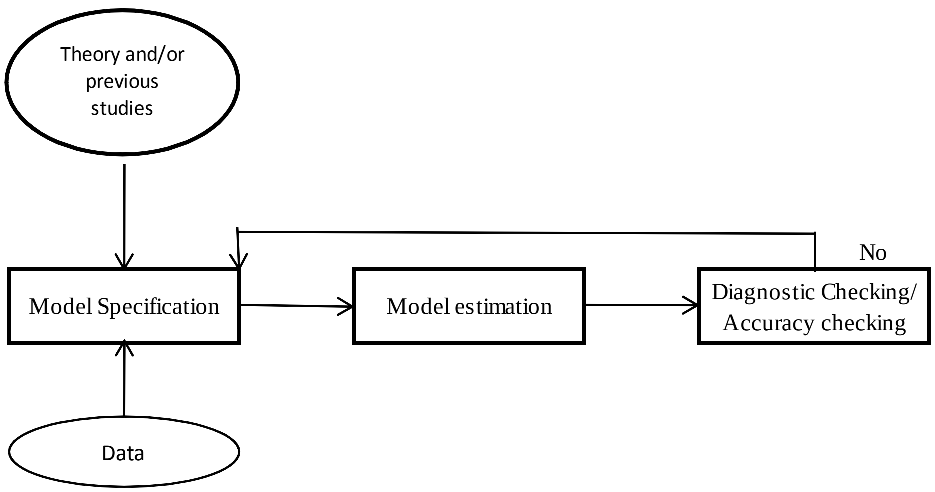


Figure 4.1 Phases of "Model Building" Stage (Abraham and Ledolter 1983)

The model is empirical; it depends on observational and historical bid prices from past HDD projects throughout the United States, and is entirely developed in accordance with the numerical values collected. The objective is to determine how the variation of these independent variables (Length (L), Diameter (D), Soil conditions (S) and Pipe Material (PM)) affect dependent variable bid price (BP) for water and wastewater projects. Scatter plots (see Appendix I) representing the variation of the dependent variable function of each independent variable; show us that an approximate linear relationship exist between the dependent variable and most independent ones. In addition, making the assumption that many non-linear relationships can locally be approximated by a linear relationship (Abraham and Ledolter 1983); the model that is specified, at the first phase of the model building for these cost variables, is a linear model (linear in its parameters β_i) of the form:

$$y_t = \beta_0 + \beta_1 x_{t1} + \cdots + \beta_p x_{tp} + \varepsilon_t \text{..} (4.1)$$

The above model was used separately to evaluate three different rig sizes: small (less than 40,000 lbs), medium (between 40,000 lbs and 100,000 lbs) and large (over 100,000 lbs) using 23, 17 and 23 projects respectively. The bid price estimation model was of the form:

$$BP = \beta_0 + \beta_1 * L + \beta_2 * D + \beta_3 * S + \beta_4 * PM + \varepsilon_t \text{……………………………………………} (4.2)$$

The objective is to determine how much project parameters contribute to the variation of the bid price of HDD projects, based on the values collected. One of the best ways to evaluate the closeness of a parameter to another one is to measure the squared distance between them. Consequently, a multiple linear regression based on least square estimates is used to find the fitted model, and all assumptions for using this method are applicable in this research. The model is determined using the statistical software SPSS version 17.0, for Windows. The different steps to implement the “model building” stage of the conceptual framework of a forecast system are the following:

- Execute an ordinary multiple regression using all dependent and independent variables cited above
- Based on the value of R square and adjusted R_a square (greater than 0.5), execute a stepwise regression for the selected models
- Execute an ordinary regression, for the selected models, using the remaining variables
- Evaluate the adequacy of the fitted model and analyze the residuals
- Decide whether the model is adopted, and analyze and present reasons why the models might not be retained

1.2.4 Linear Regression Analysis

As stated before, a linear regression model describes relationships between a response variable and one or more predictor variables by the generalization of a straight line (Weisberg 1985). An appropriate model will allow the deduction of y_t from the value of x_{ti} through equation 4.1. ε_t represents the unknown random quantity of statistical error and is the failure of the model to determine the fitted value. It was assumed that errors are normally and independently distributed with zero mean and a common variance s^2. The appropriate model will minimize the residual sum of squares. Estimating parameters β_i from historical data are such that they represent the closest observation providing the fitted model. The squared distance is usually chosen to measure “closeness”, and the estimating parameters are determined using the "least squares estimates" method that minimizes the sum of the squared deviations (Abraham and Ledotler 1983). The strength of the relationship between response and predictors is evaluated by the correlation coefficient R, which represent the proportion of variability of the response explained by the predictors. It is generally assumed that a correlation greater than 0.8 is described as strong while a correlation less than 0.5 is described as weak. Besides the correlation coefficient, significance tests are also important to evaluate the adequacy of the fitted model. The t-significance test is important to evaluate hypotheses related to each individual β_i coefficient, while the F-significance test is important to evaluate the regression itself. Large values of t and F significance usually provide evidence against the null hypothesis; for example the larger they are, the more adequate the model might be. The level of significance α used in this research is 0.05, along with a confidence interval of 95% (default value in SPSS). These statistics are also evaluated by the value of the probability p associated to them. It is generally assumed that a value of p less or equal to 0.05 means that the parameter evaluated is significant. Adjusted R_a^2, the adjusted correlation coefficient is used instead of the unadjusted (regular) one; because unadjusted R^2 always increases with the number of variables while adjusted R_a^2 introduces a penalty for each parameter since it also considers their degree of freedom. Tables 4.1, 4.2 and 4.3 present the regression results for the total cost models, along with significance and adjusted R_a^2 values for different rig sizes.

Table 4.1 Multiple Linear Regressions for Large Rigs

Model	Variable	Predictor estimate	t test		F test			R_a^2
			t value	p value	DoF	F value	p value	
BP	Intercept	2165849.406	0.761	0.4570	4	5.153	0.006	0.534
	L	448.751	3.480	0.003				
	D	113369.991	2.473	0.024				
	S	-293307.468	-0.678	0.506				
	PM	-586493.677	-1.326	0.202				

Table 4.1 provides the results of a regression analysis looking for a fitted model to explain total project cost utilizing large rigs, explained by bore length (L), pipe diameter (D), soil type (S) and pipe material (PM). Soil type and pipe material are 2 categorical variables that have been recoded into ratio variables to be used in the regression. The value of the F statistic and the p value associated to it, show that this regression is significant because the p value is exactly 0.006. Adjusted R^2 is 0.534 which means that D, L, S and PM together explain 53.4% of the total cost variation. The t significance for L and D has an adequate value because the associated p value is 0.003 for L and 0.024 for D. However, the significance of S and PM is low since the associated p values are 0.506 for S and 0.202 for PM. These values are greater than 0.05 and show that S and PM are not significant enough to directly explain the variation of the total cost. It is normal that the intercept (constant) is not significant for the model because with no project parameters (D and L = 0), there is no project and eventually no cost at all.

Table 4.2 Multiple Regressions for Medium Rigs

Model	Variable	Predictor estimate	t test		F test			R_a^2
			t value	p value	DoF	F value	p value	
BP	Intercept	-2911615.601	-1.267	0.231	4	6.5	0.006	0.594
	L	248.216	3.007	0.012				
	D	87430.712	1.626	0.132				
	S	-30397.765	-0.119	0.908				
	PM	304587.323	0.876	0.4				

Table 4.2 provides the results of a regression analysis looking for a fitted model to explain total project cost utilizing medium rigs, explained by bore length (L), pipe diameter (D), soil type (S) and pipe material (PM). As for large rigs, the fitted model is significant to predict total cost of projects based on the parameters previously cited. The value of adjusted R^2 is 0.594 which means that D, L, S and PM together explain only 59.4% of the total cost variation. The F significance has an associated p value of 0.006. The most significant parameter explaining the cost model is the length (L) with an associated p value of 0.012 for the t significance. The p value are 0.132 for D, 0.908 for S and 0.4 for PM; these values are greater than 0.05 and it is concluded that D, S and PM are not significant enough to explain the total cost variation for medium rig projects.

Table 4.3 Multiple Regressions for Small Rigs

Model	Variable	Predictor estimate	t test		F test			R_a^2
			t value	p value	DoF	F value	p value	
BP	Intercept	-353193.308	-1.022	0.320	4	27.896	0.000	0.830
	L	86.146	9.284	0.000				
	D	39949.849	2.292	0.034				
	S	178960.099	3.084	0.006				
	PM	-70975.135	-1.869	0.078				

On the contrary, the regressions results for small rigs, presented in Table 4.3, show a high level of significance for the total cost model. Adjusted R^2 shows a strong value of 0.830 meaning that these 4 variables together explain 83% of the total cost variation. The F significance also has high value of 27.986 and an associated p value of almost 0. L, D, and S are significant in explaining the variation of total cost. The associated p value is 0 for L, 0.034 for D and 0.006 for S. PM is not highly significant; its p value is 0.078.

The previous regressions were performed using the 4 variables altogether. However, a better combination of them might exist providing a higher value of R_a^2. Several techniques can be used to determine these combinations; for example all possible regressions procedure or stepwise regressions procedure. In this research, the method called stepwise regression is used to investigate and choose a cost model based on comparison of different values of R_a^2. Stepwise regression is a semi-automated procedure used to build models by successively adding or removing variables based on the t-statistics of their coefficients. This procedure puts more information at the fingertips of the investigator than ordinary multiple regression because it allows enhancing the model by removing or adding variables. This process looks one step forward or backward, and selects the variable to be entered or removed based on its t of F statistics. There are different uses of stepwise regression, they are: backward elimination, forward selection, and both of them simultaneously. Backward elimination procedure starts with the largest possible model and looks at the individual t statistics. If all of them are significant, the model cannot be simplified. If one or more are insignificant, only the least significant is removed from the model. The simplified model is reevaluated and the procedure is repeated until no variable can be removed (Abraham and Ledotler 1983). Forward selection is starting with the simplest model and then adds variables as necessary. When dealing with a modest size of potential variables from which it might be possible to remove a few, it is recommended to use the backward elimination procedure. Also, the first regression performed in this research was with all variables, so it was necessary to check the existence of an acceptable model with fewer variables. Consequently, in this research the backward elimination procedure is used to determine the most adequate model. The method used to remove a variable when performing a backward elimination is to evaluate its F statistic value, which is the same as the square of its t statistic (t^2), against a fixed F value called F-to-remove. It is recommended to use an F-to-remove less or equal to 4, for significance at the 5%

level. Since the number of variables is large compared to the number of observations (more than 1 variable for each 10 observations), a value of 3 was chosen for F-to-remove. Tables 4.4, 4.5 and 4.6 present the results of the stepwise regressions for different rig sizes.

Table 4.4 Stepwise Regressions for Large Rigs

Model #	Variable	Predictor estimate	t test		F test			R_a^2
			t value	p value	DoF	F value	p value	
BP (1)	Intercept	2165849.406	0.761	0.457	4	5.153	0.006	0.534
	L	448.751	3.480	0.003				
	D	113369.991	2.473	0.024				
	S	-293307.468	-0.678	0.506				
	PM	-586493.677	-1.326	0.202				
BP (2)	Intercept	1612853.515	0.6	0.556	3	6.913	0.002	0.522
	L	446.350	3.513	0.002				
	D	110713.655	2.459	0.024				
	PM	-594820.854	-1.364	0.51				
BP (3)	Intercept	-1568653.158	-1.147	0.265	2	9.049	0.002	0.48
	L	368.238	3.178	0.005				
	D	89544.648	2.074	0.051				

Table 4.4 shows three different total costs models using three distinct combinations of L, D, S, and PM. The first model BP (1) has a higher value for adjusted R^2, which is 0.534. This means that together the 4 variables explain 53.4% of total cost variation. This result is similar to the results of the first multiple regression, and only L and D are significant parameters. The second model BP (2) has a slightly lower adjusted R^2 (0.522), but a greater significance than BP (1); compare p value for BP (1) which is 0.006 to p value for BP (2) which is 0.002. Only D and L are significant parameters. The third model BP (3) has a lower adjusted R^2 (0.48) than BP (1) and BP (2), but is more significant with an F of 9.049 and an associated p value of 0.002. D and L are both significant to model BP (3).

Table 4.5 Stepwise Regressions for Medium Rigs

Model #	Variable	Predictor estimate	t test		F test			R_a^2
			t value	p value	DoF	F value	p value	
BP (1)	Intercept	-2911615.601	-1.267	0.231	4	6.497	0.006	0.594
	L	248.216	3.007	0.012				
	D	87430.712	1.626	0.132				
	S	-30397.765	-0.119	0.908				
	PM	304587.323	0.876	0.4				
BP (2)	Intercept	-3064885.066	-1.682	0.118	3	9.433	0.002	0.628
	L	250.379	3.246	0.007				
	D	88495.979	1.743	0.107				
	PM	310766.273	0.944	0.364				
BP (3)	Intercept	-1456281.115	-2.277	0.04	2	13.820	0.002	0.631
	L	224.769	3.126	0.008				
	D	117187.906	2.893	0.013				

Table 4.5 shows three different total costs models using three distinct combinations of L, D, S, and PM. BP (3) has the highest adjusted R_a^2 of 0.631 and is the most significant. BP (1) and BP (2) are significant models, but the parameters S and PM are redundant and they are not significant at all because

their t statistics are either too low or negative. L and D are the most significant parameters to the model, and together they explain 63.1% of the total cost variation in TC (3). This value of adjusted R_a^2 is not strong; however, it is significant enough to provide an estimation of total cost. Later in this document, an analysis of the reasons causing a low value of adjusted R_a^2 will be provided.

Table 4.6 Stepwise Multiple Regressions for Small Rigs

Model	Variable	Predictor estimate	t test		F test			R_a^2
			t value	p value	DoF	F value	p value	
BP	Intercept	-353193.308	-1.022	0.320	4	27.896	0.000	0.830
	L	86.146	9.284	0.000				
	D	39949.849	2.292	0.034				
	S	178960.099	3.084	0.006				
	PM	-70975.135	-1.869	0.078				

Table 4.6 is similar to Table 4.3 and show the evidence that the 4 parameters L, D, S and PM are significant to explain total cost variation of small rigs projects. Together they explain 83% of the model, and this represents a strong correlation between predictors and response. However, only L, D and S are significant for the model.

