University of Alberta

Surface Heave Associated with Horizontal Directional Drilling Construction Techniques

by

Jason Sierzant Lueke ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

Construction Engineering and Management

Department of Civil and Environmental Engineering

Edmonton, Alberta
Fall 2005

Library and
Archives Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

0-494-08685-8

Your file Votre référence
ISBN:
Our file Notre reterence
ISBN:

NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:
L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ABSTRACT

This thesis presents the results of research associated with understanding how construction practices contribute to the development of surface heave during the backream phase of a shallow horizontal directionally drilled (HDD) utility installation. Several construction techniques or factors were identified to contribute to the development of surface heave through interviews with industry practitioners. To limit the number of factors studied to a reasonable amount, the analytical hierarchy procedure (AHP) was utilized to rank the factors in terms of perceived order of importance. Using the ranking identified by the AHP, a full factorial experiment was designed and implemented under actual field conditions with ground movements measured at various stages along four uniquely designed borepaths. Borepaths were designed with a prescribed installation procedure to determine the interaction effects of backream rate, depth of cover, mud flow, and reamer type on the development of surface heave. Results collected from the factorial experiment were utilized in the development of a neural network model to determine the relationships between the various factors. The relative strength of importance of the various factors is determined utilizing the trained network connection weights to determine which factor has the greatest effect on surface heave development. Further examination of the behavior of the system is provided through a sensitivity analysis which studied the effect of each drilling factor on the predicted surface heave. Based on the results of the model and field observations, an understanding of how construction practices relate to the development of surface heave is determined, and recommendations are provided to assist in reducing surface heave on shallow utility installations conducted by horizontal directional drilling. With a better understanding of the factors associated with directionally drilled installations, contractors and engineers may better select tooling and construction techniques to minimize the magnitude of surface heave.

ACKNOWLEDGEMENT

I would like to express my sincerest thanks and appreciation to the following people who contributed in making this thesis a success:

I would like to thank my wife Marie for her patience and support over the past many years while writing this thesis.

Thank you to the members of my family; Mom, Dad, Jonathan, Grandma, Papa, AJ, and Maryann – for their continual encouragement throughout my university career.

My supervisor, Dr. Samuel T. Ariaratnam, for his guidance, encouragement, support, and mentorship throughout the course of my program.

My co supervisors, Dr. Simaan AbouRizk and Dr. Dave Chan, for taking an active role in assisting me in the completion of my program.

Thank you to Dr. Raymond L. Sterling for participating as my external examiner for the defense. His comments and observations of the research were most appreciated.

Thank you to the members of my examination committee, Dr. Horacio Marquez and Dr. Thian Gan, for taking time out of their busy schedules to participate in the defense.

I also would like to thank Gerry Cyre for his assistance in the field testing programs.

For their financial support during my studies and research I would like to thank the Natural Sciences and Engineering Research Council of Canada.

TABLE OF CONTENTS

Chapter 1: INTRODUCTION **1**
1.1 INTRODUCTION 1
1.2 RESEARCH SCOPE 3
1.3 RESEARCH OBJECTIVES 4
1.4 THESIS ORGANIZATION 5

Chapter 2: BACKGROUND & LITERATURE REVIEW **8**
2.1 INTRODUCTION 8
2.2 HORIZONTAL DIRECTIONAL DRILLING 8
  2.2.1 Background 8
  2.2.2 Applications 10
2.3 DIRECTIONAL DRILLING INDUSTRY 11
2.4 HORIZONTAL DIRECTIONAL DRILLING PROCEDURE 15
  2.4.1 Pilot Bore 15
  2.4.2 Reaming 16
  2.4.3 Pullback 17
  2.4.4 Drilling Fluid 17
2.5 SURFACE HEAVE 19
  2.5.1 Current Guidelines 19
  2.5.2 Damage from Surface Heave 21
2.6 RESEARCH RELATED TO HDD GROUND MOVEMENTS 24
  2.6.1 Laboratory Simulation of Surface Heave 24
  2.6.2 Displacement Monitoring 25
  2.6.3 Finite Element Modeling 27
  2.6.4 Modeling Using Cavity Expansion Models 29
  2.6.5 Ground Movement Research in Pipe Bursting 31
  2.6.6 Numerical Methods to Predict Surface Heave 34
2.7 REFERENCES 36

Chapter 3: EXPERIMENTAL DESIGN AND PROCEDURE ______________ **40**

3.1 INTRODUCTION 40

3.2 HORIZONTAL DIRECTIONAL DRILLING 41

3.3 GROUND MOVEMENT FACTORS 42

3.3.1 Annular Space 42

3.3.2 Backream Rate 43

3.3.3 Borehole Pressure 44

3.3.4 Depth of Cover 45

3.3.5 Reamer Type 45

3.3.6 Reamer Diameter 46

3.3.7 Soil Composition 46

3.3.8 Soil Density 47

3.4 ANALYTICAL HIERARCHY PROCESS 47

3.4.1 Development and Implementation 48

3.4.2 Analysis of Results 50

3.5 EXPERIMENTAL DESIGN 53

3.5.1 Factor Levels 55

3.5.2 Borepath Design 58

3.5.3 Layout of Investigation 61

3.5.4 Installation Procedure 63

3.6 FIELD RESULTS 64

3.7 MODELING 67

3.8 CONCLUSIONS AND RECOMMENDATIONS 69

3.9 REFERENCES 71

Chapter 4: FIELD TESTING AND RESULTS ______________ **73**

4.1 INTRODUCTION 73

4.2 HORIZONTAL DIRECTIONAL DRILLING 74

4.3 SURFACE HEAVE FACTORS 75

4.3.1 Annular Space 76

4.3.2 Backream Rate 76

4.3.3 Borehole Pressure 76
4.3.4 Depth of Cover 77
4.3.5 Reamer Type 77
4.3.6 Reamer Diameter 77
4.3.7 Soil Composition 77
4.3.8 Soil Density 78
4.4 EXPERIMENTAL DESIGN 78
4.4.1 Analytical Hierarchy Process 78
4.4.2 Selecting Factor Levels 79
4.4.3 Field Investigation 80
4.5 GROUND MOVEMENT RESULTS 82
4.5.1 Backream Rate 84
4.5.2 Reamer Type 88
4.5.3 Depth of Cover 92
4.5.4 Mud Flow 96
4.5.5 Centerline Heave Observations 98
4.6 CONCLUSIONS 99
4.7 REFERENCES 101

Chapter 5: MODELING AND TREND ANALYSIS ________ **103**
5.1 INTRODUCTION 103
5.2 BACKGROUND 104
5.3 MONITORING SURFACE HEAVE IN HORIZONTAL DRILLING 106
5.4 NEURAL NETWORK BASED MODELING 110
5.4.1 Data Preprocessing 112
5.4.2 Model Development 116
5.5 RELATIVE IMPORTANCE OF FACTORS 123
5.6 SENSITIVITY ANALYSIS 124
5.7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK 129
5.8 REFERENCES 132

Chapter 6: CONCLUSIONS AND DISCUSSION **134**
6.1 CONCLUSIONS 134
6.1.1 Surface Heave Factors 134
6.1.2 Field Investigations 137
6.1.3 Surface Heave Modeling 137
6.2 RELEVANCE OF RESEARCH 138
6.3 RECOMMENDED HDD CONSTRUCTION PRACTICES 140
6.4 AREAS FOR FUTURE RESEARCH 141

Appendix A **145**

Appendix B **147**

Appendix C **157**

Appendix D **161**

Appendix E **170**

Appendix F **177**

Appendix G **178**

Appendix H **189**

LIST OF TABLES

Table 2.1: Areas of Activity and Years of Experience 13

Table 2.2: Breakdown of Pipeline Product Installed by Diameter and Material 14

Table 2.3: CALTRANS Depth of Cover Guidelines 20

Table 3.1: Reamer Configuration 45

Table 3.2: AHP Matrix Formulation 48

Table 3.3: Scale of Importance 49

Table 3.4: Sample Criteria Weights Matrix 50

Table 3.5: Sample Normalized Criteria Weight Matrix 50

Table 3.6: Summary of Normalized Weights by Respondent 51

Table 3.7: Summary of Factor Weights 51

Table 3.8: Drilling Factor Relationship with Borepath and Site 54

Table 3.9: Summary of Factors and Levels........ 58

Table 3.10: Design Installation Summary 64

Table 4.1: Relative Factor Weight 79

Table 4.2: Surface Heave at 900 mm Installation Depth 83

Table 4.3: Surface Heave at 1,200 mm Installation Depth 83

Table 5.1: Summary of Factors and Associated Surface Heave 110

Table 5.2: Surface Heave Factor Levels and Modeling Range 113

Table 5.3: Statistics of Data Point Configuration 115

Table 5.4: Summary of Neural Network Model Predictive Error 122

Table 5.5: Relative Importance of Input Variables 123

Table 5.6: Depth of Cover Trends 126

Table 5.7: Reamer Efficiency Trends 127

Table 5.8: Backream Rate Trends 128

LIST OF FIGURES

Figure 2.1: Pilot Bore Installation 15
Figure 2.2: Pullback 17
Figure 2.3: Surface Heave due to HDD Crossing 22
Figure 2.4: Heave Effects on Road and Sidewalk 23
Figure 2.5: Heave Effect on Roadway and Curb 23
Figure 3.1: Fluted and Spiral Compaction Reamers 56
Figure 3.2: Vermeer 24X40a Drill Rig 57
Figure 3.3: Design Borepath 59
Figure 3.4: Typical Surface Point Configuration at Monitoring Points 60
Figure 3.5: Typical Configuration of Surface Point 61
Figure 3.6: Layout of Borepaths 62
Figure 3.7: Displacements at 1,200 mm Depth with Slow Backream Rate 65
Figure 3.8: Displacements at 1,200 mm Depth with Fast Backream Rate 66
Figure 4.1: Borepath Design 81
Figure 4.2: Displacements from 900 mm Depth with Fluted Reamer 85
Figure 4.3: Displacements from 900 mm Depth with Spiral Reamer 85
Figure 4.4: Displacements from 1,200 mm Depth with Fluted Reamer 86
Figure 4.5: Displacements from 1,200 mm Depth with Spiral Reamer 87
Figure 4.6: Displacements from 900 mm Depth with Slow Backream Rate 89
Figure 4.7: Displacements from 900 mm Depth with Fast Backream Rate 89
Figure 4.8: Displacements from 1,200 mm Depth with Slow Backream Rate 90
Figure 4.9: Displacements from 1,200 mm Depth with Fast Backream Rate 91
Figure 4.10: Displacements from the Fluted Reamer with Slow Backream Rate 93
Figure 4.11: Displacements from the Fluted Reamer with Fast Backream Rate 94
Figure 4.12: Displacements from the Spiral Reamer with Slow Backream Rate 95
Figure 4.13: Displacements from the Spiral Reamer with Fast Backream Rate 95
Figure 4.14: Summary of Centerline Displacements by Borepath 99
Figure 5.1: HDD Pilot Bore Phase 106
Figure 5.2: HDD Pipe Pullback Operation 106

Figure 5.3: Layout of Borepaths for Field Investigation 109
Figure 5.4: Typical Processing Element 111
Figure 5.5: Network Output for Different Hidden Elements 118
Figure 5.6: Effect of Momentum on Network Error 119
Figure 5.7: Effect of Learning rate on Network Error 119
Figure 5.8: Network Model Configuration 120
Figure 5.9: Predicted and Observed Surface Heave Utilizing Neural Network 122

Chapter 1 INTRODUCTION

1.1 INTRODUCTION

As municipalities continue to grow and expand, demand is placed on the existing underground service infrastructure to sustain this growth and provide an acceptable level of service. Residential, commercial and industrial expansion contributes to this increased demand and has spawned the adoption of new technologies by service providers to deliver their product in a safe and efficient manner. In today's environmentally friendly recover, reuse, recycle, and protect paradigm, techniques for the installation of underground infrastructure that had been acceptable in the past, are now deemed undesirable in some circumstances. Traditional cut and cover techniques are simple and cost effective means for the installation of these services in a monetary sense, though are often associated with high social costs. Where an installation of this type may be acceptable in an area that is relatively undeveloped; in congested urban developments, pristine neighborhoods, or environmentally sensitive areas; this method may result in increased restoration and installation costs, destruction of irreplaceable sanctuaries, and potential damage to surrounding properties. As a result, several construction techniques described as trenchless or "no-dig" methods have developed to provide an alternative to conventional open trench construction.