Having determined which variables and combinations were the most significant for the three models; it was necessary to reevaluate the model by using only L and D and obtain a simpler model. An important principle in model building is the *principle of parsimony* which stipulates that “In a choice of competing hypotheses, other things being equal, the simplest is preferable” (Abraham and Ledotler 1983). Following this principle, new models based on the most significant variables were investigated. For large rigs (Table 4.4), even when BP (1) has the highest R_a^2, BP (3) was the most significant model with a p value of 0.002 against 0.006 for BP (1). Since the associated R_a^2 were not too different, the simplest model was chosen to be investigated. For medium rigs (Table 4.5), the simplest model BP (3) has the highest R_a^2 and was chosen for investigation. For small rigs (Table 4.6) only one model was provided but with the four variables, where only L, D and S were significant. Since it was observed that L and D were the most significant for large and mediums rigs, and that S is an indicator variable that can increase uncertainties in the model evaluation in future use, it was decided to investigate the model for small rigs using L and D. Tables 4.7, 4.8, 4.9 and 4.10 present the results of multiple linear regressions using only L and D for large, medium and small rigs. Figures 4.1, 4.2 and 4.3 present the verification of the assumption stipulating that errors or residuals should follow a normal distribution with mean 0 and a common variance.

Table 4.7 Multiple Linear Regressions for Large Rigs Using L and D

Model	Variable	Predictor estimate	t test		F test			R_a^2
			t value	p value	DoF	F value	p value	
BP	Intercept	-1568653.158	-1.15	0.265	2	9.049	0.002	0.475
	L	368.238	3.178	0.005				
	D	89544.648	2.074	0.05				

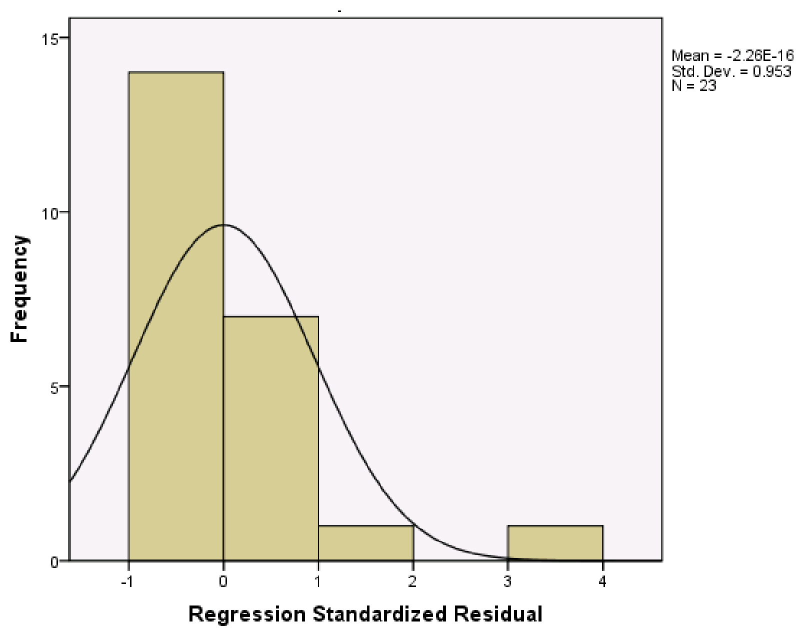


Figure 4.2 Errors Distribution for Large Rigs Model

Table 4.7 provides the final regression results for large rigs model using only two variables: Length (L) and Diameter (D). This model is significant with an F value of 9.049 and an associated p value of 0.002. However, R_a^2 is only

0.475; which means that these two variables explain 47.5% of total cost variation. The two variables are significant; but the results show that L is much more important than D, when comparing the significance of L (0.005) against the significance of D (0.05). Figure 4.2 show the verification of necessary assumptions proving the adequacy of a fitted model from linear regressions: errors are normally distributed with mean 0 and constant variance. These errors follow an N (0, 0.9) distribution. This model is ready for interpretation.

Table 4.8 Multiple Linear Regressions for Medium Rigs Using L and D

Model	Variable	Predictor estimate	t test		F test			R_a^2
			t value	p value	DoF	F value	p value	
BP	Intercept	-2073679.34	-2.23	0.043	2	13.267	0.001	0.61
	L	300.243	2.879	0.012				
	D	156513.867	2.652	0.019				

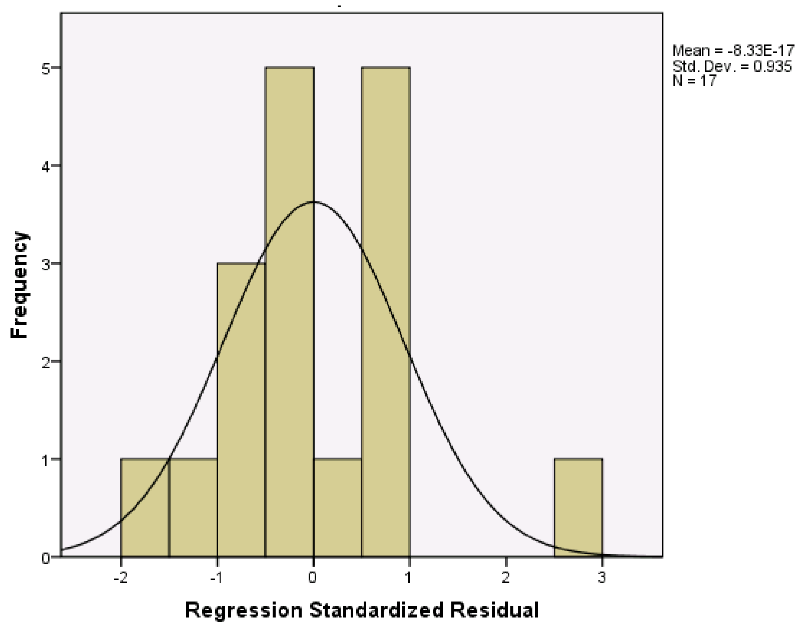


Figure 4.3 Errors Distribution for Medium Rigs Model

Table 4.8 provides the final regression results for medium rigs model using only two variables: Length (L) and Diameter (D). This model is significant with an F value of 13.267 and an associated p value of 0.001. R_a^2 is 0.61; which means that these two variables explain 61% of total cost variation. The two variables are almost equally significant, with L having a 0.017 significance and D having 0.019. Figure 4.3 show the verification of necessary assumptions proving the adequacy of a fitted model from linear regressions: errors are normally distributed with mean 0 and constant variance. These errors follow an N (0, 0.87) distribution. This model is ready for interpretation.

Table 4.9 Multiple Regressions for Small Rigs Using L and D

Model	Variable	Predictor estimate	t test		F test			R_a^2
			t value	p value	DoF	F value	p value	
BP	Intercept	-361929.690	-1.81	0.086	2	32.431	0.000	0.741
	L	76.477	6.98	0.000				
	D	46264.513	2.162	0.043				

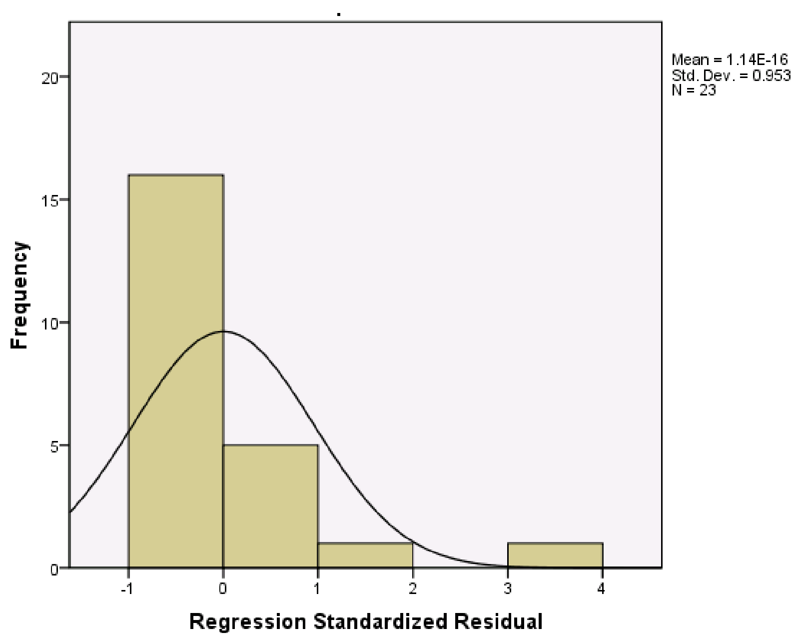


Figure 4.4 Errors Distribution for Small Rigs Model (1)

Table 4.9 provides the final regression results for small rigs model using only two variables: Length (L) and Diameter (D). This model is highly significant with an F value of 32.431 and an associated p value of 0.000. R_a^2 is 0.741, which means that these two variables explain 74.1% of total cost variation. The two variables are significant; but the results show that L is much more important than D, when comparing the significance of L (0.000) against D significance (0.043).

Figure 4.4 show the verification of necessary assumptions proving the adequacy of a fitted model from linear regressions: errors are normally distributed with mean zero and constant variance. These errors follow an N (1, 0.9) distribution. This model is not ready for interpretation because the errors mean is different from zero. Consequently, it was necessary to reevaluate the small rigs model by adding the other significant variable, S, observed in the stepwise regression (Table 4.6). Table 4.10 and Figure 4.5 present the result for multiple regression using L, D and S.

Table 4.10 Multiple Regressions for Small Rigs Using L, D and S

Model	Variable	Predictor estimate	t test		F test			R_a^2
			t value	p value	DoF	F value	p value	
BP	Intercept	-839993.515	-3.48	0.003	3	31.848	0.000	0.808
	L	83.699	8.566	0.000				
	D	40329.930	2.176	0.042				
	S	174368.329	2.828	0.011				

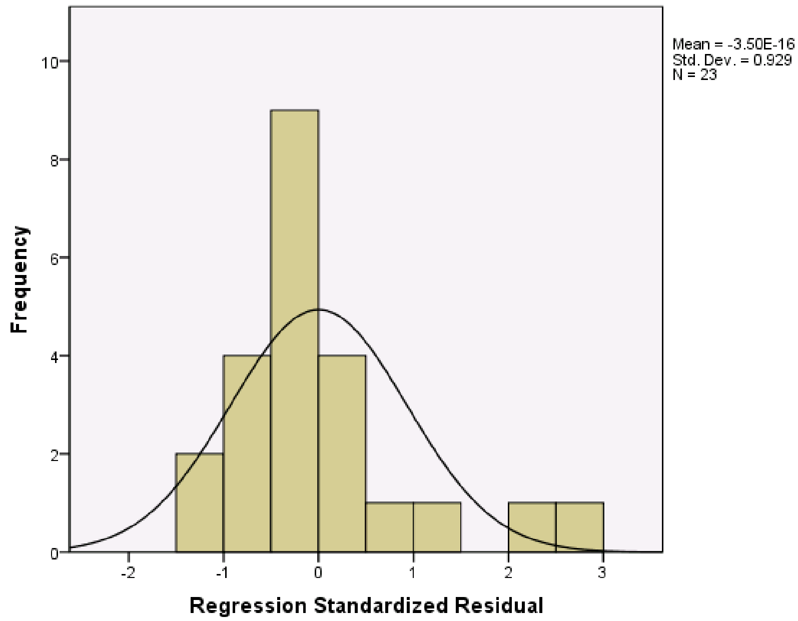


Figure 4.5 Errors Distribution for Small Rigs Model (2)

Table 4.10 provides the final regression results for small rigs model using three variables: Length (L), Diameter (D) and Soil (S). This model is highly significant with an F value of 31.848 and an associated p value of 0.000. R_a^2 is 0.808, which means that these 3 variables together explain 80.8% of total cost variation. The three variables are significant, but the results show that L and S are much more important than D. When comparing the p values significances: L is of 0.000, S is 0.011 and D is 0.042. Figure 4.5 shows the verification of necessary assumptions proving the adequacy of a fitted model from linear regressions: errors are normally distributed with mean 0 and constant variance. These errors follow an N (0, 0.86) distribution. This model is ready for interpretation.

1.2.5 Analysis and Interpretation of Regression Results

Observation from regression results shows that the correlation coefficient is decreasing when rig size is increasing. Compare the value of R_a^2 of 0.475 for large rigs, 0.61 for medium rigs and 0.808 for small rigs. This means that the larger the rig, the more design variables failed to affect the total cost of projects. This tendency might be caused by different reasons. This part of the chapter analyses the different aspects of HDD jobs in order to understand why project parameters seem to be important for the cost of small rig projects, while they are less important for medium and large rigs. The following paragraphs analyze and compare the challenges and particularities incurred by the utilization of each rig size and extract the main practices of HDD contractors for the purpose of explaining the difference between the natures of bid prices for small, medium and large rigs projects.

The cost of drilling with large HDD equipment is exponentially higher than the cost of using medium-size or small-size drilling machines (Griffin 2007). Pullback forces are usually the first specification considered to choose HDD equipment; and the higher the forces, the bigger the equipment (Bennett and Ariaratnam 2008). But many other factors directly and not directly related to jobs also affect the choice of rigs by a contractor. Investigated in this research and as proven in regressions, some of the parameters directly influencing equipment choice and projects costs are: length, soil condition and diameter. Tables 4.11, 4.12 and 4.13 present the average dimensions of length and diameter (parameters used in last regression model) for each rig size, along with dominant soil condition for projects used in this research and can be used as a comparison for length and diameter between HDD rigs.

Table 4.11 Average Dimensions for Small Rig Projects

Dia. ranges (inch)	Number of projects	Weighted avrg. D (inches)	Avrg. L (feet)	Dominant soil cdts.
Less than 4	2	3.5	1,502	ML-OL
4-8	11	7.82	1,282	ML-OL
8-12	12	11.33	1,881	ML-OL
12-16	4	14.6	1,158	ML-OL
16-20	1	17.4	960	ML-OL

Table 4.11 shows that small rigs were mostly used to install small diameter pipelines, for lengths up to approximately 1,500 foot and for cohesive soils like clays and silts. When small rigs are used for medium-size diameters, it is generally for short lengths. The average length of installation for pipelines ranging from 16 to 20 inches is only 960 feet.

Table 4.12 Average Dimensions for Medium Rigs Projects

Dia. Ranges (inch)	Number of projects	Weighted avrg. D (inches)	Avrg. L (feet)	Dominant soil cdts.
4-8	6	7.82	1,280	ML / SP-SM
8-12	5	10.15	2,757	SC-SM
12-16	7	15.03	1,611	SP-SM
16-20	7	18.9	2,275	CH/CL
20-24	2	23.9	728	ML / CL
24-28	3	27.45	1,075	SM
28-32	1	30	1,550	SM

Table 4.12 shows that medium rigs were mostly used to install pipeline diameter from 4 to 32 inches, for lengths up to approximately 2,750 feet. Soil condition may vary from clays, silts and sands.