Trenchless technology refers to a family of methods, equipment and materials capable of being used for the installation, replacement, or rehabilitation of new and existing underground infrastructure with minimal disruption to surface traffic, businesses, and other activities (ISTT 2000). For the installation of new infrastructure, trenchless construction techniques have several advantages over conventional trenching methods. Some of these advantages include: lower installation cost, preservation of existing surface structures such as roads and landscapes, minimal impact on residential and business traffic, and improved construction safety. One trenchless method of construction that has experienced significant growth in application and market development is horizontal directional drilling.

Since its inception, horizontal directional drilling (HDD) has been one of the fastest growing construction methods utilized in North America. Growth in this industry culminated with the advent of the fiber optic industry in the late 1990s. As a trenchless construction method, there are minimum if any excavation requirements to install pipe and conduit of varying size and depth. This technique allows for great design flexibility as installation paths, or bore paths, may be curved or straight, with the path changing alignment and depth to avoid surface and subsurface obstacles. First employed in 1971 for a river crossing near Watsonville, California, the horizontal directional drilling industry has grown to encompass 17 manufactures and several thousand rigs operated by several hundred contractors (Allouche et al. 2000). Directional drilling has been utilized in several industries, first in the oil and gas industries in the early 1980s, and then expanded to include utility installation, environmental remediation, and the installation of gravity sewers and forcemains (Allouche et al. 2000). HDD has seen application in the installation of fiber-optic, electrical, gas, and municipal distribution systems, and is particularly suitable for installations beneath traffic right of ways and existing structures. As a result, many utility and service providers are adopting horizontal directional drilling as the preferred method of installation for their distribution networks.

Significant and rapid growth of the horizontal directional drilling industry has contributed to concerns by municipalities and regulatory agencies as to the qualifications of drill rig operators and crews, as well as the availability of guidelines to regulate installation procedures. It was not uncommon for contractors with little or no experience to obtain a horizontal drill rig, and start installing cables and conduits for the fiber optic industry in the late 1990s. The demand was so great for the installation of product pipe, that qualifications and experience became secondary, to that of an available drill rig and crew. Subsequently, as the utilization of horizontal directional drilling increased in urban areas, damage resulting from surface heave during installations became common. There was one incident where a regulatory agency placed a moratorium on the utilization of horizontal directional drilling because of damage caused by surface heave, and began a process of training and licensing contractors. However, even experienced and competent drill crews caused damage to existing surface infrastructure through the surface heave mechanism. Partly an art, and partly a science, horizontal directional drilling relies as much on instinct and feel as it does on good practices, borepath design, and geotechnical information. Being a relatively new technology, horizontal directional drilling is subject to critical observation and examination. Each successful installation encourages the utilization of this technology on future projects by both municipal planners and contractors alike. Each failure of the technology both through uncompleted installations or damage caused to surrounding infrastructure, damages the reputation of the directional drilling industry and may prevent adoption of this technology by others to solve their infrastructure requirements. The development of surface heave, being the most noticeable consequence of improper drilling practices, must be better understood from a construction perspective, to determine how contractors can modify their drilling practices to prevent such damage from occurring.

1.2 RESEARCH SCOPE

There are many issues and concerns related to the installation of utilities using the horizontal directional drilling technology. The issue of damage resulting from surface heave is one which is common to many contractors and owners that use this technique. The scope and methodology of the proposed research would be as follows:

a) Advance the study of ground movements resulting from installations conducted using horizontal directional drilling. Conduct detailed and extended literature search, and interview contractors and researchers on topics and work in the area of ground movements for other trenchless methods, and in particular horizontal directional drilling.

b) Identify factors that contribute to ground movements occurring during horizontal directionally drilled installations. Interview academics and contractors to ascertain the factors that are of the greatest concern when conducting an installation.

c) Design a field experiment and data collection procedure based on the factors previously identified in the research. The field experiment will be designed on a statistical basis to gather information on the magnitude and extent of surface heave based on various combinations of these factors. Experiment will be efficiently designed to limit the amount of installations required, though maximizing the number of factors that may be compared against one another.

d) Conduct field research to collect data on ground movements as outlined in the experimental design. Installations to be conducted at the University of Alberta's research farms in a clay type soil. Throughout the installations surface points will be utilized to measure ground movements.

e) Utilizing the data collected a model may be developed to determine how the various factors relate to each other. The ultimate goal of this model is to predict the combination of factors that will produce the minimal amount of surface heave on installations conducted in that particular soil type. The model developed will specifically address how construction practices affect surface heave development.

f) Utilizing the model developed from the field experiment, perform a sensitivity analysis to understand how the changing drilling factors relate to each other under the field conditions examined in this research.

1.3 RESEARCH OBJECTIVES

The primary objective of this research is to develop an understanding of how various factors related to horizontal directional drilling contribute to the development of surface heave during the backream phase of an installation. This is to try to understand how construction practices impact the development of surface heave, and how practices may be changed to prevent excessive surface heave damage from occurring. An understanding of how construction practices affect the development of surface heave may allow contractors and design engineers to plan HDD installations to prevent damage to existing infrastructure.

There are three components of this objective that will be examined in this thesis. The first component is to identify the factors that contribute to surface heave during the backream phase of a horizontal directionally drilled installation, and using these factors design an experiment to analyze how these construction practices affect surface heave. The second component is to conduct a full scale experiment to observe the effect of construction methodology through the systematic manipulation of variables under actual field conditions. The final component of this objective is to develop a model to quantify surface heave and how the identified factors relate to one another towards the development of surface heave.

The secondary objective of this research is to expand the general body of knowledge of the horizontal directional drilling industry for the benefit of contractors, municipalities, consultants, regulatory agencies, and academia. It is anticipated that with a greater understanding of this construction technique, it will gain acceptance and experience increased utilization for the installation of shallow subsurface utilities.

1.4 THESIS ORGANIZATION

Chapter 2 provides an introduction to various aspects of the research program and identifies some previous research related to surface heave and horizontal directional drilling (HDD). An introduction to the horizontal directional industry is provided, along with an overview of directional drilling procedure. Research on surface heave developed from HDD installations is relatively new, and therefore minimal research has been performed in this area to date. Summaries of research performed in data collection and surface heave modeling is presented.

Chapter 3 describes the design and implementation of the field experiment to study the horizontal directional drilling (HDD) surface heave mechanism. Several factors were identified that contribute to the development of surface heave through previous field investigations and consultation with industry practitioners. These factors were ranked using the analytical hierarchy process to determine their perceived level of importance in influencing surface heave development. Using the rankings, factors were selected to design a factorial experiment that was implemented under actual field conditions. Following the prescribed installation program, surface heave data was gathered from four uniquely designed borepaths during the backreaming phase of the HDD installation. Included is a discussion of the instrumentation and data gathering process. This chapter is an expanded version of the paper published in the Canadian Society for Civil Engineering (CSCE) Canadian Journal of Civil Engineering (Lueke and Ariaratnam 2003).

Chapter 4 discusses the results and observations from the field investigation. This chapter is an extended version of a paper published in the American Society of Civil Engineers (ASCE) Journal of Construction Engineering and Management (Lueke and Ariaratnam 2005). There is a brief overview of the problem statement and experimental design and implementation, followed by presentation of monitoring results in tabular and graphical form from the four installations. Discussion of the trends and behaviors observed from the field investigation is summarized by each factor investigated.

Chapter 5 describes the process of developing a neural network model of the horizontal directional drilling surface heave system. Field data was preprocessed to allow input into the model, and several training and testing data sets were created. During development, training and testing sets were statistically created to ensure the entire factor space was explored. Factors were examined using regression analysis to confirm each factor contributed to the response of the surface heave system. In addition, an analysis was performed to determine the relative importance of each factor was in the system's response. Lastly, the calibrated model was utilized to analyze trends in the system's behavior as each factor level was methodically changed under various installation scenarios. This chapter is an expanded version of the paper accepted for publication in the Tunnelling and Underground Space Technology Journal.

Chapter 6 contains a summary of conclusions developed from the field and modeling programs from this research. Recommendations for future research directives are presented based on the findings made in this thesis.

1.5 REFERENCES

Allouche, E.N., S.T. Ariaratnam, and J.S. Lueke (2000). "Horizontal directional drilling: profile of an emerging industry." Journal of Construction Engineering and Management, Vol. 126, No. 1, pp. 68-76.

International Society for Trenchless Technology (ISTT) (2000). "International Society for Trenchless Technology Trenchless Technology Guidelines." ISTT, London, United Kingdom.

Lueke, J.S. and S.T. Ariaratnam (2003). "Experimental procedure for evaluating ground displacement factors in directional drilling." Canadian Journal of Civil Engineering (CSCE) Vol. 30, pp. 830-840.

Lueke, J.S. and S.T. Ariaratnam (2005). "Surface heave mechanisms in horizontal directional drilling." Journal of Construction Engineering and Management (ASCE) Vol. 131, No. 4, pp. 540-547.

Chapter 2 BACKGROUND & LITERATURE REVIEW

2.1 INTRODUCTION

This chapter provides a background on the horizontal directional drilling process through an examination of its origins, a description of the industry, and the explanation of the installation procedures and equipment. A discussion is provided on ground movements associated with this process, and a demonstration of the potential damage that may be caused when incorrect drilling practices are employed. The chapter is concluded with a summary of previous research conducted in the area of ground movements associated with horizontal directional drilling, and other trenchless construction techniques.

2.2 HORIZONTAL DIRECTIONAL DRILLING

2.2.1 Background

Horizontal directional drilling is a trenchless method of pipe installation. As a trenchless construction method there are minimal if any excavation requirements to install pipe and conduit of varying size and depth. Typical pipe installation diameters range from 50 to 900 mm, and installation lengths up to 1,700 m (Ariaratnam and Allouche 2000). This technique, evolved from the merging of water well, oil field and utility industries, and allows for great design flexibility as installation paths, or bore paths, may be curved or straight, with the path changing direction and depth to avoid subsurface obstacles. First employed in 1971 for a river crossing near Watsonville, California, the horizontal directional drilling industry has grown to encompass 17 manufactures and several thousand rigs operated by several hundred contractors (Allouche et al. 2000). Directional drilling has been utilized in several industries, first in the oil and gas industries in the early 1980s, then expanded to include utility installation, environmental remediation, and the installation of gravity sewers and forcemains (Allouche et al. 2000).

Directional drilling has several advantages over conventional open cut construction methods. The primary advantage is that directional drilling is a trenchless method of installation, as previously noted. The installation of underground utilities has previously been associated with large-scale excavations. There are many costs associated with open cut excavation, these include the time to excavate around and support existing utilities; restoration of surface structures including sidewalks and surface pavements removed to conduct the excavation; and increased social costs. Social costs may be considered as the costs of construction to society that are not included in the overall construction costs (McKim 1997). These costs are difficult to quantify as it is challenging to gauge the actual costs that a business or resident may incur do to loss of access or increased noise pollution.

Costs to society can be quantified into four major categories; cost of redirected traffic, lost revenues, restoration, and public awareness (McKim 1997). Costs resulting from redirection of traffic include motorist delays, increased traffic on detour routes and damage to detour routes due to increased traffic volumes. Lost revenues to businesses in the vicinity of the construction may result from lack of access and customer avoidance of the construction zone. Restoration costs to the vicinity of the construction due to inadvertent actions of the construction itself and increased maintenance costs to detour routes are difficult to quantify until construction is completed. And lastly, the public awareness of the construction due to noise, dust, increased feeling of safety hazards, and perception of environmental damage. With the utilization of horizontal directional drilling many of these social costs may be substantially reduced or eliminated enhancing the total value of the construction.

In comparison to other trenchless technologies, directional drilling has several advantages: (1) no vertical shafts are required as drilling commences from the surface; (2) relatively short setup time; (3) the installation path need not necessarily be straight; and (4) the single drive installation length exceeds that of any other non-man entry trenchless method (Allouche et al. 2000). The unique capabilities of horizontal directional drilling may be adapted and adopted for several applications, and create new possibilities for geotechnical investigation and construction methods. Directional drilling has been applied to the installation of pipe and conduit in highly congested surface and subsurface areas. In dense urban environments where open cut excavation is physically impossible because of installation depth and surrounding buildings, directional drilling may be the only alternative. Additionally, where excavation is difficult as a result of subsurface utilities, directional drilling may provide the means to steer around and avoid the utilities all together, eliminating the risk of damaging the utility from the redistribution of the soil in its vicinity or the placement and compaction of soil around exposed utilities during backfilling and surface restoration.

2.2.2 Applications

Horizontal directional drilling has also been employed for the installation of utilities and conduit in the vicinity or beneath environmentally sensitive or historically significant areas. In these situations, a borepath may be directed beneath rivers, ravines, lakes, beaches, estuaries, or forests preserving the balance of the ecosystem. With no excavation required during the installation process, differential ground settlements associated with traditional trenching installations is eliminated (Allouche and Como 1997). Subsequently, installations may be conducted in the vicinity of or beneath existing structures, roads, railways or airport runways with minimal risk of damaging foundations or causing settlements that may damage these structures or render safety concerns during their operation. As a result, pipe and conduit may be installed beneath areas and locations that have been previously inaccessible using traditional construction methods.

New applications including the installation of horizontal wells, and horizontal sampling and logging have been developed to take advantage of the installation characteristics of horizontal directional drilling. In the context of non-oilfield horizontal directional drilling, horizontal wells may be employed in the extraction of water or contaminates from various soil structures. During the installation process of a horizontal well, a perforated pipe is installed as a product rather than a continuous sealed product pipe. The perforations in the pipe allow for the collection of the water or contaminant for removal. Horizontal wells are considerably more efficient than conventional vertical wells due to the nature of contaminate plumes being orientated on a horizontal plane. The larger contact area of horizontal collection pipes results in a larger zone of influence and capture, resulting in a higher well efficiency (Looney 1991). Looney indicated that some studies have concluded that 10 to 35 vertical wells could be required to achieve the equivalent contact area of one horizontal well.

Horizontal sampling and geotechnical logging are relatively new applications utilizing the installation method of horizontal directional drilling to collect discrete soil samples along the borepath (Allouche et al. 1999). Sampling tools and techniques vary by manufacturer, however the basic premise is similar; collect in-situ samples in areas and in orientations that conventional vertical boring is incapable of performing. Horizontal sampling may be conducted beneath most surface structures or obstacles, and subsequently allows discrete access to locations of social value. Sampling in this nature has seen application in contaminate mapping and identification, and soil characterization in the path of tunneling operations.

With advancements in locating and tracking systems, horizontal directional drilling has seen recent application in the installation of gravity sewers. Gravity sewer installation for residential and commercial application has traditionally been the domain of microtunneling and conventional open cut installations, as both these methods allow for highly accurate surveying and placement procedures to ensure proper line and grade. Recent studies have shown that gravity sewer installations conducted utilizing directional drilling are both feasible and cost effective, allowing placements of up to 0.6 % grade accuracy maintained during installation (Harper et al. 1997).

2.3 DIRECTIONAL DRILLING INDUSTRY

In the summer of 1997, the Department of Civil and Environmental Engineering at the University of Alberta conducted a North American survey of the horizontal directional industry. A total of 169 surveys were sent to directional drilling contractors and utility companies across Canada and the United States. Of these surveys, a total of 53 questionnaires were returned, representing a response rate of 31%. Due to issues of completeness of the survey questionnaire only 49 responses were utilized in the compilation of the results. The purpose of this survey was to achieve a current snapshot of the industry through the examination of various issues including company profiles, typical project characteristics, and applications. The results of this survey have been published in Allouche et al. (2000). Presented in this section are selected portions of the results to develop an understanding of the industry and typical contracting practices.

In the early years of horizontal directional drilling, 1971 to mid 1980s, the technology and methodology had been primarily utilized in the oil and gas industries for exploration, production and pipeline installation. Over the past 10 years, directional drilling has begun to be utilized for the installation of utilities, environmental remediation, and the installation of force mains and gravity sewers. The installation of gravity sewers is a relatively new application of horizontal directional drilling primary motivated by the advancement of tracking and locating technologies that allow for accurate monitoring of the bore path and installation.

Results from the survey indicated that 89% of the contractors surveyed were involved in the installation of underground utilities, 74% in municipal applications, 63% in pipeline installation, and 28% in the environmental market as presented in Table 2.1 (Allouche et al. 2000). Additionally, it can be seen that this industry is relatively new as demonstrated by the distribution of experience in each of these areas. There are the greatest numbers of experienced contractors involved in the installation of utilities, as this is common in all urban centers and has been considered by some to be the "bread and butter" of the directional drilling industry. The underground utility sector of the industry includes the installation of fiber-optic conduit, telephone and cable. Municipal applications include installations of gravity sewers and force mains. Installations pertaining to the oil and gas industry were included in the pipeline installation segment, while environmental applications include site remediation. It may be concluded from these results that the majority of contractors utilizing horizontal directional drilling techniques are working in urban environments as shown in the figures for utility and municipal applications. Subsequently, it may be concluded that these contractors may be working in the vicinity of existing utilities and pipe installations, as well as beneath engineered urban structures such as roads and highways.

Table 2.1 Areas of Activity and Years of Experience (Allouche et al. 2000)

Experience	**Utility** (%)	**Municipal** (%)	**Pipeline** (%)	**Environmental** (%)
Not involved	11	26	37	72
Involved	89	74	63	28
5 years or more	70	52	53	18
2-4 years	15	9	4	0
2 years or less	4	13	8	10
0 years	11	26	35	72

The survey assessed typical sizes and common pipe materials installed. This information would provide the basis for selection of pipe diameters to monitor in the research program described in subsequent chapters. The 49 contractors were asked to indicate the total length of pipe installed by their firm categorized by pipe diameter and material composition. The results indicate that during the 1994-95 contracting season the respondents installed a combined length of pipe and conduit of 1,654,800 meters. Table 2.2 summarizes the results of pipeline product installed by diameter and material.

Table 2.2 Breakdown of Pipeline Product Installed by Diameter and Material (Allouche et al. 2000)

Diameter	**Pipeline Product Material**					
	PVC	HDPE	Steel	Other	Total	Percent of 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 installed	248,572 m	1,029,253 m	372,476 m	4,500 m	1,654,800 m	---
Percent of Total	15	62	23	0.3	---	---

The results indicated the most common pipe material installed was high-density polyethylene (HDPE) pipe. Approximately 62% of the total length of pipe installed by the contractors was HDPE, 23% steel, and 15% polyvinyl chloride. High-density polyethylene is an ideal pipe material for use in horizontal directional drilling installations due to its high tensile strength and flexibility, which lends itself well to the steering capability of the directional drilling rigs (Allouche et al. 2000). Of the total length of pipe installed approximately 72% of the installations were of pipe that was 50 to 100 mm in diameter, 11% between 150 and 200 mm, 5% between 250 and 300 mm, and 12% greater than 300 mm in diameter. Product pipe of 100 mm diameter or less is typically employed in utility installations including telecommunication, electrical conduit and natural gas distribution systems (Allouche et al. 2000).

2.4 HORIZONTAL DIRECTIONAL DRILLING PROCEDURE

Installations conducted utilizing horizontal directional drilling are typically completed in three distinct phases; 1) drilling of the pilot bore, 2) preream, and 3) pullback (DCCA 1998). The drill rig provides the thrust, pull back and rotational torque required to maneuver the drill string and product during the installation.

2.4.1 Pilot Bore

Installation commences with the drilling of the pilot bore, which provides the path along which the product pipe will ultimately be located. The pilot bore begins by the launching of a small diameter drill string that is pushed into the surface at an angel between 8 and 20 degrees, and then gradually becomes horizontal when the desired depth is achieved (Figure 2.1). The pilot bore follows a predetermined path called the bore path or bore plan. Bore plans are developed prior to the commencement of the drilling operation, and outline the proposed path of the installation based on the capabilities of the equipment and location of subsurface obstacles.

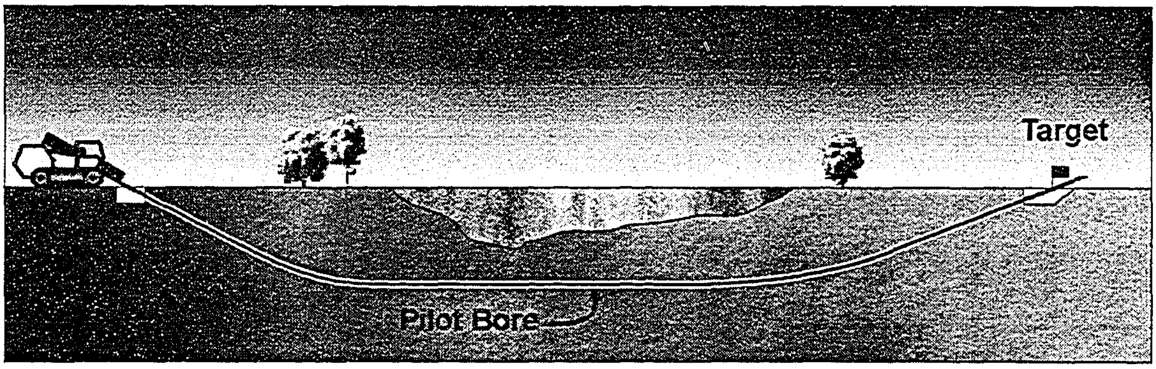

Figure 2.1 Pilot Bore Installation

In typical utility installations, the drill string is advanced rod-by-rod while simultaneously pumping drilling fluid to the drill head. The drill head may be steered during the boring of the pilot bore through the orientation of a bias at the drill head. To drill in a straight line the drill string and drill head are continuously rotated while the drill rig advances the drill sting forward. To initiate a change in trajectory, the bias is orientated in the desired plane, and the drill string advanced without rotation. In this manner, the bias behaves as a sail pushing against the soil to direct it in the desired direction. After the trajectory has been adjusted accordingly, the drill string is again advanced with rotation until another change in direction is required (DCCA 1994).