Table 4.13 Average Dimensions for Large Rigs Projects

Dia. Ranges (inch)	Number of projects	Weighted avrg. D (inches)	Avrg. L (feet)	Dominant soil cdts.
4-8	4	6	4,750	CL
8-12	1	11.55	4,454	SP-SM
12-16	1	16	3,652	PT
16-20	8	17.7	3,412	PT
20-24	8	24	3,548	SC
24-28	3	25.33	1,379	SM
28-32	3	30.67	1,879	ML / CL
32-36	3	36	1,595	ML / CL
40-50	3	45.93	5,161	SW-SC/GW-GC
50+	1	60	1,200	MH-OH/CL

Table 4.13 shows how large rigs were used to install all sizes diameter pipelines, over different ranges of lengths. However, the particularity with large rigs is that at least one of these two parameters is high. When large rigs were used for short lengths, it was usually with a large diameter pipe; and when used for small diameters, it was generally over long lengths. For example, the average length for small diameters from 4 to 8 inches was 4,750 feet; and the length for pipe product greater than 50 inches was only 1,200 feet. Nevertheless, large rigs are generally used for long length and large diameter projects.

Besides diameter, length and soil conditions; depth is another design parameter that greatly affects rig size and eventually the cost of its utilization. Depth determines the choice of the tracking system. Usually a non-walkover system is used to install water and wastewater pipelines when they have large diameters and long lengths, require tight grades and are installed at important depths (Bennett and Ariaratnam 2008). Large HDD contractors use wireline systems because they have higher accuracy than walkover system to detect signals coming from important depths or below the water level when performing water crossings. Oftentimes, HDD contractors hire a subcontractor for this part of the job (Griffin 2007). It is not common for small or medium rigs contractors to use such systems, and it is evident that this factor can make a big difference on cost because wireline systems are significantly more expensive than walkover systems. In 2000, a walkover system cost from $15,000 to$ 25,000 while a wireline system cost from $75,000 to $125,000 (Griffin 2000). Walkover system is one of the required equipment to perform HDD installation and every contractor owns one; however , not all contractors own a wireline system and they often hire a subcontractor. When they own a wireline system, they have to invest in specialty training for their operators. In 2000, it cost a contractor approximately $3,000 to $4,000 a day to use services from a wireline subcontractor and a contractor charging approximately $25/foot when using a walkover system would charge approximately $37/foot when using a wireline system (Griffin 2000). Subsequently, the type of tracking system used on the project is a determinant factor in bid prices calculation and makes a big difference on how it affects the cost for each particular rig.

Besides these factors directly involved in the pipeline installation, many other factors indirectly involved greatly affect jobs and their costs. Mobilization requirements are not the same for projects using different rig sizes. Large rigs have bigger footprint and require more space for mud systems, hoses and cables. Larger space is also necessary to store fluid additives and tools to support equipment. For small and medium rigs vertical space is not as important; however, large rig have booms and cranes and making vertical space is important to avoid overhead cables to prevent jobsite accidents(Griffin 2007) . The working area for small rigs is normally 40 by 60 feet while it is at least 200 by 250 feet for large rigs. These situations confirm the fact that large contractors charge more for mobilization and operating costs than do small or medium rigs contractors, because ething is 2 to 5 times larger and heavier when using a large rig instead of a small rig (Griffin 2007).

HDD projects are risky; different types of non-anticipated issues occur during installation. These problems include and are not limited to: loss of fluid circulation, obstructions, hydrolock, collapse of borehole, failure of drill pipe or downhole tooling, striking or damaging existing utilities, hydrofracture and inadvertent fluid return (Bennett and Ariaratnam 2008). Even though these issues might be encountered in all classes of projects, the risk level involved in large rig HDD projects set them aside from those with small or medium rigs(Griffin 2007). The larger the diameter, the riskier it is to perform a successful pullback because more weight, torque, mud volume and larger reamer are involved. Contractors say that by the time to have the hole ready, a great amount of their own money is involved in the job; therefore, a big risk is on their shoulder (Griffin 2007).

Drilling fluid management is demanding for large rigs compared to small rigs, and it requires personnel training and experience to make it successful.

The market rate is another important factor affecting bid prices, and it has nothing to do with project parameters. A survey conducted in 2007 by *Trenchless Technology Magazine* shows that small and medium rigs contractors were concerned about the lagging state of a project price per foot (or rates) in the HDD industry. They thought it was too low (Bueno 2007). Even when rates are related to project specifications, they are also greatly affected by competition among HDD contractors and by the class of contractor performing the job. Low quality contractors poorly trained, ill-equipped or careless in their drilling charge less for their work than experienced contractors. For example, some small rig contractors feel they can make more money by putting on more footage, but they end up with not enough money to realize potholing; consequently this increases the risk of accidents and damaging existing utilities (Bueno 2007). It is on the sole responsibility of the customer to verify that the contractor is experienced enough to perform the job as specified (Carpenter 2008). However, these issues are mostly encountered in the small rig market because these contractors represented 67% of the market in 2008. Large rigs contractors represented only 8.4% of the market and medium rig 24.6% (Carpenter 2009). Therefore, the competition among medium and large contractors was lower and they could modify their rates not only based on the scope of the work but also using their own markup percentages. Because of the small number of large rig contractors, pipelines companies tend to know the majority of them and their work performance; it was assumed that this results in having the best large rig contractors charging “ the price they want” because they will get the job anyway. Also, these contractors have large and expensive equipment that needs to be profitable. So, it is concluded that there is a lack of uniformity in HDD prices around the country and most particularly within a single region because the bid prices are affected by the number of contractors, their experiences and the awareness or concern of the customer.

Analyzing the characteristics of the HDD market for each type of rig makes it obvious that these three markets are distinct and bid price calculation is highly affected by that. Small rigs contractors do not have the same practices as large rigs contractors, and they do not charge the same rate for their work. This evidence is clearly shown in the regression results where it was determined that project parameters affected the bid prices of small rig more than large rigs. For small rigs it was approximately 80%, for medium rigs it was approximately 60% and it was approximately 47% for large rigs. The nature of large rig projects linked to the small market share that they represent, makes it complex to calculate the cost of a large rig HDD project. In addition, the value of large rig contracts (especially in unfavorable conditions or in water crossings) is high compared to small rig contracts (Carpenter 2008). Small rig contractors rely on volume to make profit; for example, they try within the allowable ranges to put more length and larger diameter in order to have higher margins, and this is one of the primary reasons why project parameters were so significant in the regression (see Table 4.10). On the other hand, medium and especially large rig contractors do not rely on volume for profitability. Their contracts are worth millions, and because of the complexity of the work, it is quite difficult to determine the exact share of overhead, contingencies and margins in the bid price. These data are undisclosed by contractors, and they represent their “weapon” to make their business work. However, it is known that many large rigs HDD contractors add on a percentage basis: 5% for bonds and insurance, 15% for overhead and profits and 20% for contingencies. This represents 40% of the bid price, and there is one of the main reasons why project parameters failed to explain a big portion of the regression model (see Table 4.8). Medium rig contractor practices fluctuate between those of large and small rigs contractors. Regression shows that project parameters affect their bid prices more than large rig prices, but less than small rig prices.

The nature of HDD projects, for example project scope and type of equipment involved, determines the bid price of project. However the relationships between elements affecting the prices are not the same for each type of rigs. Project parameters are important for small rigs; a correlation of 0.808 was obtained in the regression analysis. Small rig contractors rely on volume, for example length, diameter and soil condition, to make their projects profitable. Medium rig contractors are following with a correlation coefficient of 0.61, meaning that design length and diameter still explain more than 50% of bid prices. Large rig contractors have a regression correlation of only 0.475, where length and diameter affect less than 50% of the bid price. It is assumed that if the parameter depth was included in the regression calculation, it might have increased these correlation coefficients because it is an important design factor.

However, it would not have explained the entire remaining lag between these correlations and 1. An important part of these bid prices are affected by the level of contingencies, the bonds required by municipalities, the class of contractors and the state of the market.

4.3 Cost Analysis per Category

This section of the research presents the calculations and results necessary to compare the unit cost of projects per defined categories. As cited earlier, these categories can be classified as follow: community type (urban and rural), product type (water and wastewater), regions (Northeast, South, Midwest and West) and general soil conditions (USCS).

The unit cost per foot per inch is calculated using: the inflation adjusted total cost, the total bore length, and the largest diameter of product pipe or casing when applicable. Projects are sorted by categories, and results provide information regarding the current state of the market as of 2009 – 2010. These values are proposed here for the sole purpose of comparison of one category to another, and represent the straight average of all projects' unit cost for each category.

4.3.1 General Conditions and Characteristics of Projects

Projects investigated for this portion of the research are the same ones on which the regression analysis is based, and from which models were deducted. They are regular water and wastewater HDD projects, from 1997 to 2009, that have been successfully completed, with products currently in used by municipalities over the country. Bids prices vary from one contractor to another, from one project to another or from one period to another, because each project has unique and custom conditions and specifications. However, because they have used the same installation technology, there is evidence that they follow a pattern that can be tracked when the conditions are known and specified.

Projects happened mostly in urban areas; among the 63, only 6 locations were rural. Trenchless construction methods utilization grew up because of the constraints encountered mostly in urban areas: low disruption, maintenance of traffic during operations, rail transportation, and minimum restoration; consequently, as of today, these needs and requirements are not always that important in rural areas and therefore most of these rural municipalities keep using open-cut as their preferred method for pipe installation or rehabilitation. Table 4.14 provides cost information for urban and rural areas.

Table 4.14 Unit Cost by Community Type

Community type	**Urban**	**Rural**
# of projects	57	6
Average unit cost ($/foot/inch)	21.83	28.66

The unit cost in rural areas is slightly greater than in urban areas. Working in rural areas typically incurred higher transportation costs for material and equipment. Labor cost is typically higher.

As previously stated, only Water and Wastewater projects were considered to compare costs. Forty projects were for water pipeline installations and 23 for wastewater pipeline installations. Table 4.15 presents information for these two categories.

Table 4.15 Unit Cost by Product Type

Product type	**Water**	**Wastewater**
# of projects	40	23
Average unit cost ($/foot/inch)	16.7	28.3

Wastewater pipeline installation was found to be almost twice as costly as water line installation because wastewater installation projects require more expertise and accuracy for line and grade requirements. Wastewater pipes necessitate minimum solids deposition, and incur line and grade constraints that are not expected for water lines, because water lines are often pressure pipes. Subsequently, wastewater installations convey greater challenges which result in HDD contractors having higher levels of risk associated with the construction of gravity-flow systems. Najafi (2005) described "grade control" as the first constraint for making sewer installation with HDD because regular tracking equipment only measures in 1% increment, low precision for grade work. To increase accuracy, it would be necessary to make more frequent location readings. Doing so, decreases productivity, lengthens the installation time and increases costs. Dimitroff (2008) identified the main challenges and risks associated to the construction of a sewer line using HDD. Usually grades need to be below 0.5 percent and a tight-fit back reamed hole is required to prevent pipe flotation. Owners need to be assured that the sewer main is in its accurate position before the entire pipe length is put in place. Traditional HDD methods do not easily meet or exceed such requirements because: 1) regular locating equipment has a percentage of error because of interferences, and accurate verification for line and grade take place only when the entire length of pipe is installed; 2) borehole size for sewer pipes should be almost as large as the outside diameter of the pipe to prevent pipe flotation; which is difficult to achieve with HDD since we know that regular practices require the borehole be at least 1.5 times larger than the outside diameter of the pipe. Two potential problems encountered in HDD installations and stated by Najafi (2005) can be associated to these requirements cited above: the lost of drill head when the locator is showing inaccurate readings and difficulties in pullback where the pipe is pushed into the sidewalls of the curved borehole. These difficulties raise the risks incurred by these sewer projects and require a higher level of expertise and more sophisticated equipment use, which forces HDD contractors to charge more for a sewer project than a water project.

Categorizing the projects by USCS, most of the projects, located in the Midwest, were installed in silts and clays (ML-OL). Seven projects were in gravels (GW-GC), fifteen in sands (SW-SC), thirty-three in silts and clays (ML-OL), five in silts and clays (MH-OH) and three in organic type of soil (PT). Table 4.16 provides the unit cost per foot per inch by soil classification.

Table 4.16 Unit Cost by Soil Classification

USCS	**GW-GC**	**SW-SC**	**ML-OL**	**MH-OH**	**PT**
# of projects	7	15	33	5	3
Avrg. unit cost ($/foot/inch)	44.66	24.74	13.74	19.72	32.4

Soil condition is an important factor to HDD project success. It determines the choice of equipment (drill bits, reamers) and the composition of the drilling fluid necessary to meet project requirements. Usually, it plays a key role in estimating project cost. Based on the results presented in table 4.16, gravels incur higher HDD construction costs than any other soil classification. Gravels have been identified as one of the potential HDD job showstoppers, and their presence is associated with a high level of construction risk. Allouche, Ariaratnam and Lueke (2000) specified that HDD technology is highly suitable for soft soils like clays, silts and compacted sands, but becomes risky when the soil is non-cohesive and consists, for example, of large-grains materials like gravels, cobbles and boulders. Najafi (2005) also identified that clay and cohesionless fine sands and silts, generally behave well in a fluid manner and therefore represent good soil condition for HDD application. However, he acknowledged a marginal applicability of HDD in gravels. The results of this research, based on real project bid prices, support these assertions because projects costs are lower for clays and silts and higher for gravels. The less cohesive the soil, the more challenging it is to stabilize the borehole pressure and avoid collapse of its walls. Therefore, it is more complicated to monitor the drilling fluid since it is necessary to modify its composition and quantity to better increase soil cohesion while at the same time avoiding fluid loss and hydrofracturing. Working in large-grain materials also increases the risks to harm the environment and decreases productivity: compare 100 foot/day for cobbles to 600-700 foot/day for clay (Willoughby 2005). These challenges require more expertise and know-how from contractors and their crews, which incur greater project costs.