The drill path may be monitored from the surface using a location device located in the drill head called a sonde. The sonde emits signals to a receiver on the surface that displays the depth, rotation orientation, and inclination of the drill head. This data is utilized by the tracking person and driller to direct and steer the drill string along the predetermined bore path. For deeper installations, or instances when access to the location directly above the drill head is impossible, a wire line tracking system is utilized. Data is transmitted to the surface through wires running through the drill string back to the surface at the drill rig, where calculations are made to determine the location of the drill head. Location of the drill head is generally monitored at each joint in the drill sting as the installation progresses. In circumstances where drill string location is critical; readings may be taken at smaller intervals. If the drill sting is determined to be located at a position outside the accepted tolerance of the bore path, the drill string may be retracted and that section of the bore path re-drilled. Drilling continues until the drill string reaches the target or exit location, where the drill head is removed and the drill string prepared for reaming.

2.4.2 Reaming

Reaming is the process through which the pilot bore is enlarged to a suitable diameter to accommodate the installation of the product pipe. Reaming typically is accomplished by pulling a reamer from the target or exit location back to the drill rig through the pilot bore. As a rule of thumb, the borehole is enlarged to 1.5 times the diameter of the product line (DCCA 1998). The annular space created during this process is required to allow for continuous flow of drill fluid to transport cuttings and spoil from the reaming process, and to provide adequate space for the bend radius of the product line. Depending on the size of the product, multiple passes may be required with increasingly larger diameter reamers to increase the diameter of the bore hole in gradual stages to maintain the integrity of the hole. Generally, all reams prior to the actual product installation are referred to as pre-reams, and the final ream to which the product pipe is attached is refereed to as the back ream or pullback.

2.4.3 *Pullback*

Once the borehole has been enlarged to the appropriate diameter, the product line may be installed in a process referred to as the pullback. Prior to pullback, the product line must be prefabricated to form a continuous string of pipe for the length of the installation. The product line is attached to a pull head that is attached to a reamer with a swivel. The swivel is used to prevent the product line from twisting or turning during the pullback. Additionally, the reamer is required to ensure that the borehole remains open during the installation and to pump drill fluid into the bore for lubrication and borehole stabilization. The product line, with the pull head, swivel and reamer, are pulled from the target location to the drill rig along the path that was originally designated during the drilling of the pilot bore (Figure 2.2). During the pull back the drill string is rotated and pulled back to the rig, as drill fluid is pumped into the bore. The installation is complete once the product line reaches the entrance pit at the drill rig.

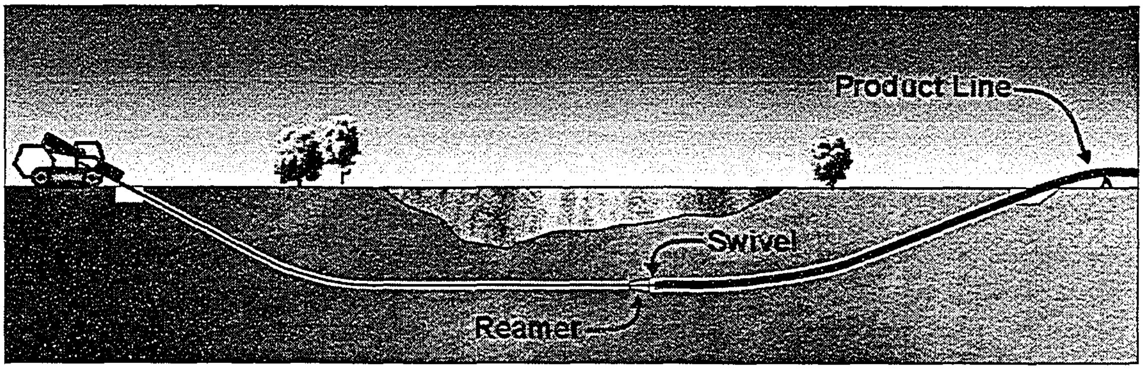

Figure 2.2 Pullback

2.4.4 *Drilling Fluid*

Drilling fluids are utilized throughout the installation process and provide a number of functions designed to assist in completing a successful installation. In general, a drilling fluid may be described as water that has been enhanced through the addition of various admixtures and chemicals to create a slurry with characteristics that are desirable for use in horizontal directionally drilled installations. During an installation the drilling fluid is mixed on the surface and pumped down the drill string to the drill head or reamer where it is released into the annular space, or the location between the pipe and the cavity made by the drilling or reaming operation. Under proper drilling procedures, adequate volumes of drilling fluid are pumped into the borehole to provide circulation of the fluid back to the entrance or exit pit at the surface.

Drilling fluid has many functions during the drilling procedure, the primary function of the fluid is to provide integrity to the borehole and prevent the borehole from collapsing during the installation. Additionally, the drill fluid must suspend or transport the soil cuttings generated during drilling and reaming back to the entrance or exit pit at the surface. It is essential that the fluid suspend the cuttings to prevent their settling around the drill string and ultimately packing and impeding its rotation or movement. In cohesionless soils such as sand and gravel, drilling fluids provide a means to stabilize the bore wall by providing a substitute internal pressure similar to the original condition after the borehole is created. During the pullback, drilling fluid acts as a lubricant to assist in pulling the product line through the borehole. While throughout the pilot bore drilling, the fluid cools the electronics housed in the sonde behind the drill head. The composition of the drilling fluid may be modified during drilling to impart the desired characteristics required for changing soil composition to prevent borehole collapse or seizure of the drill stem due to cutting buildup.

In general, a drilling fluid is composed of water mixed with bentonite, polymer, and other admixtures depending on the composition of the soil structure being drilled. The primary function of bentonite is to act as a thickening agent to assist in sealing the borehole in unconsolidated formations and to provide a means to suspend the drill cuttings for transport to the surface. Polymers primarily provide suspension properties and assist in neutralizing the effects of swelling clays by encapsulating the water and preventing its adhesion to the clay. There are additional mixtures that may be added to the drill mud to inhibit the cohesion of clay to the drill string and tooling, prevent the swelling of active clays, and neutralize chemicals or conditions in the ground that may impede the functioning of the drill fluid.

2.5 SURFACE HEAVE

The first step in the planning of a directionally drilled crossing after the selection of the site is the determination of an adequate depth of cover (Richards 1996). Ground movements are a concern for municipalities or directional drilling contractors where installations are conducted beneath roadways, buildings, and environmentally sensitive areas. According to a survey conducted in 1997 (Allouche et al. 2000), 89% of the contractors surveyed were involved in utility installation and 74% in municipal applications. With almost 75% of all directional drilling contractors involved in municipal applications, there is a definite possibility of a contractor drilling within the vicinity of engineered surface and subsurface structures. Where the existing ground is disturbed there is potential for either settlement or heave depending on the mechanics involved in the disturbance. In directional drilling ground disturbance may occur during the initial pilot bore, though this is relatively small as the drill head for most utility type installations is only 100 to 125 mm (4 – 5 inches) in diameter, as well as during the prereaming and final product installation. It is during the reaming and product installation phase where most ground movements occur, due to the diameter of the tooling and the cutting and expansion mechanism of the reamer.

2.5.1 Current Guidelines

To mitigate the amount of damage that could occur as a result of directional drilling installations, some organizations have developed guidelines for depth of installation to reduce if not eliminate the effects of surface heave on roadways and improved surface features. One such guideline is from the California Department of Transportation; it provides guidelines for safe installation depths beneath roadways (Caltrans 1999). These guidelines state that as the diameter of pipe increases the depth of installation should also increase according to a predetermined chart of values (Table 2.3). In many circumstances these guidelines provide a factor of safety that far exceeds practicality, thus increasing installation cost and in some cases limiting the application of the method. There is no indication in these guidelines as to which soil conditions these values were developed for or how the values may change in relation to soil conditions. However, soil conditions are a primary factor contributing to the amount of surface heave or displacement occurring for an installation.

Table 2.3 CALTRANS Depth of Cover Guidelines

Pipe or Product Diameter	Minimum Depth of Cover
Under 6 inches	4 feet
8 to 14 inches	6 feet
15 – 24 inches	10 feet
25 – 48 inches	25 feet

To determine the necessary depth of cover for the directional crossing of a body of water such as a river, it is recommended that a crossing profile be constructed and appropriate geotechnical investigations be conducted (DCCA 1994). There are several factors that influence the depth of cover for river crossings including the river flow characteristics, scour depth, future channel widening or deepening, and the location of existing pipe or conduit on the proposed borepath. The DCCA (1994) recommends that the minimum depth of cover be 6.1 meters or 20 feet. However no indication or guidelines are provided for typical utility or crossings not involving the crossing of a river channel. Additionally, this guideline provides no differential treatment for product pipe diameter.

Though there is no documentation in the literature, it has been suggested by members of the industry that a rule of 300 mm (1 foot) of cover for every 25 mm (1 inch) diameter of pipe installed would be an effective determination for depth of cover. This method closely resembles the guide outlined by CALTRANS previously noted. Like the CALTRANS and DCCA guidelines for depth of cover, this suggested rule of thumb also makes no differentiation between soil types in its application. No other guidelines or recommendation for depth of cover in horizontal directionally drilled installations have been found in the literature.

According to preliminary investigations of ground displacements associated with directional drilling conducted at the University of Alberta, it has been determined that soil conditions and structure influence the magnitude and lateral extent of surface disturbances, this is discussed further in Chapter 4. Subsequently, it may be determined that these guidelines for diameter of product and depth of installation may be conservative under some circumstances. This results in increased cost of installation, overly conservative installations, and needlessly congested underground right of ways.

2.5.2 Damage from Surface Heave

The results of insufficient depth of cover and damage resulting from surface movements manifest themselves in various means depending on the soil conditions and any surface structures located in the vicinity of the installation. When installing pipe or conduit utilizing horizontal directional drilling in an urban environment, the main concern associated with ground movements is surface heave. In urban environments, it is easy to see the results of surface heave, especially if the heave occurs beneath engineered pavements or other surface structures. The results of surface heave may be seen in the humping of roads and sidewalks, or even the adjustment in elevation of foundations. Most damage resulting from directionally drilled installations may be attributed to improper drilling practices or unforeseen soil conditions.