Projects were also sorted by four regions: Northeast, South, Midwest and West. Information provided for each region is impacted by the characteristics of the collected projects for the region. All projects did not have the same project parameters, or the same conditions; however, there are common aspects related to each area. This analysis is going from specific to general (for example from the characteristics of these projects, a general pattern will be defined and analyzed for the region). The most expensive areas to install water and wastewater utilities using HDD are the West with a cost of $40 foot/inch and the Northeast with a cost of $28 foot/inch. The Midwest is the least expensive with a cost of $12 foot/inch, and the South region with a cost of $21 foot/inch. All regions, except South had an average project length between 2,000 and 3,000 foot. The average length for the South region was approximately 6,500 foot. Projects average diameter lies between 20 and 30 inches, except for the Midwest where average diameter was 13 inches. Each region has its own general soil condition, and projects were classified by finding the dominant condition among all projects in the region. It was observed that projects involving the utilization of heavy large rigs, and particularly those from 700,000 to 1.2 million lbs, have high unit cost/foot. While falling in different categories for calculations in table 4.1 to table 4.3, their cost did not have a real effect on the results. However, when determining the cost per region, four of these projects were in California and Washington and they have altered the unit cost of projects in the West region. Without these projects the cost would be of $577 /foot and the cost of $32.66 /foot/inch. Table 4.17 provides specific information about each region.

Table 4.17 Installation Cost of Water and Wastewater Utilities per US Regions

Regions	NE	S	MW	W	Non-continental	
					Hawaii	Alaska
# of projects	5	11	32	12	2	`1
Avrg. Unit cost ($/foot/inch)	27.45	21	11.43	39.71	28.35	70.75
Avrg. Unit cost ($/foot)	622.53	586.56	157.83	948.15	950.34	707.47
Avrg. Total cost ($)	1,063,335	3,142,122	346,548	1,984,744	2,859,830	141,494
Avrg. Length (foot)	2,187	6,375	2,403	2,644	1,984	200
Avrg. Diameter (inch)	23	29	13	20	27	10
1000 foot/20 inches project	420,154	342,471	223,475	736,485	1,068,007	1,414,940
Dominant soil condition	PT/ SW-SC	SW-SC	ML-OL	GW-GC/ SW-SC	MH-OH	PT

4.4 HDD Project Cost from an Economic Viewpoint

The construction market follows the trends and patterns of society. It is affected by the amount of spending, the capacity and experience of contractors and the complexity of projects. This part of the thesis looks at the evolution of the HDD market for the last decade, analyzes the variations of the US economy for the same period and correlates these two to understand the cost situation over the years from 2001 to 2009.

4.4.1 Evolution of Horizontal Directional Drilling

The first HDD project took place in 1971, when 615 foot of 4-in diameter steel pipe was laid for the oil and gas industry (Allouche, Ariaratnam and Lueke 2000). By the early 1980s, more sophisticated equipment (compared to that of the1970s) was already available, and the technology was experiencing its first growth. However, HDD wasn't yet a common method to be used because it was new and had not been used in any other market than oil and gas.

During the 1990s, HDD went through a big expansion when telecommunications in the US experienced tremendous modifications, and huge projects were undertaken to install fiber optics. As more environmental friendly methods were needed, HDD became an attractive alternative to cross beneath rivers, lakes, parking lots, highways and railroads, and to work in congested urban areas. In 1996, approximately 30% of underground work was completed with directional drilling equipment and approximately 50% by 1999-2001, this occurred concurrently with the availability of new types of equipment to apply the technology. Most products installed during this period were of small diameters and contractors were operating small HDD rigs of 40,000 lbs maximum thrust/pullback force capacity (report 2005). Table 4.5 provides information about the type of product installed at the end of the 1990s (Allouche et al 2000).

Table 4.18 Pipeline Product Installed by Diameter / Material (Allouche et al, 2000)

Diameter	Pipeline product material					
	PVC	HDPE	Steel	Other	Total	%total
50-100 mm	241,428 m	891,494 m	64,573 m	4,500 m	1,201,994 m	72
150-200 mm	6,686 m	11,688 m	55,717 m	0 m	179,288 m	11
250-300 mm	457 m	7,730 m	72,042 m	0 m	80,229 m	5
> 300 mm	0 m	13,146 m	180,144 m	0 m	193,290 m	12
Total	248,572 m	1,029,253 m	372,476 m	4,500 m	1,654,800 m	-
%total	15	62	23	0.3	-	-

However, there was not many HDD experienced contractors, and the competition was low.

By the end of 2000, the US faced an economic recession, and the telecommunication and internet-broadband industries recorded a significant downturn. Nevertheless, the HDD market remained strong until the last months of 2001 when the consequences of the telecommunication recession took effect and the market saw a contraction by as much as 40%. Many small rig contractors, particularly those specialized in fiber-optics, went broke while other were struggling to stay in business, cutting prices and charging below their actual costs, wishing that projects would be awarded to them. On the other side, there was still oil and gas, water and wastewater projects going on, even if only a few municipalities were choosing HDD to install their water and sewer lines.

It was only in the early to mid 2000s that HDD come into play for the public works (water and wastewater) market, because public works engineers have been skeptical about the technology for years, specifically for sewer line installation. But new equipment models became available for both small and large diameter pipe, and by 2004 there was much more awareness, knowledge and experience regarding HDD, on the part of contractors, operators, public officials and regulators because contractors, manufacturers and engineers teamed together to develop educational programs. As a result, municipalities started to consider HDD as a suitable method to install water and wastewater pipe beneath rivers and roadways e time the contractual, technical and economical aspects of the method was more advantageous than any other method, for example open-cut. At this time, lots of jobs were in place for the public works market. Even with more experienced contractors, the competition was low for the large rig market because most of the experienced contractors were involved in utilities (small diameter, mini-HDD) and did not have either the large rig experience or the capital required to enter the large rig market. Yet, many small and medium rig contractors have adjusted to public works operations and have found a stable market in water line installation, because most water lines are pressure pipes and do not require tight line and grade tolerances. The same trend remained for 2 to 3 years.

By late 2007 the small rig market started to slow, while medium rig and large rig contractors continued to increase their share of the pipeline and utility market with both oil and gas and public works. Figures 4.2 and 4.3 provide information about variation of market share, by rig size, from 2006 to 2009(Carpenter 2009). By 2009, the US faced another economic deterioration, considered harder than 2001 because all sectors were affected. By this time, there were more experienced contractors using the technology and competition was tight, additionally public and private construction expenditures were decreasing. In a survey conducted by *Underground Construction Magazine* in 2009 among US HDD contractors only 15.7 % expected an increase in their HDD volume of work, while 40.2 % expected the same amount of work and 44.1 % of the respondents affirmed that contracts volume had significantly decreased. Again, in all markets, contractors had to lower their costs in order to get work. It was reported that many of them predicted a flat market for 2009 with a 10% increase in 2010 due to stimulus money.

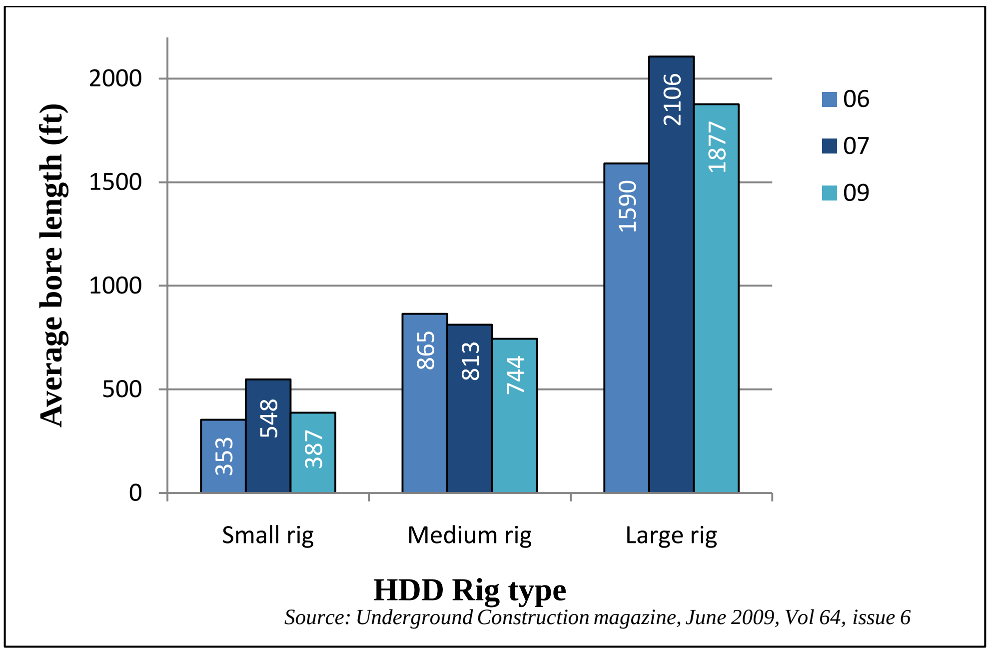


Figure 4.6 Average Bore Length Installed per Rig Type from 2006 to 2009

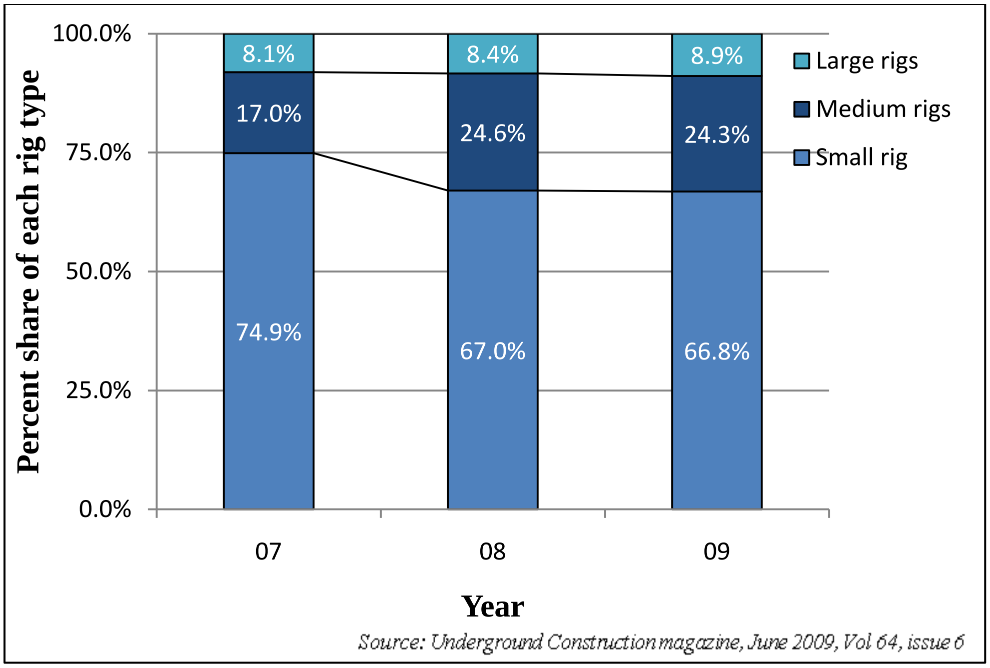


Figure 4.7 Percent Share of HDD Market per Rig Size from 2007 to 2009

Using the 106 water and wastewater projects collected for this research, an additional repartition of the rig share, per diameter ranges can be shown, Figures 4.8 and 4.9 show what size of rigs are mainly used by contractors, based on water/sewer product size. For the purpose of this particular assessment, rig sizes were divided as follows:

- Small rig : less than 40,000 lbs
- Medium rig: from 40,000 to 100,000 lbs
- Light Large rig: from 100,000 to 300,000 lbs
- Heavy Large rig: over 300,000 lbs

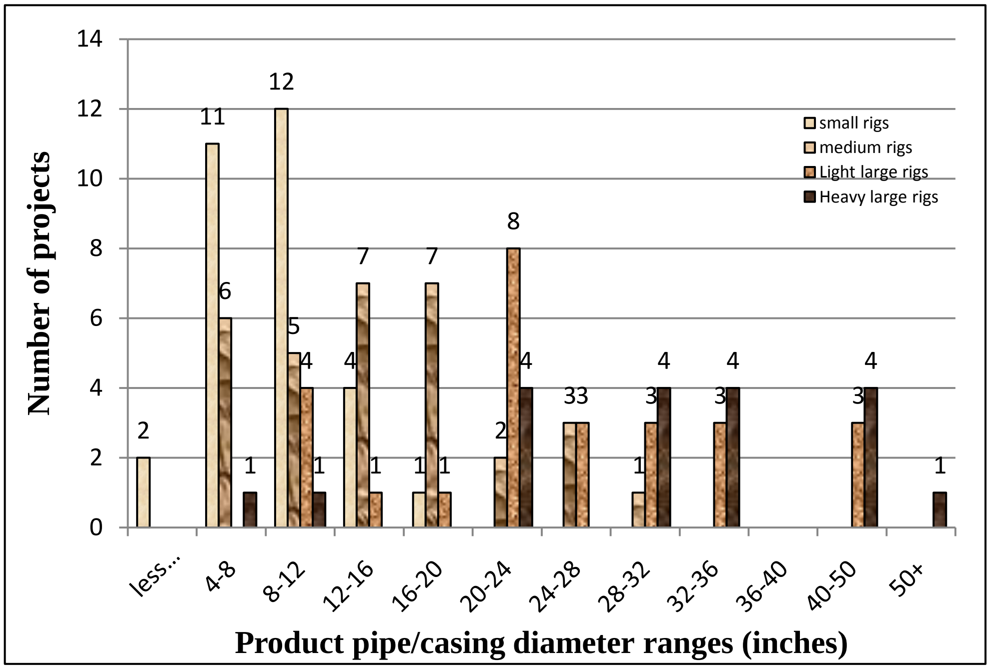


Figure 4.8 Number of Projects per Diameter Ranges

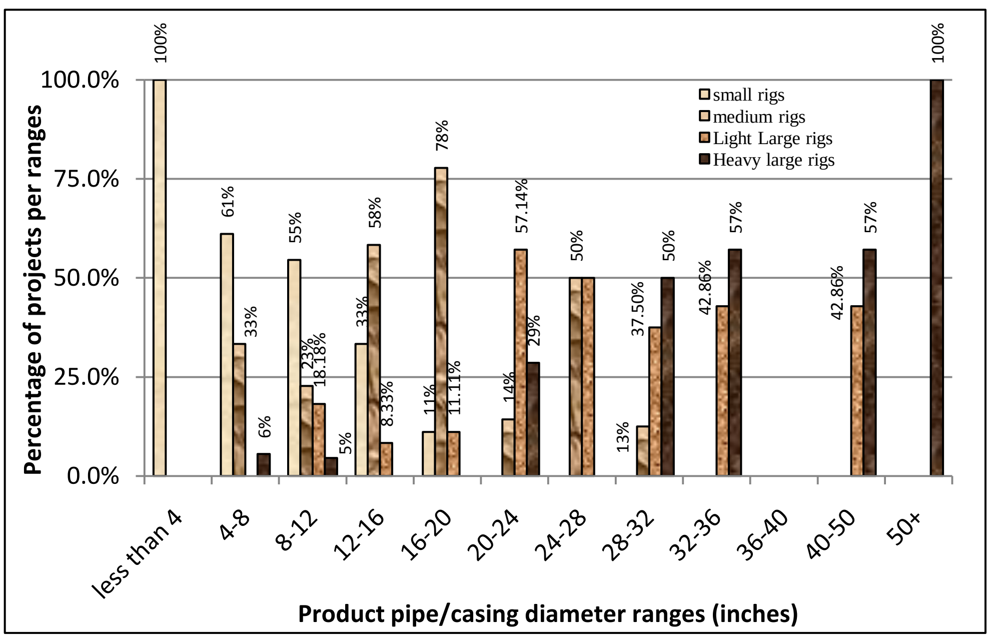


Figure 4.9 Rig Size Percent of Water/Sewer Projects per Diameter Ranges

According to the projects analyzed, small rigs are mostly used for diameter less than 16 inches, but are dominant for product size up to 12 inches. Medium rigs install product from 4 to 24 inches, but are mostly being used for 12 to 20 inches pipes. Light large rigs go up to 50 inches, but mostly install 24 to 45 inch pipes; while Heavy large rigs are used for diameter of 32 inch and up.