An example of some of the damage that may occur during a horizontal directionally drilled installation is presented in Figure 2.3. This installation involved the crossing of a major highway in Northern Alberta. During the installation of a bundle of four 100 mm (4 inch) diameter conduits, a localized surface heave in excess of 450 mm (18 inches) occurred resulting in the temporary closing of a section of the highway. This is an extreme example of the damage that can occur during a directionally drilled installation.

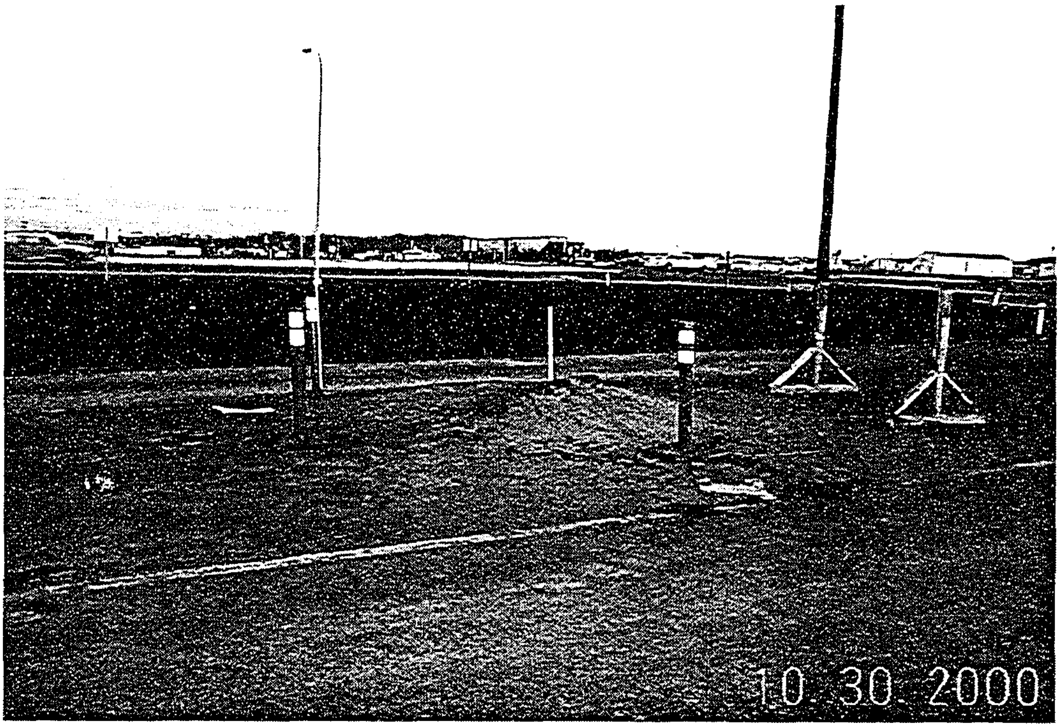

Figure 2.3 Surface Heave due to HDD Crossing

Similarly, Figures 2.4 and 2.5 show damage resulting from surface heave in California. On this project, the contractor was installing a single 100 mm (8 inch) diameter pipe across a roadway in a developed commercial neighborhood. It can be seen that significant damage was caused to the roadway, sidewalk, and the short retaining wall paralleling the sidewalk. Not only had a crack developed in the retaining wall, but the grade of the gutter had been significantly modified to prohibit proper runoff drainage to the catch basin. What is not seen in the picture is the damage that may have occurred to any utilities that may have been in the vicinity of the installation.

Figure 2.4 Heave Effects on Road and Sidewalk

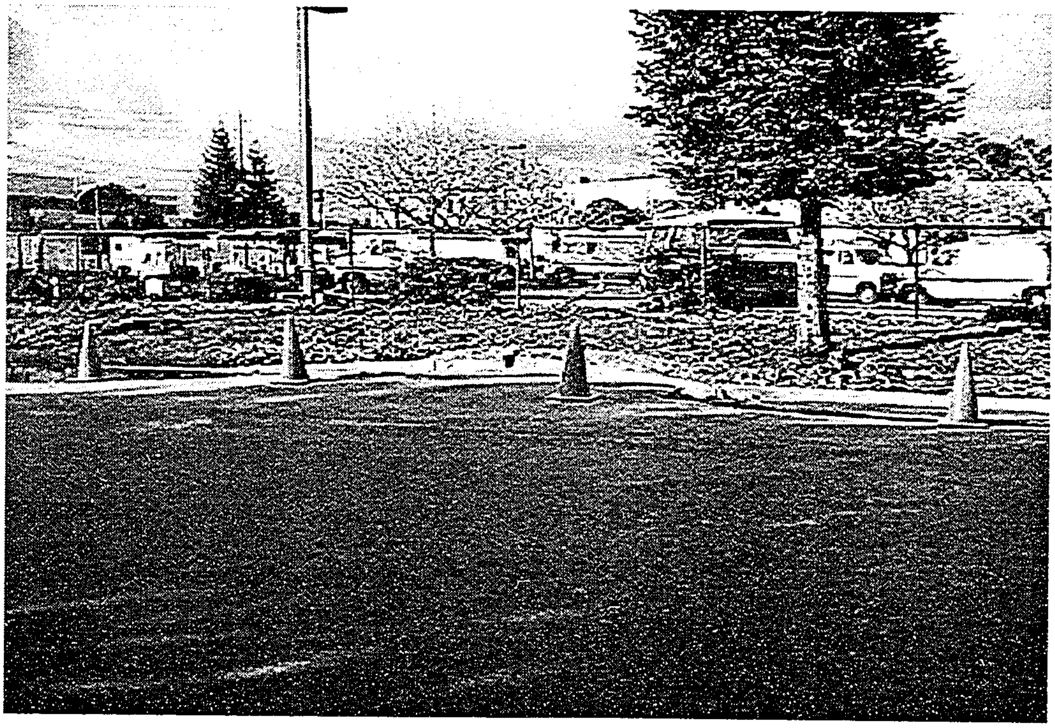

Figure 2.5 Heave Effect on Roadway and Curb

2.6 RESEARCH RELATED TO HDD GROUND MOVEMENTS

The monitoring of ground displacements during a horizontal directionally drilled installation is a relatively new field of research comprising only a few recorded installations. Literature discussing surface heave monitoring and modeling is presented for the limited work found. In addition, work in ground movements associated with another trenchless construction method, pipe bursting, is discussed.

2.6.1 Laboratory Simulation of Surface Heave

The University of Waterloo conducted laboratory investigations of surface movements due to near surface horizontal pressure bores (Marshall et al. 2001). In this research, a test apparatus was developed to measure soil deformations around a horizontal circular cavity when the fluid pressure within the cavity is varied. The goal of this research was to model deformation trends that have been observed in the field and determine the impact of key factors on these trends. This research is based on the premise that soil deformations occur when drilling fluid pressures within horizontal directionally drilled bores are either inadequate to sustain the weight of the soil surrounding the bore or when pressures exceed the shear strength of the surrounding soil.

Examination of the ground movements were conducted in a test box that was constructed out of plywood reinforced with steel bracing. The box had an internal dimension of 91 cm for length, 44.5 cm in width and 45.5 cm in height. A Plexiglas sheet was mounted on the front of the box to allow for visual observation of the soil movements. Holes were cut in the Plexiglas front panel and plywood rear panel to allow for the insertion of a bladder. These holes were approximately 6.35 cm in diameter, with centers set approximately 15 cm above the bottom of the box. A 25 mm diameter tire inner tube was determined to be the most suitable material to be used as the bladder for the test apparatus. Preliminary testing was performed using loosely packed, cohesionless, silica sand while varying the amount of water pressure or degree of bladder inflation.

Surface displacements were measured using a total station and optical targets arranged to form a grid across the surface of the soil. Subsurface ground movements were qualitatively described using colored sand placed in horizontal bands viewable through the Plexiglas front of the box. An accuracy of +/- 1 mm could be achieved in measuring the surface movements. Sand was placed in compacted lifts, with the bladder inflated to a predetermined diameter. Sand depths were varied for each test to explore the ratio of depth of cover to diameter of the borehole. Ratios were varied from 0 to 6 and surface heave observations recorded. These observations determined that increasing the depth of cover increased the inflation pressure required to create a surface displacement. The researchers concluded that a test box could be developed to study near surface pressurized bore surface elevation changes; that boundary effects were minimal; surface displacement patterns are consistent with theoretical shapes; and that increasing the depth of cover to borehole diameter over 4 allows for the creation of borehole pressures without the development of surface heave.

This research is based on the premise that ground movements are caused by the pressurization of the borehole by the drilling fluid, and that the expansion of the borehole leads to surface heave. While the bladder is a convenient way to simulate borehole pressure, it does not accurately simulate drilling fluid behavior. Excess pressure in the borehole could be relieved by causing a hydro-fracture, a release of drilling fluid from the borehole lowering borehole pressure. This small scale examination provides interesting results in determining the borehole pressures that may cause surface heave, however it does not account for the dynamics of the horizontal directional drilling process and the effect of drilling fluid circulation.

2.6.2 Displacement Monitoring

Najafi and others have conducted research with the University of Missouri-Columbia, Michigan State University, and the Trenchless Research and Development Center on the effects of major road crossings utilizing trenchless technologies. This research has been widely published in Najafi et al. 2002a, 2002b, 2003a, and 2003b. Much of the published material describes the horizontal directional drilling process and summarizes innovative applications of horizontal directional drilling including gravity sewer installation, pipe reaming, and pavement stabilization techniques. The objective of this research is to monitor and compare ground displacements associated with various trenchless methods including pipe jacking, pipe ramming, auger boring and guided boring, as well as horizontal directional drilling.

To evaluate ground movements resulting from a pipe jacking installation, monitoring was performed on the installation of two 1,500 mm diameter concrete pipes in April of 2002 under an actual highway. The installations were approximately 32 m in length with no depth of installation provided. Ground movements were monitored during and after installations by measuring predetermined survey points on the pavement surface. No appreciable surface movements were measured during the installation.

In July 2002, a field trial was conducted at the Capsule Pipeline Research facility at the University of Missouri to determine the effect of pipe ramming on surface displacements. Five 6 m sections of 600 mm diameter steel pipe were installed with pipe ramming equipment supplied by TT Technologies Inc. A series of settlement plates were placed before the installation began and the elevations of these points were measured. The depth of installation was not indicated in the references. Measurements were taken during and after the installation of the pipe segments. Results from the surface profiles indicate no surface displacement.

In August 2002, a guided boring installation was conducted at the Capsule Pipeline Research facility in the same embankment as the previous pipe ramming installation was conducted. Akkerman Inc. provided the equipment necessary for the installation, and Mission Clay pipe provided 36 m of 200 mm diameter clay pipe for the trial installation. As with the previous pipe ramming installation, the surface of the embankment was instrumented with settlement plates, and their elevations recorded during and after the installation. As with the previous installations the depth of installation was not disclosed and no surface movements were observed. Installations were not concluded utilizing horizontal directional drilling at the time of publishing. Plans were to install 30 m of 600 mm diameter fiberglass reinforced polyester mortar pipe. Other details of the proposed research were not indicated.

Through the field work conducted, the researchers concluded that they have proved that trenchless road crossing methods are capable of installation a pipe with minimal or no ground movements and disturbance to the pavement. They indicate that before this conclusion can be finalized that additional installations should be performed in other soil conditions. These results will be incorporated in the Missouri Department of Transportation performance specifications for trenchless crossings.

This work focused on large diameter crossings which are different than utility type installations being studied in this thesis. There were limited installation parameters identified and measured, and no indication of how installation parameters affect surface heave. In addition, the work attempted to prove that surface heave would not occur, rather than determine how or what parameters during the installation may affect installation. No surface heave was observed as some of the installations were completed for an actual project, and the contractor's goal for the installation was not to produce surface heave. Application of information from these field installations would be limited as only one installation was conducted utilizing each technology, pipe material, and installation diameter. The findings of this research do not provide insight into behavior of various trenchless construction processes in relation to ground movements

2.6.3 Finite Element Modeling

Researchers from the University of Waterloo constructed a simulation of borehole and surface heave behavior using a finite difference program (Duyvestyn and Knight 2000). The objective of this research focused on the utilization of good drilling fluids, good drilling practices, and good borehole design to minimize soil deformations above a horizontal directionally drilled installation. This was accomplished by reviewing the behavior and function of drilling fluids and the development of a numerical prediction model of a pressurized near surface bore. The role of a good drilling fluid was explained, specifically focusing on the characteristics of a good drilling fluid in cohesionless soil. Ensuring that the fluid has adequate viscosity, gel strength, and being able to develop a filter cake to prevent loss of fluid into the formation was explained from various literature sources. In addition, an explanation of borehole pressure was provided.

Numerical simulations were undertaken to characterize soil deformation trends and to highlight the importance of good installation practices in a cohesionless soil. The simulation was based on a two-dimensional analysis of the borehole, modeling only one half of the borehole due to the vertical line of symmetry. All numerical simulations were carried out using FLAC, a two dimensional explicit finite difference program developed by Itasca Consulting Group Inc. which is capable of simulating complex geomechanical structures. Materials are represented by elements or zones within a grid representing the cross section of the borehole. The behaviour of each element is governed by a prescribed stress/strain constitutive model in response to applied forces or boundary constraints. The grid created is able to deform and move with the material it is representing. The simulation modeled a 400 mm diameter soil void at a depth of 2.0 m, and the response to varying stresses induced by changing the borehole or drilling fluid pressures.

Results from the simulation indicate that maintaining fluid pressure in a horizontal directionally drilled installation can minimize soil deformations. Surface settlement was observed when the borehole pressure was reduced to less than 7.5% of the effective vertical stress. In situations where the borehole pressure was greater than 7.5% and less than the effective vertical stress insignificant soil movements were observed. When the applied pressure was greater than the effective vertical stress, surface heave was observed. In summary, they determined that if the borehole pressure was not maintained during or after an installation, soil movement would occur. To prevent surface heave during a horizontally drilled installation, drilling fluid pressures should be minimized by maintaining circulation and by having the installation at a suitable depth. The researchers indicate that further development of the model is required to quantify the magnitude of surface settlement predictions using the FLAC model.

The limitation of utilizing finite difference or finite element modeling in the studying of ground movements associated with horizontal directional drilling is the focus on geotechnical parameters. The model misses many other factors that contribute to the development of surface heave resulting from construction techniques. To make a finite element model work, the researcher needs to limit and make assumptions as to the behaviour of the system, rather than discover how the system actually works. This work focuses on borehole pressure and its relation to surface heave. For a contractor to apply the results of this model to their particular installation they would be required to determine the effective vertical stress of the soil above the borehole and be able to accurately monitor the borehole pressure during the installation. Technology to accurately measure borehole pressure is not readily available to most utility contractors. Though the research discusses good drilling practice, it can not account for drilling practices in the finite element model, only soil parameters and borehole pressure.

2.6.4 Modeling Using Cavity Expansion Models

Francis et al. (2003a and 2003b) conducted research into the analysis of heave and subsidence risk for horizontal directional drilling utilizing cavity expansion modeling. To reduce the risk associated with ground movements, they propose the review of risk management practices and field quality controls as well as the analysis of the potential for ground movements based on the governing geotechnical conditions. The research presents an application of geomechanical modeling utilizing cavity expansion theory to provide a quantitative assessment of borehole pressure and minimum depth of cover requirements. A finite element analysis method is presented to assess the influence of borehole fluid pressures on the surrounding soils. By estimating the borehole pressure, non-linear cavity expansion theory combined with limit pressure equilibrium, an estimate of the heave or subsidence can be calculated.

The limit pressure equilibrium, or the allowable borehole pressure for a given installation, may be used to assess minimum depth of cover requirements and insight into soil behavior. The allowable borehole pressure may be calculated based on overburden and average shear strength reactions. Conditions during the pullback phase of the installation may serve as the critical case for the borehole limit pressure. Pressure is developed during the pullback phase as a combination of displacement, frictional forces on the pipe, and drill fluid pumping rates. It is also during the pullback phase where the greatest risk of hydro-fracture may occur due to over pressurization of the borehole.

The application of the cavity expansion theory to horizontal directional drilling requires the assumption that the borehole will be uniformly circular. However, this does not account for geometric irregularities and other factors related to the hydro-fracture mechanism which are complex and beyond reasonable current practice (Staheli 1998). In the development of the model, the researchers utilized a plane-strain cylindrical model for two dimensional analysis of the borehole. Other geotechnical conditions could be considered in the model including irregular geologic profiles, sloping ground, and minimum allowable drilling fluid gel strength to prevent borehole collapse.

A limit pressure analysis was performed on several horizontal drilling projects in Hawaii using the finite element program Plaxis v7.11. These projects were large scale installations with pull lengths ranging from 75 to 950 m in length and 250 to 1250 mm in diameter, in both cohesive and granular materials. Mohr-Coulomb material properties were developed for five local soil conditions. Calculations were performed on a range of cover depths and ground water levels to determine stress conditions in the various horizontal drilling projects studied. This information was utilized to define the finite element model parameters and several iterations were conducted to determine mesh deformations, plastic yield points, soil displacement contours, and displacement vectors for various borehole pressures.

Recommended practices were developed at the end of the study to manage surface heave and subsidence risk. These recommendations included having each installation analyzed and monitored to determine allowable drilling pressures, incorporation of ground improvement or underpinning to protect critical structures, continuous monitoring of the ground surface above the borepath, and measuring the drilling fluid pressures to maintain them within the limits prescribed in the analysis. The research determined that, through analysis, allowable drilling pressures could be determined, and that these vary based on site conditions. Based on the allowable borehole pressures, minimum depth of cover estimates can be determined. The researchers noted that other system parameters can assist in developing surface heave risk including tooling mechanics and pipe material properties, though they do not account for them in their research.

Similar to other research utilizing finite element modeling to predict surface heave on horizontal directional drilling installation, the model only considers fluid pressures and depth of cover as contributing factors. There is no consideration of other factors related to the construction process. In addition, the installation monitored and studied in the model are larger than typical utility installations in urban environments where most damage resulting from surface heave occurs making it not practical for utility installations.

2.6.5 Ground Movement Research in Pipe Bursting

Research has been conducted in ground movements associated with pipe bursting, another trenchless method of construction. Pipe bursting, also known as trenchless pipe replacement, is a process in which an existing pipe is replaced by fragmenting or splitting the pipe by pulling a tool through the existing pipe which has a larger outside diameter than inside diameter of the existing pipe being replaced. Immediately behind the bursting tool, the new pipe is pulled into the cavity that the original pipe once occupied. During this installation process the cavity in which the original pipe was once located is enlarged by displacing the old pipe fragments into the surrounding soil. This displacement of soil and pipe fragments creates ground movements which in some cases may manifest as surface displacements. Previous research has been based on laboratory work and actual field replacements. The author has conducted research in the area of ground movements associated with the pipe bursting process in Lueke and Ariaratnam (2000). A summary of portions of the literature review from this paper and is provided in the following text.

Laboratory tests to determine pulling forces and ground movements associated with pipe bursting were conducted by Lapos et al. (2004) at the GeoEngineering Centre at Queen's – RMC. The researchers focused specifically on the replacement of a 184 mm diameter clay tile pipe backfilled with a poorly graded dense sand, with a new 202 mm diameter high density polyethylene pipe. The replacement was conducted in a large box under laboratory conditions. Utilizing a commercially available bursting head to burst the pipe, ground movements were recorded above the centerline of the pipe as well as perpendicular to the pipe's path. Linear potentiometers were also installed 250 mm and 500 mm above the pipe to measure subsurface movements. Ground movements on the surface were measured using reflective survey markers and a total station. Measurements of surface heave were obtained at various stages during the bursting process to create profiles related to the position of the bursting head. Results indicate a large displacement wave ahead of the bursting tool, followed by a gradual settlement. A residual surface heave remained after the tool had past the monitoring location. Information collected during this investigation is to be compared to numerical solutions to determine a manner to estimate ground movements for various project conditions.

The Trenchless Technology Center at Louisiana Tech University conducted research focusing on ground vibrations associated with the pipe bursting process, and to determine safe distances for existing utilities from the pipe being replaced (Atalah et al. 1997). Utilizing peak particle velocities as an indicator of potential to cause structural damage, several projects were monitored under various conditions. Peak particle velocities versus distance relationships were developed and compared against criteria used in the blasting industry and other sources of construction vibration. This analysis indicated that the ground vibrations associated with pipe bursting in the energy/size range studied did not cause even cosmetic damage to buildings, and has negligible effects on buried structures and utilities at distances of 8 feet and 2 feet respectively. Rogers (1990) analyzed ground movements associated with trenchless and conventional open cut construction techniques in work conducted at Loughborough University of Technology. Field observations determined that soil displacements caused by trenchless pipe replacement are typically smaller than those caused by trenching operations. In addition, laboratory tests were conducted with bursting heads pushed through observation containers filled with sand of various densities. These containers had Plexiglas sides to allow direct observation of the sand movement as the bursting head advanced. Through the determination of displacement vectors, magnitudes of ground movements cold be extrapolated. These laboratory experiments determined that most displacement movements diminish at distances greater than 300 mm from the pipe being replaced in the dense sand material, and over a smaller distance in loose sand.

Leach and Reed (1989) conducted a series of field installations at the Water Research Centre to determine the effect of the bursting process on utilities in close proximity to the pipe being replaced. Several cast iron and clay tile pipes of various diameters were installed in a field site, than burst and replaced with high density polyethylene pipe with various upsize factors. To determine the effects of the soil displacements on adjacent utilities, instrumented ductile iron pipes were buried both perpendicular and parallel to the pipe being burst. The data collected was used to develop proximity charts to determine safe distances for buried utilities for various pipe replacement configurations.

Though both pipe bursting and directional drilling may produce surface heave, the method in which the ground displacement is created is quite different. Pipe bursting is characterized as a method requiring brute force to break apart the pipe and push the pipe in to the surround soil medium, and to displace the soil to create an annular space large enough to accommodate the new pipe. Directional drilling cuts and removes soil from the bore hole to accommodate the size of the product pipe. Additionally, drilling fluid is utilized to transport cuttings out of the borehole rather than displace into the soil surrounding the borehole. The difference in how space is created to accommodate the new pipe is why it is difficult to apply research from pipe bursting into the studying of ground movements resulting from the horizontal directional drilling process.