An important fact about rig choice is that contractors mostly use rigs they have to work on jobs they have been awarded. Rig size choice is affected by soil conditions, length, diameter and depth; and there exists a full range of different models of equipment to be adapted to each situation. However, contractors do not buy all of them; they mostly stick to a few models that they used on every project. In case the equipment differs slightly from the requirements, they execute necessary modifications or use additional equipment if necessary.

4.5 Main Fluctuations of the US Economy through 2000 to 2009

To underline the impact of the US economy on construction cost, it is important to analyze and show the main variations of the US economy from 2000 to 2009.

These variations are actually predicted and studied using a number of parameters specifically called US economic indicators. These indicators cover a broad variety of economic processes that were proven to be important in business cycles. Three categories of US economic indicators exist: the leading indicators, the coincident indicators and the lagging indicators. Leading indicators are measures of anticipation, prediction and new commitments. Highly sensitive to economic changes, they provide a look-ahead of future economic conditions.

Within this category fall the number of housing building permits and the number of housing starts for the period. Coincident indicators are measures of economic performance. Their variations indicate the current state of the economy and they are the required measures to determine if a nation is prosperous or depressed. An example of a coincident indicator is the Gross Domestic Product (GDP). Lagging indicators are those that react after the economic change. They are useful to confirm that predictions and coincidences were effectively occurring. An example of lagging indicators is the Consumer Price Index (CPI).

Among the 50 plus indicators used to describe the US economy, four of them have been chosen to describe the variations of the economy through 2001 to 2009. They are: Building permits, Housing starts, Gross Domestic Product (GDP), and Construction Spending. These indicators have been selected because they describe either a significant portion of the economy's variation or the fluctuations within the construction industry.

4.4.2 The Gross Domestic Product (GDP)

The GDP is a medium to high market sensitivity coincident indicator, which measures how slow or fast the US economy is growing. It is the most important economic statistic to come out e quarter of the year, and is used by the economic sector, the White House and Federal Reserve Officials, economic forecasters and CEOs of all types of businesses. GDP variation mildly affects bonds and stock value, but highly affects the dollar value. In the case of a growing economy, the value of GDP growth for several following quarters will determine how it affects stocks and bonds. Usually, GDP growth less than 3.5% for several consecutive quarters will result in an increase in stocks if inflation is contained (Baumohl 2008). When GDP growth shows a economic expansion equal or less than predicted, bond prices still react positively and increase in value; however, a significant economic expansion greater than predicted will bring down bond prices. GDP growth incurs in a higher dollar value because foreign investors find more opportunities for higher profit in a strong economy.

The GDP represents the total price tag in dollars of all goods and services produced in the US, including power plants, baby toys, houses, food and so on. It reflects the final value of all output in the US economy, by national or foreign entities, whether sold or in inventories. The GDP report computes the size of the economy in two different ways: one is in current (nominal) dollars which considers the price of the good at the present moment, and the second is in real (chained) dollars where it counts the value of what is physically produced. It is important to do so in order to evaluate whether the economic growth depends on greater production or higher prices due to inflation. A higher real GDP shows improvement in the economy and the living of Americans, while a growth in the nominal one depicts an inflation increase (Baumohl 2008). Both of these measures are fundamental to analyze the variation of the economy; however, this research will consider the real GDP variation because we want to determine the amount of production over the years of interest. Figure 4.10 presents the GDP in 2005 chained dollars, seasonally adjusted annual rates from 2000 to 2009.

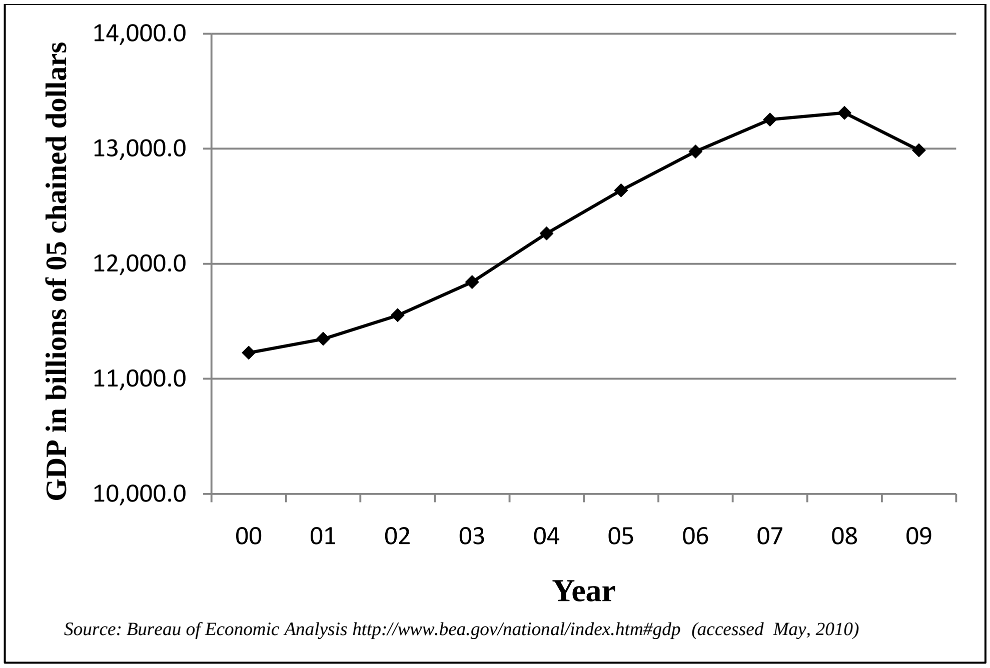


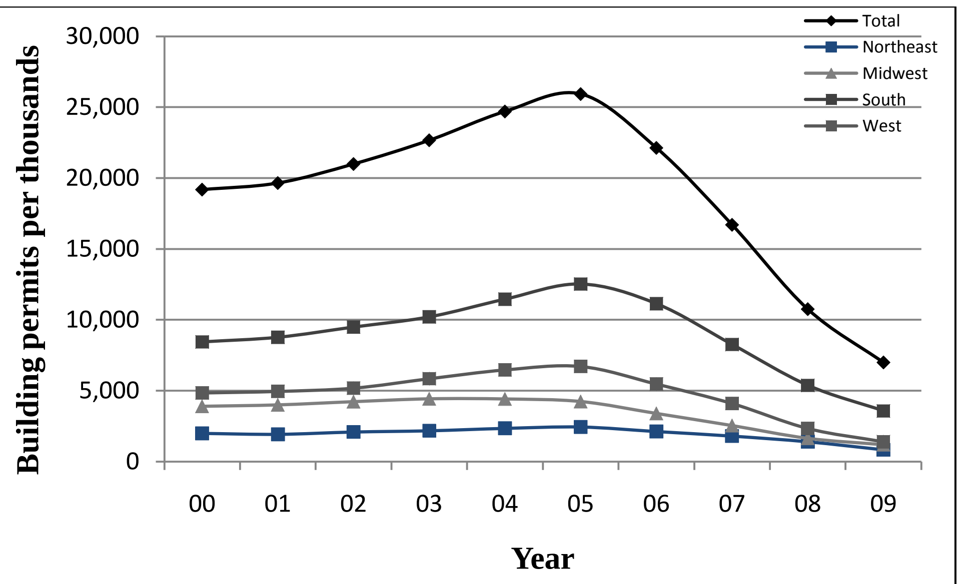
Figure 4.10 GDP Variations through 2000 to 2009

4.4.3 Building Permits and Housing Starts

Building Permits and Housing Starts are two economic indicators tightly related to the construction industry; the latter representing an important part of the US economy since it contributes about 10% of the GDP. These economic indicators are mostly sensitive to bonds; an increase in the number of housing starts and building permits usually influence bond prices to decrease, which is a good situation for construction contractors (Baumohl 2008).

Ninety-five percent of all US localities require new builders to file for a permit in advance. The number of permits issued for the entire country over a period in time is recorded and computed, and represents the “building Permit” economic indicator. Housing starts record how much groundbreaking occurred for residential real estate every month. It tracks data for three types of structures: single-family houses (75% of residential market), two to four apartments or units

(5% of residential market) and structures with five or more units (20% of residential market). These two indicators are among those, over the years, that have presented an impressive potential to predict the variations of the economy, far before the actual change occurs. The housing market is a leading indicator predicting far ahead what could happen in the country, because of its sensitivity to interest rates. In an overheated economy, interest rates are high and it discourages both builders and homebuyers; if there is no balance, demand for new homes will go down. In a weak economy, interest rates become low, and homebuyers and builders rush into banks to borrowed money, which start to increase the number of house construction far before the economy restarts to grow (Baumohl 2008). Figure 4.11 and 4.12 present variation of building permits and housing starts in the US, respectively, from 2000 to 2009.



Source: US Census Bureau, http://www.census.gov/cgi-bin/briefroom/BriefRm (accessed in May, 2010)

Figure 4.11 Building Permits Issued per Year in the US from 2000 to 2009

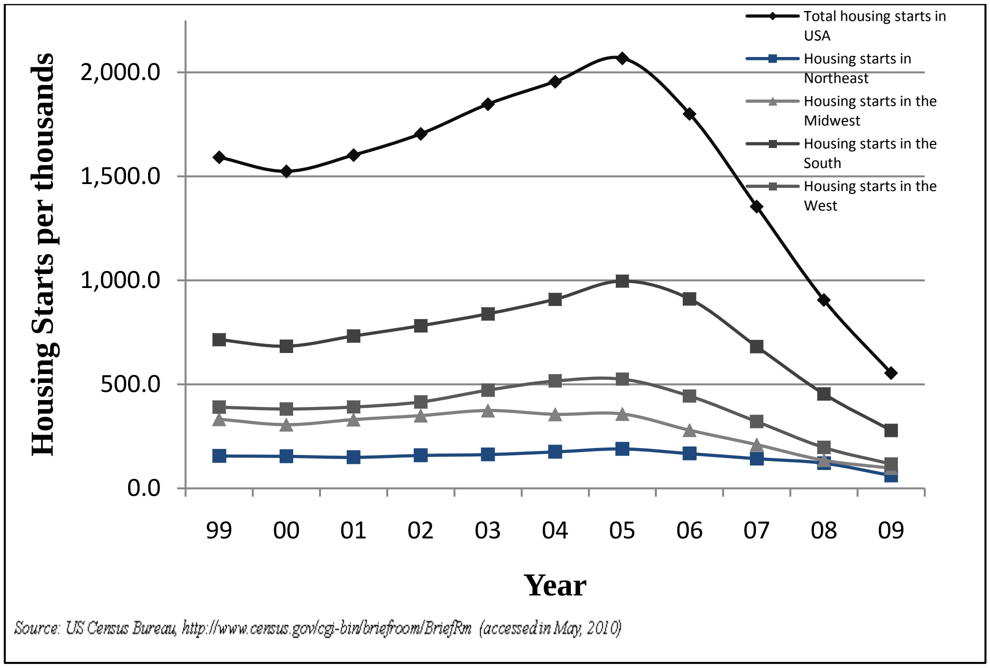


Figure 4.12 Housing Starts in USA from 1999 to 2009

4.4.4 Construction Spending

The construction spending economic indicator records all public and private spending in construction e month. It is computed monthly and annually. This indicator does not have a significant importance for bond and stock holders but is more important to the construction industry since it shows the economic tendencies of construction investors. This report considers both residential and non-residential construction and is the most comprehensive parameter to evaluate economic activities of the construction industry. Construction is a major part of the economy which is about 10% of the US GDP (Baumohl 2008).

Construction spending is divided into three main categories:

1) Private construction for residences (5% of GDP)

2) Private nonresidential structures (2.4% of GDP)

3) Public construction (2% of GDP)

The report provides information about total spending, and then is brokendown by sectors and products. Figure 4.12 describes total construction spending in the US from2000 to 2009.