2.6.6 Numerical Methods to Predict Surface Heave

Several established numerical methods exist to predict surface heave and soil displacement based on cavity expansion theory. The Author has explored some of these methods in researching ground movements associated with pipe bursting (Lueke 1999). During this research a field installation was monitored in detail using tilt meters and linear potentiometers. As compared to finite element models, numerical methods provide simpler solutions based on closed form solutions from theory and practice. These analytical solutions are easy to implement, yet are still accurate enough to provide a good prediction of the ground movements that may be expected under a given set of soil and project parameters.

In the field of pipe bursting, four model solutions have been identified to predict surface heave. These include the a) modified Sagaseta analysis, b) Vafaeian's analysis, c) cavity expansion theory, and d) analysis based on geometric parameters. When determining the maximum surface heave above the center line of the pipe, the Vafaeian's analysis becomes the same as the Sagaseta analysis, as the lateral distance away from the axis of the pipe becomes zero (Rogers and Chapman 1998). Additionally, cavity expansion theory is not able to predict movements at specified distances above the centerline of the pipe, only to determine the distance of the zone between the plastic and elastic zone of the soil (Atalah et al. 1997). A detailed description of the modified Sagaseta and Vafaeian's analyses may be found in Rogers and Chapman (1998), cavity expansion in applications of pipe bursting in Atalah et al. (1997), and the geometric analysis in Heinz et at. (1992).

According to Rogers and Chapman (1998), the modified Sagaseta analysis was developed as a means to predict ground movements around tunneling operations where localized subsidence occurs. It can be modified to predict ground movements due to expansion similar to those associated with pipe bursting. The method is based on the assumption that the soil behaves as a fluid and flows radially towards a point of volume loss, or away from a point of volume addition. The formulation considers the soil shear resistance, radius of the void, and increase or decrease in void radius.

The geometric analysis for ground movements is based on concepts introduced by Wroth and Windle (1975). This method may be used to estimate displacements around the pipe being burst based on the displacement of the cavity wall. The displacement may be estimated assuming the soil around the cavity deforms under plane strain conditions, the soil is homogenous, axial symmetry prevails, and small stains are assumed. These assumptions limit the prediction of ground displacements to a radial direction away from the axis of the pipe. This formulation considers the soil dilation and drained or undrained conditions, and can predict ground movements at some point away from the pipe considering the original and final position of the wall of the cavity.

Both numeric methods work on the basis that the ground expands or contracts, and that the actual movement or change in void diameter can be determined. Additionally, these methods only consider soil parameters and not construction techniques or practices. These methods cannot incorporate dynamic effects such as backream rate and rate of mud flow. They would not be suitable methods for determining ground movements associated with horizontal directional drilling as the models assume the soil volume stays constant and is displaced. During an actual directionally drilled installation, most soil is removed from the borehole through the circulation of drilling fluid. If utilizing good drilling practices soil should not be displaced into the surrounding soil medium. In addition, it would be difficult to determine the ratio between soils displaced and removed on a typical horizontally drilled installation.

2.7 REFERENCES

Allouche, E.N. and C. Como (1997). "Horizontal directional drilling – technology, techniques and applications." Proceedings on the 1997 NASTT/University of Alberta Technical Seminar on Trenchless Technologies, University of Alberta, Edmonton, Alberta, Canada, pp. 18-26.

Allouche, E.N., S.T. Ariaratnam and S.M. AbouRizk (1999). "The use of advanced site characterization techniques to reduce risk in underground construction projects." Proceedings of the No-Dig 1999 Conference, NASTT, Orlando, Florida, May 23-26, pp. 133-149.

Allouche, E.N., S.T. Ariaratnam, and J.S. Lueke (2000). "Horizontal directional drilling: profile of an emerging industry." Journal of Construction Engineering and Management, Vol. 126, No. 1, pp. 68-76.

Ariaratnam, S.T. and E.N. Allouche (2000). "Suggested practices for installations using horizontal directional drilling." Practice Periodical on Structural Design and Construction, Vol. 5, No. 4, pp. 142-149.

Atalah, A., R. Sterling, P. Hadala, and F. Akl (1997). "The effect of pipe bursting on nearby utilities, pavement, and structures." Trenchless Technology Center Technical Report, Ruston, Louisiana.

Baroid Industrial Drilling Products (2000). "Workshop Manual: Basic Drilling Fluids." Workshop on Industrial Drilling Fluids Applications, Halliburton North Belt Center, Houston, Texas, April 3 – 7.

California Department of Transportation (CALTRANS) (1999). "Guidelines and specifications for horizontal directional drilling installations." CALTRANS Headquarters Office of Encroachment Permits.

Directional Crossing Contractors Association (DCCA) (1994). “Guidelines for successful directional crossing bid package.” [Online] www.dcca.org/guidleines, Directional Crossing Contractors Association, Dallas, Texas.

Directional Crossing Contractors Association (DCCA) (1998). “Guidelines for successful mid-sized directional drilling projects.” [Online] www.dcca.org/guidleines, Directional Crossing Contractors Association, Dallas, Texas.

Duyvestyn, G. and M. Knight (2000). “Soil deformations due to horizontal directional drilling pipeline installation.” Proceedings of the NASTT No-Dig 2000 Conference, Anaheim, California, April 9 -12.

Francis, M., J. Kwong, and K. Kawamura (2003a). “Management of heave and subsidence risk for horizontal directional drilling.” Proceedings of No-Dig International 2003, NASTT/ISTT, Las Vegas, Nevada, March 32 – April 2.

Francis, M., J. Kwong, and K. Kawamura (2003b). “Analysis of heave and subsidence risk for horizontal directional drilling.” Proceedings of the ASCE International Conference on Pipeline Engineering and Construction, Baltimore, Maryland, July 13-16, pp. 1481-1495.

Harper, R., D. Swanson and B. Holitzki (1997). “Construction of gravity sewers by directional drilling.” Proceedings of No-Dig 1997 Conference, NASTT, pp. 541-556.

Heinz, H.K., J.W. Cassie, and P.A. Evans (1992). “Soil displacements associated with pipe bursting.” Proceedings of the 10th Annual Canadian Tunneling Conference, Banff, Alberta, 317-327.

Lapos, B., R.W.I. Brachman, and I.D. Moore (2004). “Laboratory measurements of pulling force and ground movement during a pipe bursting test.” Proceedings of No-Dig 2004 Conference, New Orleans, Louisiana, March 22-24.

Leach, G. and K. Reed (1989). “Observations and assessment of the disturbance caused by displacement methods of trenchless construction.” Proceedings of No-Dig 1989, Forth International Conference and Exhibition on Trenchless Construction for Utilities, London, United Kingdom, 67-78.

Looney, B.B. (1991). “Full scale field test of the in situ air stripping process at the Savannah River integrated demonstration test site.” WSRC-RD-91-22, Westinghouse Savannah River Co., Aiken, South Carolina.

Lueke, J.S. (1999). “Lessons in trenchless pipe replacement.” Masters of Science Dissertation, University of Alberta.

Lueke, J.S. and S.T. Ariaratnam (2000). “Risk reduction in subsurface ground movements associated with trenchless pipe replacement.” Proceedings of the No-Dig 2000 Conference, Anaheim, California, April 9-12.

Marshall, A., M. Knight, and G. Duyvestyn (2001). “Laboratory investigation into surface movements due to near surface horizontal pressurized bores.” Proceedings of the No-Dig 2001 Conference, Nashville, Tennessee, April 1-4.

McKim, R.A. (1997). “Bidding strategies for conventional and trenchless technologies considering social costs”, Canadian Journal of Civil Engineering, Vol. 24, pp. 819-827.

Najafi, M, and B.W. Gunnink (2002a). “Ground displacement monitoring during horizontal directional drilling and other trenchless methods.” Pipelines 2002 Beneath Our Feet: Challenges and Solutions, Pipeline Division Specialty Conference, Cleveland, Ohio, August 5-7.

Najafi, M, and B.W. Gunnink (2002b). “Stability analysis of boreholes in innovative horizontal directional drilling (HDD) applications.” Proceedings of 2002 Underground Construction Technology International Conference, Houston, Texas, January 15-17.

Najafi, M, B.W. Gunnink, G. Davis, and R. Humphreys (2003a). "Field testing of major trenchless technology methods for road crossings." Proceedings of ASCE 2003 Construction Research Conference, Honolulu, Hawaii, March 19-21.

Najafi, M, G. Davis, and B. Gunnink (2003b). "Stability analysis of road crossings for trenchless technology." Proceedings of No Dig International 2003, NASTT/ISTT, Las Vegas, Nevada, March 31 – April 2.

Richards, J.E. (1996). "Guidelines simplify horizontal directionally drilled crossings." Pipeline & Gas Journal, January, pp. 36-38.

Rogers, C.D.F (1990). "The influence of pipe bursting on buried services and surface structures." Report from Department of Civil and Building Engineering, Loughborough University of Technology, Leicestershire.

Rogers, C.D.F. and D.N. Chapman (1998). "Analytical modeling of ground movements associated with trenchless pipe laying operations." Proceedings of the Institute of Civil Engineers Geotechnical Engineering, Vol 131, October, pp. 210-222.

Staheli, K., D. Bennett, H.W. O'Donnell, and T.J. Hurley (1998). "Installation of pipelines beneath levees using horizontal directional drilling." CPAR-GL-98-1, US Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi.

Wroth, C.P. and D. Windle (1975). "Analysis of the pressure meter test allowing for volume change." Geotechnique 25, No 3, pp. 598-604.

Chapter 3 EXPERIMENTAL DESIGN AND PROCEDURE

3.1 INTRODUCTION

This paper discusses research in the development of a model to understand the behaviour of surface displacements associated with horizontal directionally drilled installations. Ground movements are becoming a greater concern for municipalities and contractors as horizontal drilling utilization increases and underground right of ways become increasingly crowded. In January of 2000, the City of Santa Clara, California placed a moratorium preventing the use of horizontal directional drilling due to numerous incidents involving the humping of roadways.

It is anticipated that, through the understanding of how construction techniques affect the development of ground displacements, practitioners of this technology can better plan and implement trenchless solutions to minimize the magnitude of ground movements associated with a particular installation. There are several factors that contribute to the development of surface heave including the backream rate, depth of cover, tooling utilized, annular space, and borehole pressure, and soil characteristics. The procedure used in the design of an experiment to examine the interaction of these factors on the development of surface displacements is described and a sample of the results is presented. Included is a brief introduction to directional drilling, descriptions of the drilling factors, a procedure to rank the importance of the factors, and the statistical design of the field experimentation. The design of the experiment is done such that the results may be utilized in the construction of an empirical neural network model to analyze the findings.

A version of this paper entitled "EXPERIMENTAL PROCEDURE FOR EVALUATING GROUND DISPLACEMENT FACTORS IN DIRECTIONAL DRILLING" is published by Jason S. Lueke and Samuel T. Ariaratnam in the Canadian Journal of Civil Engineering (CSCE), **30:** 830-840 (2003).