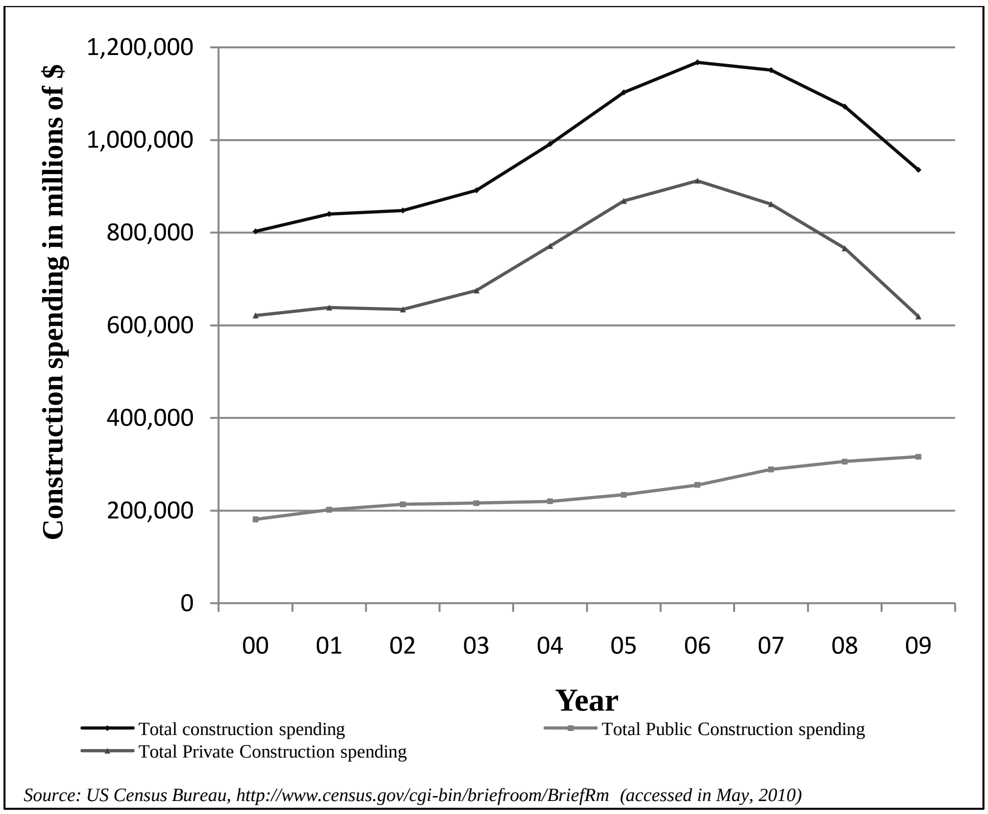


Figure 4.13 Total Construction Spending in the US from 2000 to 2009

4.4.5 Unemployment Rates

The employment situation is a highly market sensitive economic indicator, ranked as the first most sensitive economic indicators to bonds, stocks and dollar value. The employment report is full of information about households' earnings and the well-being of American workers. Indicators data in this report are all related and they present data including national employment and unemployment rates and average earnings.

In this research the national unemployment rate was used to evaluate the variation of the US economy from 2001 to 2009. This economic indicator presents the variation of the percentage of the US civilian labor force 16 years and older, that is not working. This data comes from a household survey conducted by the United States government every month. An increase of unemployment rate shows a weak economy and usually contributes to an increase in bond value and a decrease in stock and dollar value (Baumohl 2008). Figure 4.14 presents the variation of unemployment rates from 2000 to 2009.

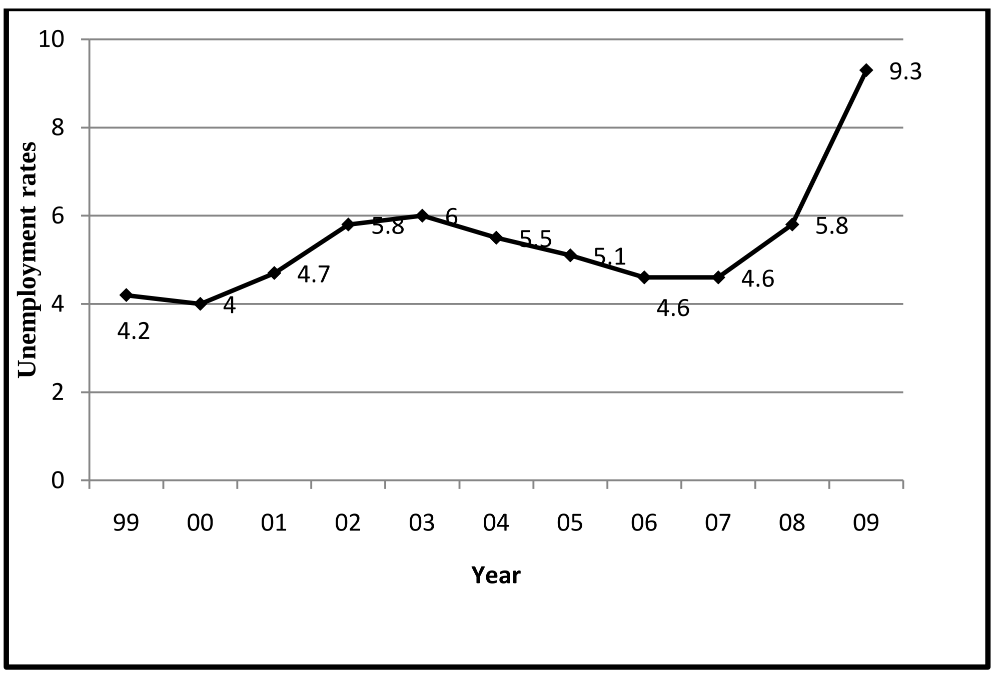


Figure 4.14 U.S. National Unemployment rate from 2000 to 2009

4.4.6 A Note on Interest Rates

The U.S. monetary policy affects all economic and financial decisions occurring in the country, whether from an individual, a household, a corporation or a bank. It greatly influences the value of bonds, loans and interest rates from private financial organizations. The first objective of this monetary policy is to alter the performance of the economy, particularly regarding the aspects of inflation, economic output and employment; by affecting demand across the economy (for example the tendency of the population to spend on goods and services across the nation).

The interest rate that determines consumer behavior is not the rate set by the financial market (nominal interest rate) but rather the rate fixed by the Federal Reserve Bank of the United States (real interest rate). The real interest rate is the nominal rate minus the inflation rate; it is used by the Federal Reserve Bank to attain different economic objectives across the nation, particularly, to promote stables prices. Changes in real interest rates influence the public’s demand for goods and services by modifying borrowing costs, the availability of banks loans, the wealth of households and foreign exchange rates. A decrease in real interest rates lowers the cost of borrowing and results in businesses augmenting their investments portfolio, and in households buying more durable goods. Lower rates also result in an increase of stock value and a decrease in bond prices. Lower real interest rates also reduce the value of the dollar (Federal Reserve Bank of San Francisco). When the economic expansion is too fast, the Fed increases the real interest rate to contain inflation; for example they reduce the spending power of the public to avoid a high increase in goods' prices. The impact of the real interest rate variation is not concurrent, for example a variation of this rate usually modifies the nation's economy two to three quarters later and sometimes even two years later. Therefore, the real interest rate is a leading indicator which allows predicting what the economy will be later and can be utilized as a decision parameter for future plans(Federal Reserve Bank of San fransisco; 2004). Figure 4.15 presents the variation of the real interest rate from 2000 to 2009.

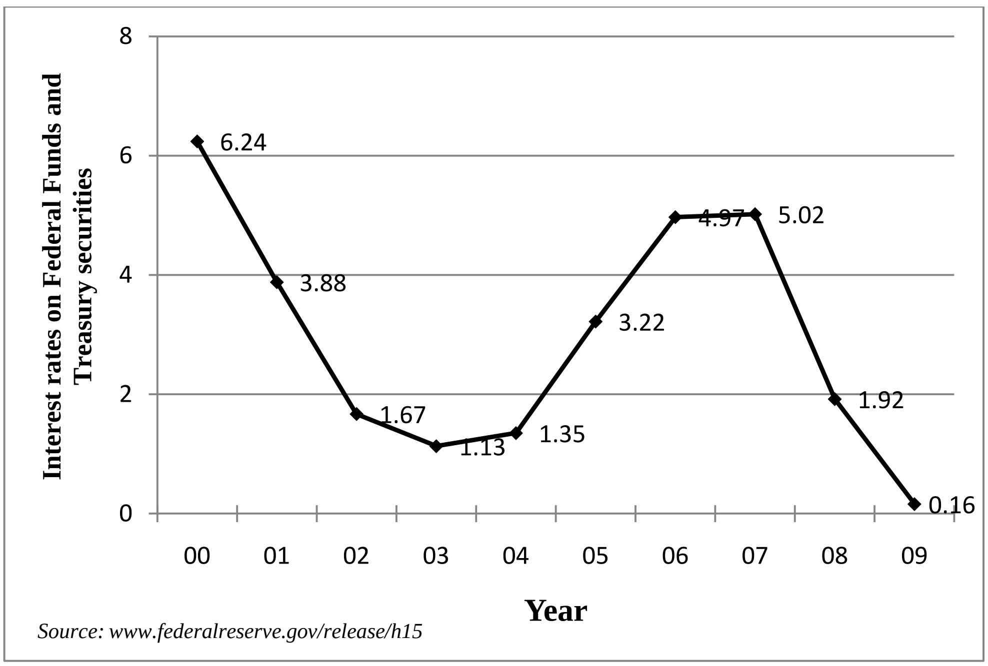


Figure 4.15 Interest Rates on Federal Funds and Treasury Securities

4.4.7 Summary

A review of Figures 4.10 to 4.15 presenting 6 economic indicators, grossly informs us about how the economy have expanded or contracted over the period from 2001 to 2009. During the second half of the 1990s, the economy was growing and was mainly influenced by the big developments in telecommunications and internet called the dot-com boom. During this period from 1995 to 2000, stock markets were at their peaks because of the founding or modifications of companies claiming themselves related to the internet sector. This resulted in an overvaluation of many of these companies, which later resulted in a crash when share prices fell. Consequently, this crash occurred in 2001 when the telecommunication and internet industry faced a downturn that engendered a short-lived, mild recession in late 2001. Often, this recession has also been associated to the 9/11 events that occurred in New York; however, it did not affect all economic sectors even if the construction industry was hit. Looking at GDP and Building permits variations, the growth was quite small compared to other periods of time; and a decrease is observed in housing starts from 1999 to 2000; housing starts being a leading indicator characterizing the state of the economy a few quarters before the event. An evidence of slow growth is shown around 2001, when total construction spending varies slowly with private construction spending almost being constant. From 2001 to 2007, the economy showed a sense of growth and stability; economic indicators were growing from 2001 to 2007, except housing starts showing important decreases since 2005. In 2008, an economic disaster blasted the world and particularly the United States, starting with the collapsing of housing markets in California and Florida. Some big companies and banks in the US, with billions of assets, have collapsed. This ongoing recession has affected all economic sectors in the country, and in 2010 a recovery is not yet effective.

4.6 Horizontal Directional Drilling Industry Trends.

Sixty-three US projects were analyzed, and a snapshot in cost variations is made, from 2001 to 2009. The variations coming from bid prices for project direct costs are presented in Figures 4.16 and 4.17.

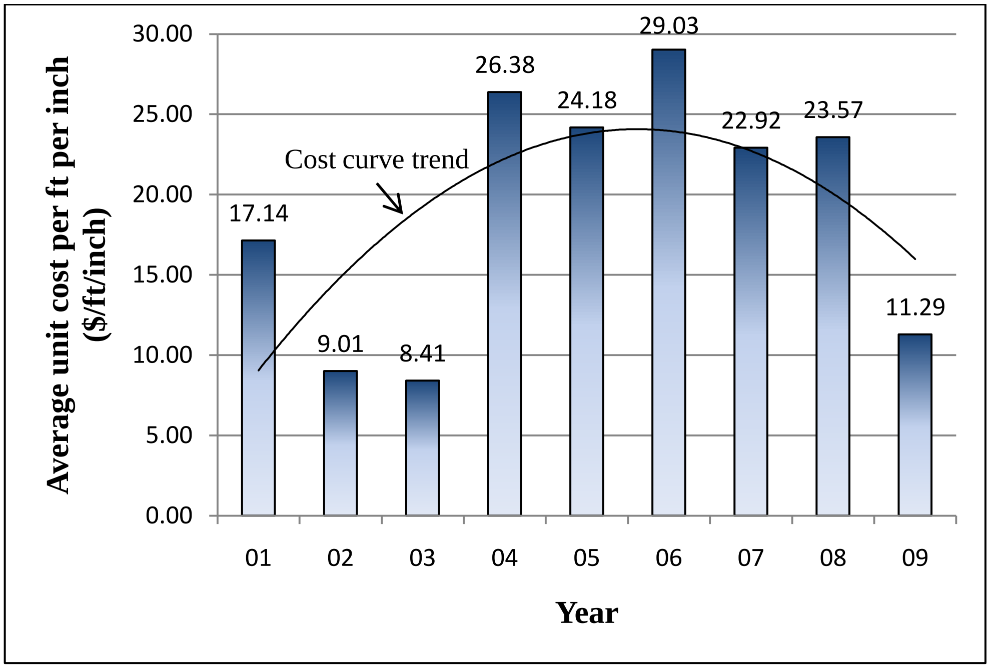


Figure 4.16 Average unit cost/foot/inch of water/wastewater HDD projects in USA from 2001 to 2009

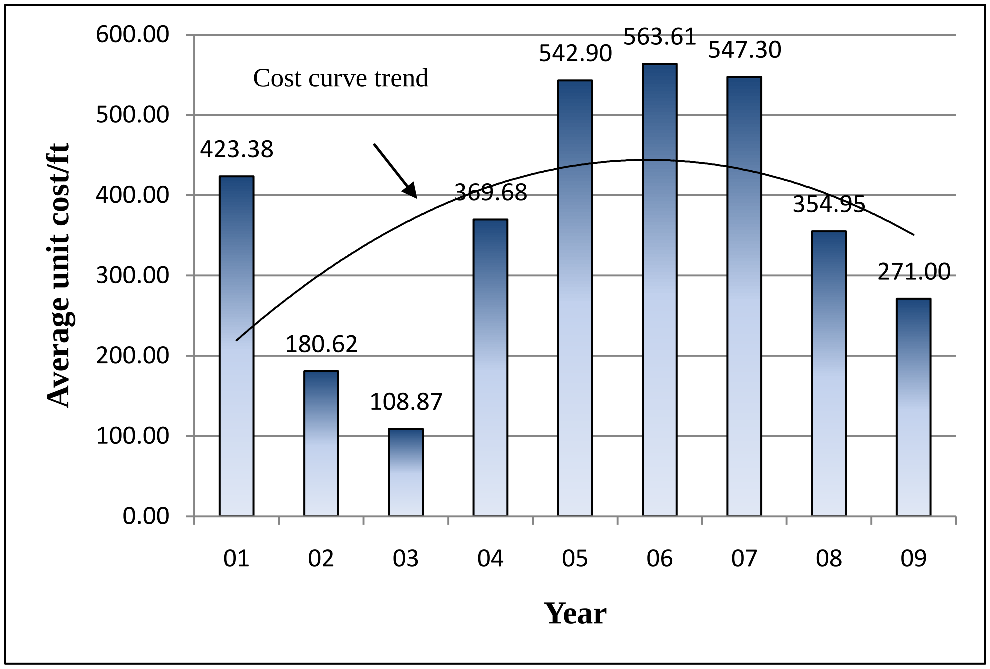


Figure 4.17 Average unit cost/foot of water/wastewater HDD projects in USA from 2001 to 2009

The level of construction prices is affected by many different factors. These factors include inflationary trends in the economy, the current level of construction activity, seasonal effects, and the cost of borrowing money (Williams 1994). The trend obtained in Figure 4.16 shows a variation similar to the economic indicators (Figures 4.10 to 4.15), with unit costs increasing from 2001 and having the peak around 2005, 2006 when the economy was at its peak before starting to decrease in 2007. The main variations in the HDD industry presented in paragraph 4.4 explains how contractors had to lower their prices in order to stay in business, because at the end of 2007, there were an increase of contractors with expertise for a decreasing number of jobs. Besides been affected by the cost of material, labor and operations, contractors reduced their markups and margins in times of bad economy in order to get jobs and stay in business. Because the amount of construction spending is cut during recessions, both private and public sectors faced a shortage of projects, which consequently will affect construction contractors, particularly HDD ones.

At the beginning of 2001, the US economy was doing pretty well and so was the HDD industry with the remaining impact of the telecommunication boom, which had since started to decline. With most of economic indicators varying in the positive direction and a decreasing real interest rate, it is assumed that the construction sector was working pretty well and construction spending was increasing. However, the leading indicator housing starts showed a decrease from 1999 to 2000 and it can be assumed that a few quarters later stocks value would become lower and bonds prices higher. This eventually occurred, since the real interest rates had consistently decreased from 1999 to 2004. HDD contractors have taken advantage of past 99-00 contracts, and because there was not a lot of competition (Carpenter, 10th annual HDD survey: Large rig market speeds ahead 2008), prices were still higher than it would be for the next two following years. At the end of 2001, the US was hit by a mild recession which did not affect all economic sectors but surely had an impact on stocks and bonds because the unemployment (leading indicator) rate was increasing.

From the end of 2001 to 2003, the some sectors of the US economy were still expanding after the effect of the mild recession. The Federal Reserve Bank kept a decreasing rate for real interest, eventually trying to stabilize prices to push the economy to a greater expansion. However, public construction spending was growing slowly, and so was the unemployment rate. These economic indicators were contradictory for a period of time and it can be assumed that the stock values were not stable because after the mild recession, the economic expansion was carefully accepted. The HDD industry started to feel the impact of the telecommunication breakdown, and many small rig contractors were struggling to stay in business. Consequently, even if costs were lower in 2002 and 2003, the cost trend was consistently following the growing economic trend, and attained a peak around 2004-2005.

From 2004 to 2007, all economic indicators had a positive explained an economic expansion. The unemployment rate was decreasing, while GDP, Housing Starts, Building Permits and Construction spending were increasing. This traduces an economic expansion, and it was expected that stock value were appealing and encouraged investments. These are in part the consequences of the Federal Bank economic policy in 2002 – 2003, known to have an effect some quarters later. HDD was at the same time experiencing an expansion while the public work sector started to choose this technology to achieve their projects. The number of large and medium rig contractors was growing, but still in a limited and slow manner. There were many investments taking place in the oil and gas industry, while engineers working for municipalities were investigating the many possibilities of HDD. It can be observed (see Figure 4.15) that between 2004 and 2007, real interest rate consistently grow, eventually to contain inflation and stabilize prices. These were the excellent days of the HDD industry, and prices were high because of the number of projects.

By 2005 – 2006, the leading indicators, housing starts and building permits, already started to decrease and predicted that the economy would start to contract a few quarter later. In addition, by 2007 – 2008 most economic indicators were indicating that economic contraction was evident. Real interest rates were decreasing, which would result in higher bond prices and a declining stock market. The US was sliding into economic recession, and the HDD cost trend was declining. Real interest rates show that the Fed took aggressive measures to improve the economy; the rates vary from 5.02 % in 2007 to 0.16% in 2009. But this reduction, will impact the economy a few quarters or years later. The 2008-2009 recessions was hard on many construction sectors and did not avoid the HDD industry. This case was different than in 2001 when there were not that many HDD contractors. Because of the 2004-2007 attractive market, a number of HDD companies went into business and the economic situation in 2007 hit them hard. Prices had to go even lower than market price, because contractors wanted to stay in business. In addition, bond values were increasing in the market while investment portfolios were declining. The cost trend shows the evidence, and a decreasing tendency is observed from 2007 to 2009.

4.7 Chapter 4 Summary

The first section of Chapter 4 discusses how project parameters affect the cost of water and wastewater HDD projects. For three different rig sizes (small, medium and large), a regression analysis was performed to determine how much parameters like diameter and length influence the variation of total cost. Based on the value of correlation coefficients, it was determined that diameter and length explain 47.5% of the total cost variation for large rigs and 61% of total cost variation for medium rigs. For small rigs soil condition was considered in addition to diameter and length, and together these three parameters explain 80.8% of total cost variation. The regression results follow a particular pattern. It is observed that the larger the rig, the smaller is the portion explained by project parameters because the correlation is decreasing when the rig size is increasing. Challenges incurred by large rig projects are significantly greater than those incurred by medium and small rig projects. Also, because of the average size of large rig contracts compared to the size of small or medium rig projects for example long length or large diameter or both with an important depth, equipment requirements, personnel experience and size, mobilization, risk contingencies are all much more important for large rig than the other ones. These reasons make large rig projects more costly than medium and large. However, HDD projects costs are not affected only by the price of material, labor, equipment and other factors related to project geometry and scope. Bid prices calculation greatly depends on contractor practices and state of the market. It was observed that contractors' practices were not similar if they were operating different rig size. Small rigs contractors depend on volume (for example length, diameter) to make profit, while large rig contractor usually make their project profitable by fixing a certain percentage of cost as their margins. The price/foot practice is more applicable to small rig contractors. Large rig contractors also charge their customer based on their experience, reputation and the type of large rig (light large or heavy large) they are operating. Another factor that was found to be important for bid price calculation is the state of the market. When there are a lot of competitors (usually for small and medium rigs) for a limited of projects, bid prices have the tendency to be lower because contractors are competing hard to get jobs. When there are enough projects, bid prices are greater. However, in the large rig market there is not that many competitors (8.9% of contractors in 2009) and contractors have more freedom to practice higher rates. It was observed in the collected data that heavy large rig contractors even had bid prices higher than usual large rig projects bid prices because of their experience and reputation.

The second section of Chapter 4 uses unit cost to compare and analyze how bid prices differ from one category to another. These unit costs are used only for the comparison, and were not intended to be included in any calculation procedures. Four categories were considered: community type (urban and rural), product type (water and wastewater), USCS - soil classification (GW-GC, SW-SC, ML-OL, MH-OH and PT) and US regions (Northeast, South, Midwest and West). Rural projects were found to be a little more expensive than urban projects, because of higher transportation and labor costs. It was observed that wastewater projects were more expensive than water projects because wastewater projects present greater challenges and risks due to tight line and grade requirements. Wastewater projects require more sensitive equipment, more experienced personnel and have a greater risk mitigation plan. Soil conditions incurring greater costs are the less cohesive ones. Gravel is the most expensive; this is the least suitable soil condition in regard to HDD installation because gravel, cobbles and boulders present difficulty for borehole stability and equipment utilization. Sands react better than gravels and incurred lower costs than gravels, but higher than silts and clays. Silt and clays are the most suitable soils, and certainly incurred lower costs because they have good cohesion. The most expensive US regions for HDD installation are the West and the Northeast, followed by the South and ending with the Midwest as the least expensive. In this section also was a current rig utilization chart where the percent of each rig size used for different diameter ranges was presented. The last section and one of the most important of this research, was to analyze the evolution of unit cost over years and briefly compare with the evolution of the US economy, in an objective to determine how it can affect bid prices. Effectively, observing the variation of US economic indicators like; unemployment rate, Gross Domestic Product, Housing Starts and Buildings Permits, Construction Spending and Real interest rates on federal Funds; it was determined that the HDD project cost trend was following the same pattern than US economic variation showed by the economic indicators used. A brief link was made between bond, stock, dollar value and HDD unit cost variation.

CHAPTER 5 – CONCLUSION

5.1 Summary

The main findings of this research are summarized in the following.

- Geometric parameters involved in water and wastewater pipelines installation using HDD technology don't have the same effect on bid prices when the drill rigs size changes.
- Because small rig contractors rely more on volume for profitability; bid prices depend more on the value diameter, length and soil condition. The trend is a decreasing effect of these parameters on bid prices when rig size increase. Correlation coefficients were as follow: small rig (R_a^2 = 0.808), medium rig (R_a^2 = 0.61) and large rig (R_a^2= 0.475).
- Comparing costs by product type, it was found that the average bid price of wastewater projects is higher than the average bid price of water projects. This is verified because of the challenges incurred by wastewater projects when they are gravity lines.
- HDD projects in rural areas have an average bid price slightly higher than HDD projects in urban areas. Usually projects in rural areas incurred higher transportation costs for labor and equipment. Additionally, the count of rural projects was small (6) comparing to the count of urban projects (57); so the comparison is indicative.

- The average bid price for HDD project is higher in gravels and sands, than in clays and silts.
- This research shows the evidence that HDD projects bid prices are greatly impacted by the market state and the economic situation of the United States. The cost curve trend from years 2001 to 2009 follow the same pattern than the variation of key economic indicators like the gross domestic product, unemployment rate, building permits, housing starts, construction spending and real interest rate of the federal bank of the United States.

5.2 Limitations

The main limitations of this research were data availability and data collection. Since the topic was a little touchy and sensitive, it was difficult to find a reasonable number of projects' description where bid prices were reported. Most of conference proceedings presenting Horizontal Directional Drilling case studies, do not report the bid price of the contract. Most contractors do not report their prices because it constitutes their principal asset to compete with their peers. It is understandable that they are reticent to give exact information on how they calculate their bid prices, above all in an economic recession like this of 2009.

In addition, there are no defined rates for the HDD industry; and it does not exist any official document where one can track the cost of projects. The Construction Financial Management Association (CFMA) does not yet have a section for HDD contractors. Most of the projects used for cost investigation in this research were awarded publicly, and therefore, the bid price was made available for the community where the job was taking place. Also, a number of conference proceedings, journal papers or magazine provide the bid price of projects; but usually when it is necessary for a comparison with another method or to show the advantages of HDD. Another issue was when the HDD installation represented a portion of a larger job; in such cases, the bid prices usually reported are for the entire project and not just for the HDD installation.

A cost survey was considered to be conducted in the first place, however; due to time restriction and the reluctance of contractors to reply to these questions, this idea was soon excluded. Sometimes, the most important information (bid price) was available but almost all other parameters were not. Often times, there were no information about equipment or soil condition.

Unavailability of data was the primary reason why this research was made on 2 different data sets: one using only 63 projects, and another using the total number of projects which was 106; because it was possible to include all project with no bid price information in the rig size evaluation chart and the tables comparing sizes for each category of rig.

5.3 Recommendations for Future Work

This research represents an insight and a start for the HDD industry about the bid price/cost topic, because there were not that many documents available about it. However, it is only one of the many orientations that a cost investigation can have. To further develop the work done in this study and make deeper investigation, recommendations have to be considered on some particular aspects.

5.3.1 Data Collection

The data sample collected for a deeper research should be of the same size for each category; for example it would be important to have the same number of projects for each product type, of each soil condition, or each region or each year, in order to have a better repartition when calculating averages. When all categories have the same number of projects, the outcome will not be altered too much by the dominant category or condition.

Rig Size

Observations from this research show that costs of light large rig projects are not similar to those of heavy large rigs, and it would be important to consider these 2 categories separately to better understand the practices or large rigs contractors. Heavy large rigs are owned by a handful number of contractors who have outstanding reputation and experience in the North American HDD industry. These heavy large rigs cost a lot to buy and to maintain, and it is evident that projects in which they are involved have uncommonly high bid price. However, the quality of these jobs is usually excellent; and it will take time for the industry to have a lot of heavy large contractors with that kind of experience. To enter this market one must have both capital and experience, 2 assets that are not easily acquired. So, I think it would be interesting for the industry to understand their practices; and a distinct cost model evaluation for both light large and heavy large rigs will better explain these differences.

Cost Model Deduction

This study was investigated for the 4 US census regions which are: Northeast, South, West and Midwest; but a deeper evaluation for the US census divisions would better explain the effect of location on bid prices. Labor cost, soil condition and environmental regulations are usually different on the state level and breaking down the data by regions does not consider all the details coming from these differences between states. It exists 9 US divisions, each including from 4 to 9 states.

Parameter to be added in further regressions would be the depth which is an important design parameter, which unfortunately was not reported enough to be included in this current analysis. It would be interesting to find data enough data about the average markups and gross margins of HDD contractors which could be included in regression and analyzed to determine how they relate to total cost of projects and increase the correlation coefficient of these models.

HDD Costs within the US Economy

The parallel between unit costs of projects and the variation of the US economy was briefly conducted because this research did not go deeply into economic data analysis. However, an economic study that relates the fluctuations of the HDD industry with the variation of bond, stock and dollar value based on the value real and nominal interest rates would be important for a growing industry. It would allow investors, contractors and owners to understand the market and better plan their portfolios based on the variations and predictions coming from leading economic indicators like housing starts, building permits and unemployment rates.

5.4 Conclusion

Horizontal Directional Drilling being a growing and expanding industry all over the world, it is important to understand how bid prices and costs are affected. This study was performed using data from projects in the US and a few in Canada. Since a lot of North American companies are looking for international markets, it would be even more interesting to see what the cost trend in other markets is.

This research has presented new information that will be useful to use in and outside of the US because most of the US is one of the leading countries in the HDD market. Municipalities and contractors in the US have at hand a useful document that will make them better understand the market, the industry cost calculation procedures and allow them to understand their peers. It will also help them evaluate the feasibility of projects knowing the characteristics of the parameters that will intervene in their projects.

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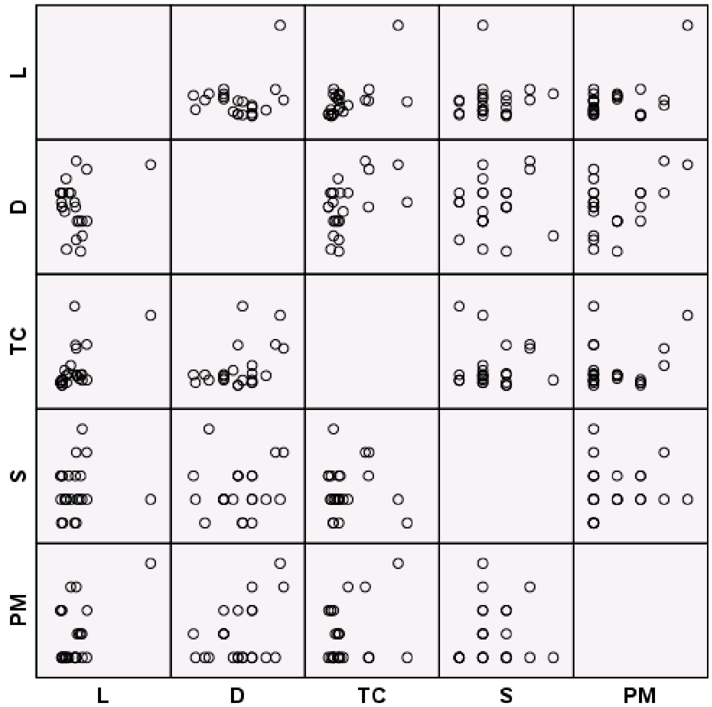
APPENDIX

I - SPSS REGRESSION OUTPUT



Matrix Scatterplots/Partial Regressions for large rigs

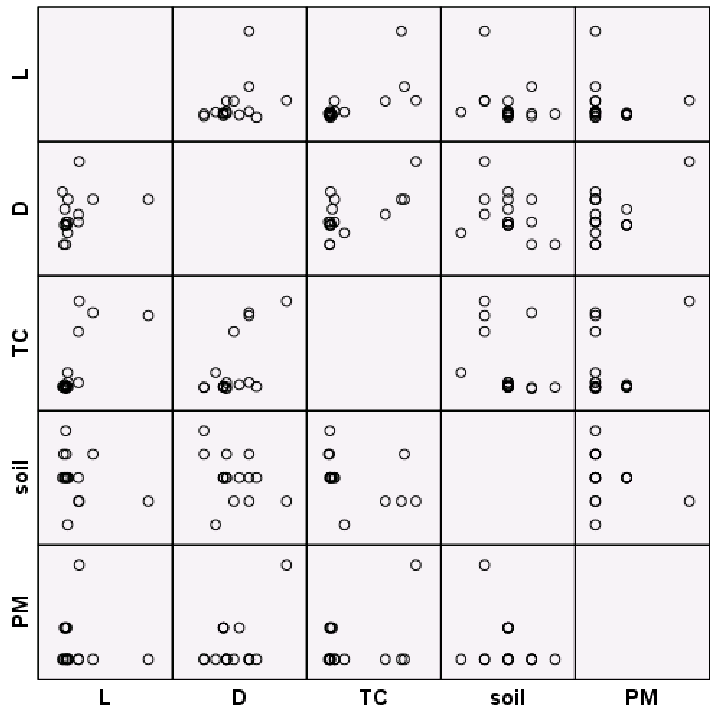
L : Bore Length

D: Pipe diameter

S: Soil

PM: Pipe Material

TC: Total Cost



Matrix Scatterplots/Partial Regressions for medium rigs

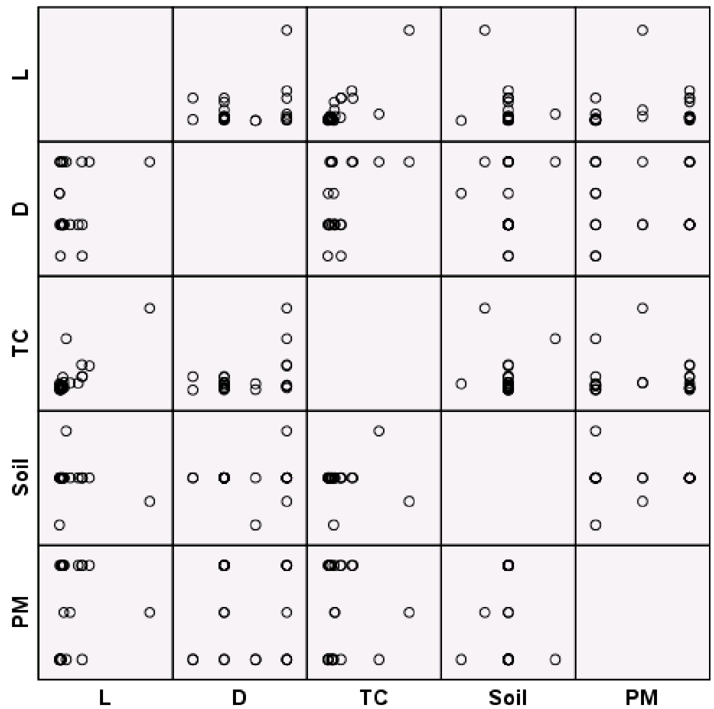
L : Bore Length

D: Pipe diameter

S: Soil

PM: Pipe Material

TC: Total Cost



Matrix Scatterplots/ Partial Regressions for small rigs

L : Bore Length

D: Pipe diameter

S: Soil

PM: Pipe Material

TC: Total Cost

SPSS regression results for large rigs

First multiple linear regression for large rigs

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	PM, S, D, L[a]	.	Enter

a. All requested variables entered.
b. Dependent Variable: TC

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.775[a]	.601	.534	2078360.872

a. Predictors: (Constant), PM, S, D, L

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	89030813562980.900	4	22257703390745.200	5.153	.006[a]
	Residual	77752510454495.000	18	4319583914138.610		
	Total	166783324017476.000	22			

a. Predictors: (Constant), PM, S, D, L
b. Dependent Variable: TC

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2165849.406	2846928.235		.761	.457
	L	448.751	128.961	.643	3.480	.003
	D	113369.991	45846.720	.436	2.473	.024
	S	-293307.468	432292.512	-.110	-.678	.506
	PM	-586493.677	442458.189	-.261	-1.326	.202

a. Dependent Variable: TC

Stepwise regression for large rigs

[DataSet1] V:\Users\ticlau\Documents\ASU\Thesis\spss\large rigs march 31st.sav

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	PM, S, D, L[a]	.	Enter
2	.	S	Backward (Criterion: F-to-remove <= 3.000).
3	.	PM	Backward (Criterion: F-to-remove <= 3.000).

a. All requested variables entered.
b. Dependent Variable: TC

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.775[a]	.601	.534	2078360.872	.534	5.153	4	18	.006
2	.722[b]	.522	.446	2048632.960	-.012	.460	1	18	.506
3	.689[c]	.475	.423	2092292.954	-.047	1.862	1	19	.188

a. Predictors: (Constant), PM, S, D, L
b. Predictors: (Constant), PM, D, L
c. Predictors: (Constant), D, L

ANOVA[d]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	89030813562980.900	4	22257703390745.200	5.153	.006[a]
	Residual	77752510454495.000	18	4319583914138.610		
	Total	166783324017476.000	22			
2	Regression	87042280896005.900	3	29014093632002.000	6.913	.002[b]
	Residual	79741043121470.000	19	4196897006393.160		
	Total	166783324017476.000	22			
3	Regression	79229527917740.600	2	39614763958870.300	9.049	.002[c]
	Residual	87553796099735.300	20	4377689804986.760		
	Total	166783324017476.000	22			

a. Predictors: (Constant), PM, S, D, L
b. Predictors: (Constant), PM, D, L
c. Predictors: (Constant), D, L
d. Dependent Variable: TC

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2165849.406	2846928.235		.761	.457
	L	448.751	128.961	.643	3.480	.003
	D	113369.991	45846.720	.436	2.473	.024
	S	-293307.468	432292.512	-.110	-.678	.506
	PM	-586493.677	442458.189	-.261	-1.326	.202
2	(Constant)	1612853.515	2688751.149		.600	.556
	L	446.350	127.069	.639	3.513	.002
	D	110713.655	45025.877	.426	2.459	.024
	PM	-594820.854	435961.658	-.264	-1.364	.188
3	(Constant)	-1568653.158	1367185.215		-1.147	.265
	L	368.238	115.859	.527	3.178	.005
	D	89544.648	43169.030	.344	2.074	.051

a. Dependent Variable: TC

Final multiple regression for large rigs, using D and L

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	D, L[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: TC

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.689[a]	.475	.423	2092292.954

a. Predictors: (Constant), D, L

b. Dependent Variable: TC

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	79229527917740.600	2	39614763958870.300	9.049	.002[a]
	Residual	87553796099735.300	20	4377689804986.760		
	Total	166783324017476.000	22			

a. Predictors: (Constant), D, L

b. Dependent Variable: TC

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1568653.158	1367185.215		-1.147	.265
	L	368.238	115.859	.527	3.178	.005
	D	89544.648	43169.030	.344	2.074	.051

a. Dependent Variable: TC

First multiple regression for medium rigs

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	PM, L, soil, D[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: TC

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.838[a]	.703	.594	863508.280

a. Predictors: (Constant), PM, L, soil, D

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	19377167772002.300	4	4844291943000.590	6.497	.006[a]
	Residual	8202112052195.660	11	745646550199.605		
	Total	27579279824198.000	15			

a. Predictors: (Constant), PM, L, soil, D

b. Dependent Variable: TC

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	-2911615.601	2297235.906		-1.267	.231
	L	248.216	82.547	.577	3.007	.012
	D	87430.712	53757.329	.361	1.626	.132
	soil	-30397.765	255669.670	-.022	-.119	.908
	PM	304587.323	347661.006	.183	.876	.400

a. Dependent Variable: TC

Stepwise regression for medium rigs

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	PM, L, soil, D[a]	.	Enter
2	.	soil	Backward (Criterion: F-to-remove >= 3.000).
3	.	PM	Backward (Criterion: F-to-remove >= 3.000).

a. All requested variables entered.
b. Dependent Variable: TC

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.838[a]	.703	.594	863508.280	.703	6.497	4	11	.006
2	.838[b]	.702	.628	827277.285	.000	.014	1	11	.908
3	.825[c]	.680	.631	823783.667	-.022	.890	1	12	.364

a. Predictors: (Constant), PM, L, soil, D
b. Predictors: (Constant), PM, L, D
c. Predictors: (Constant), L, D

ANOVA[d]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	19377167772002.300	4	4844291943000.590	6.497	.006[a]
	Residual	8202112052195.660	11	745646550199.605		
	Total	27579279824198.000	15			
2	Regression	19366627352284.500	3	6455542450761.490	9.433	.002[b]
	Residual	8212652471913.530	12	684387705992.794		
	Total	27579279824198.000	15			
3	Regression	18757225937884.700	2	9378612968942.350	13.820	.001[c]
	Residual	8822053886313.300	13	678619529716.408		
	Total	27579279824198.000	15			

a. Predictors: (Constant), PM, L, soil, D
b. Predictors: (Constant), PM, L, D
c. Predictors: (Constant), L, D
d. Dependent Variable: TC

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-2911615.601	2297235.906		-1.267	.231
	L	248.216	82.547	.577	3.007	.012
	D	87430.712	53757.329	.361	1.626	.132
	soil	-30397.765	255669.670	-.022	-.119	.908
	PM	304587.323	347661.006	.183	.876	.400
2	(Constant)	-3064885.066	1821656.929		-1.682	.118
	L	250.379	77.138	.582	3.246	.007
	D	88495.979	50781.412	.365	1.743	.107
	PM	310766.273	329331.483	.187	.944	.364
3	(Constant)	-1456281.115	639490.917		-2.277	.040
	L	224.769	71.901	.522	3.126	.008
	D	117187.906	40500.439	.483	2.893	.013

a. Dependent Variable: TC

Final regression for medium rigs

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	D, L[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: TC

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.809[a]	.655	.605	1232539.747

a. Predictors: (Constant), D, L

b. Dependent Variable: TC

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	40309699203979.800	2	20154849601989.900	13.267	.001[a]
	Residual	21268159179770.200	14	1519154227126.450		
	Total	61577858383750.000	16			

a. Predictors: (Constant), D, L

b. Dependent Variable: TC

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-2073679.392	932171.633		-2.225	.043
	L	300.243	104.297	.499	2.879	.012
	D	156513.867	59018.366	.460	2.652	.019

a. Dependent Variable: TC

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions		
				(Constant)	L	D
1	1	2.561	1.000	.01	.05	.01
	2	.391	2.560	.06	.84	.02
	3	.049	7.258	.93	.11	.97

a. Dependent Variable: TC

First multiple regression for small rigs

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	PM, L, soil, D[a]	.	Enter

a. All requested variables entered.
b. Dependent Variable: C/F

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.725[a]	.525	.352	261.68787

a. Predictors: (Constant), PM, L, soil, D

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	832863.712	4	208215.928	3.041	.065[a]
	Residual	753285.974	11	68480.543		
	Total	1586149.686	15			

a. Predictors: (Constant), PM, L, soil, D
b. Dependent Variable: C/F

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-356.015	696.182		-.511	.619
	L	-.004	.025	-.035	-.143	.889
	D	25.664	16.291	.441	1.575	.143
	soil	-92.682	77.481	-.275	-1.196	.257
	PM	86.321	105.359	.216	.819	.430

a. Dependent Variable: C/F

Stepwise regression for small rigs

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	PM, Soil, D, L[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: TC

Model Summary

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.928[a]	.861	.830	167295.884	.861	27.896	4	18	.000

a. Predictors: (Constant), PM, Soil, D, L

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3122974988447.550	4	780743747111.887	27.896	.000[a]
	Residual	503782429753.408	18	27987912764.078		
	Total	3626757418200.960	22			

a. Predictors: (Constant), PM, Soil, D, L

b. Dependent Variable: TC

Coefficients[a]

		Unstandardized Coefficients		Standardized Coefficients		
Model		B	Std. Error	Beta	t	Sig.
1	(Constant)	-353193.308	345580.740		-1.022	.320
	L	86.146	9.279	.881	9.284	.000
	D	39949.849	17427.157	.209	2.292	.034
	Soil	178960.099	58028.948	.281	3.084	.006
	PM	-70975.135	37966.445	-.166	-1.869	.078

a. Dependent Variable: TC

Final regression for small rigs

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Soil, D, L[a]	.	Enter

a. All requested variables entered.
b. Dependent Variable: TC

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.913[a]	.834	.808	177940.320

a. Predictors: (Constant), Soil, D, L
b. Dependent Variable: TC

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3025165024025.360	3	1008388341341.790	31.848	.000[a]
	Residual	601592394175.596	19	31662757588.189		
	Total	3626757418200.960	22			

a. Predictors: (Constant), Soil, D, L
b. Dependent Variable: TC

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-839993.515	241648.808		-3.476	.003
	L	83.699	9.771	.856	8.566	.000
	D	40329.930	18534.723	.211	2.176	.042
	Soil	174368.329	61665.805	.274	2.828	.011

a. Dependent Variable: TC

APPENDIX

II - PROJECT INFORMATION