3.2 HORIZONTAL DIRECTIONAL DRILLING

Horizontal directional drilling is a trenchless method of pipe installation that has evolved from the merging of technologies from the oilfield and water well drilling industries. An installation conducted utilizing horizontal directional drilling is typically conducted in two phases. First, a pilot bore is launched from the drill rig at the surface and guided or steered utilizing an electronic locator system to the target or exit location. Once the drill string reaches the surface at the exit location, a backreamer is attached to the drill string and pulled back to the entry point. As the reamer is pulled through the pilot bore, the reamer enlarges the bore by cutting or displacing soil. This process increases the diameter of the borehole to be greater than that of the pipe being installed. The product pipe is pulled from the target location to the drill rig, after the borehole is of adequate diameter to accommodate the pipe. Several reaming passes may be required to enlarge the borehole; these are referred to as pre-reams, while the final pass resulting in pipe installation is referred to as the backream. Throughout the installation process the drill rig injects drilling fluid through the drill stem to the reamer or drill head to assist in cutting and transporting soil out of the borehole to the surface. The drilling fluid is typically a mixture of bentonite and water, with additional admixtures to assist the installation by lubricating the bore for the pulling of the product pipe, as well as stabilizing the borehole.

In comparison to other trenchless technologies, directional drilling has several advantages: (1) no vertical shafts are required as drilling commences from the surface; (2) relatively short setup time; (3) the installation path need not necessarily be straight; (4) and that the single drive installation length exceeds that of any other non-man entry trenchless method (Allouche et al. 2000). The unique capabilities of horizontal directional drilling may be adapted for several applications, and create new possibilities for geotechnical investigation and construction methods. Directional drilling has been applied to the installation of pipe in highly congested surface and subsurface areas, in dense urban environments where open cut excavation is physically impossible because of installation depth and surrounding buildings, where excavation is difficult as a result of subsurface utilities, beneath environmentally sensitive or historically significant areas, and to cross rivers, roadways, and railways.

3.3 GROUND MOVEMENT FACTORS

Prior to the design of the field experiment, the various factors that contribute to the development of surface heave on directionally drilled installations were identified. In consultation with contractors, educators, consultants, and owners, several factors were identified which may have an effect on the development of surface heave. It was the intent of this research to utilize the opinion of these industry experts to devise an experimental methodology that would efficiently gauge each of the factors influence on surface heave. The eight factors identified to contribute to surface heave are described in this section. Though there are other factors that contribute to surface heave, these eight were selected based on the ability to quantify and control them in a field environment.

3.3.1 Annular Space

Annular space refers to the difference between the diameter of the borehole and the outer diameter of the drill stem during drilling or pre-ream; or the product pipe during the backream. This space is intentionally created during the drilling and reaming phase of the installation process to provide a route for drilling fluid laden with cuttings to circulate back to the surface via the entry or exit pits. Recommended practice is to select a reamer for the backream that is between 1.25 and 1.5 times greater than the outside diameter of the product pipe. If during the reaming process circulation is lost, meaning that drilling fluid is no longer able to exit the borehole either through the entry or exit location, the borehole may become pressurized. The resulting condition is referred to as hydrolock, which may be described as the situation when the reamer acts as a piston in a cylinder created by the borehole wall (Bennett et al. 2001). Pulling the reamer through the borehole under this condition may result in the build up of hydraulic pressures ahead, or a vacuum behind the reamer. Excessive pressure in the borehole may be a contributing factor to the development of surface heave (Lueke and Ariaratnam 2002).

3.3.2 Backream Rate

The speed at which the reamer is pulled through the borehole during the pre-ream or backream is referred to as the backream rate. The maximum backream rate is a function of the borehole diameter, drilling mud pump capacity and efficiency, drilling fluid viscosity and a flow factor. The flow factor is a multiplier applied to the volume of the borehole to estimate the amount of drilling fluid required to effectively transport cuttings from the bore to the surface (Bennett et al. 2001). The flow factor is typically between 1 and 5, depending on the ground conditions, size of the cuttings and the distance the cuttings must travel to the surface (Baroid 2000). In general, the flow factor is 1 for sand, gravel, rock and cobble; 2-3 for sand, gravel, rock and cobble mixed with clay; and 3-5 for clays or reactive shale. To determine the maximum backream rate Equations 1 and 2 may be utilized (Baroid 2000; Bennett et al. 2001).

[3-1] $$\frac{Dh^2}{1273} \times L = V$$

where:

Dh = Diameter of hole in millimeters

L = Length of drill rod in meters

V = Volume of borehole per length of drill rod in liters/meter

[3-2] $$T = \frac{V \times FF}{P \times E}$$

where:

T = Minutes per rod pull back rate

FF = Flow Factor

P = Pump rate in Liters per minute

E = Pump efficiency

Pump efficiency may be determined simply by comparing the viscosity of the drilling fluid to that of water. In the horizontal directional drilling industry, the viscosity of the drilling fluid is generally measured in units of seconds per quart. For use in the above formulation, the pump efficiency is equal to the difference between the numeric value of the viscosity of the drilling fluid and the viscosity of water, subtracted from 100%. Therefore, if the viscosity of the drilling fluid were 45 sec/qt, with the viscosity of water being 26 sec/qt, the difference between the two would be 19 sec/qt. The efficiency would be calculated as 100 minus 19 resulting in an efficiency of 81% (Bennett et al. 2001).

If during the reaming process, the time calculated per rod were exceeded, it would indicate that the installation is outrunning the capability of the drill rig to pump adequate volumes of drilling fluid through the borehole. Outrunning the pump ultimately leads to cuttings being left in the borehole, which may either contribute to hydrolock or an increase in volume of soil material pushed into the formation.

3.3.3 Borehole Pressure

Borehole pressure refers to the fluidic pressure developed in the borehole during the installation of the product line. There are several methods through which borehole pressure may be developed including: 1) the pumping of drilling fluid into the borehole during the installation process; 2) a difference in elevation along the borepath and; 3) the piston action of the reamer in the borehole during situations of lost circulation or exceeding the capacity of the mud pump.

The pressurization of the drilling formation may also lead to the damage of adjacent structures. In one documented case study, it was determined that only 8 psi fluid pressure acting on the base of a 1.52 m by 1.52 m by 1.22 m high concrete vault with 300 mm thick walls and 600 mm of soil cover, was required to lift the vault (Bennett et al. 2001). This magnitude of fluidic pressure is easily attained by most of the pumps on the drill rigs pumping fluid to the reamer, or from pressurizing of the borehole by hydrolock.

Ultimately, excessively high bore pressures may cause inadvertent returns at the surface, or expand the borehole inducing ground displacements in the vicinity of the borehole.

3.3.4 Depth of Cover

The depth below the surface in which drilling and the backream occurs is referred to as the depth of cover. The amount of soil between the reamer and the surface has a direct influence on the expected amount of surface heave. Intuitively, the greater the cover the less chance of surface heaves occurring due to increasing over burden pressure and arching occurring in the soil structure. There is a delicate balance between drilling at an adequate depth to prevent surface heave, and the cost of installation, as deeper installations are less cost effective (Lueke and Ariaratnam 2002).

3.3.5 Reamer Type

There are several variations in reamer design and function, each developed to provide different mixing and cutting actions during the reaming process. Though some reamers are specifically designed to operate in a particular soil medium, others may be considered multipurpose, able to operate under several soil conditions. In general reamers may be classified as: 1) compaction type; 2) mixing type; or 3) all purpose reamers (Bennett et al. 2001). Table 3.1 presents the different categories of reamers and the subsequent types of reamers within each family.

Table 3.1 Reamer Configuration (Bennett et al. 2001)

Family	**Type**	**Application**
Compaction	Barrel Spiral	Clays, Silts, Sands, Cobbles
Mixing	Wheel Blade Combination (Blade/Wheel) Off-set Bar Wing	Clays, Sands
All-Purpose	Fluted Modified Compaction	Variable soil conditions

The behaviour of the reamer within the borehole determines its likelihood of causing surface displacements and their resulting magnitudes. Compaction reamers, by nature of their design, propagate through the borehole with minimal mixing, cutting action, and cutting transport as a result of the poor flow characteristics around the reamer. Alternatively, mixing type reamers have a very open design allowing the free flow of drilling fluid through the plane of the reamer assisting in equalizing borehole pressures ahead and behind the reamer. The benefit of this design is that there is very little compaction of the borehole wall during the passing of the reamer, as most of the material along the borepath is removed by the cutting and transport action. The last family of reamers identified as all-purpose, include the fluted and modified compaction type reamers. While this family of reamers facilitates better flow of drilling fluid around the reamer when compared to the compaction type reamer, they still may induce a moderate to substantial level of compaction of the borehole wall, as they do not have the cutting ability of the mixing type reamer. The benefit of this type of reamer is that it is very flexible in the type of soil that it may be utilized, as well as being very adaptable to variable soil conditions along the borepath (Bennett et al. 2001).

3.3.6 Reamer Diameter

In terms of this research, the diameter of the reamer refers to the largest diameter bore the reamer cuts into the soil medium. The size of the reamer directly influences the volume of soil that must be displaced or removed during an installation. Additionally, the reamer configuration influences the proportion of soil that is cut and removed, rather than displaced into the surrounding formation (Lueke and Ariaratnam 2002).

3.3.7 Soil Composition

Soil composition refers to the classification of the soil by its material characteristics. This classification was primarily made by comparing particle size distribution and plasticity. The composition of the soil determines its behaviour during an induced strain event in the soil medium. For example, stiff soils typically behave differently than loose sandy soils, subsequently affecting how ground displacements propagate through the soil matrix.

3.3.8 Soil Density

Soil density is simply defined as the ratio of mass to unit volume of the soil. The density of the soil may relate to the ease of compaction or dislodging of the soil during the reaming phase of the installation. Additionally, the density of the soil has an influence on the proportion of the soil displaced by the reamer that is actually taken up by the voids within the soil matrix.

3.4 ANALYTICAL HIERARCHY PROCESS

The Analytical Hierarchy Process (AHP) is a decision-making approach developed by Saaty in the 1970's as a method to aid decision makers in the solving of complex problems (Triantaphyllou and Mann 1995). This process provides the theory and methodology for the modeling of unstructured problems by utilizing the sense of judgment of individuals whom have a common understanding of the problem or situation in question (Saaty 1980). The advantages of utilizing this process are that: 1) it can decompose complex problems into a system, or hierarchy, of interrelated smaller parts that can be easily understood to solve the larger problem; 2) a pair wise comparison of judgments is utilized for input in problems which are difficult or impossible to effectively quantify by any other means and; 3) it compares factors that may change in time and space, or in conjunction with other factors that may change their meaning in relation to each other. The process is commonly conducted utilizing the direct questioning of people who may or not be experts in the problem, but who at the very least are familiar with the problem. The AHP methodology can be found in Saaty and Alexander (1989), in this paper only the results from the analysis will be included.

3.4.1 Development and Implementation

The goal of using the Analytical Hierarchy Approach in this research was to weigh or rank the various factors that contribute to ground movements. This methodology makes it possible to rank the factors in their perceived order of importance to ground movements based on the opinion of industry experts. This ranking, along with the actual pair wise comparisons of the factors, provides the basis for the design of the field experiment. To achieve the relative weightings of each of the factors, a matrix is evaluated utilizing the Analytical Hierarchy Approach. Within this matrix, the factors outlined earlier in the paper thought to contribute to ground movements where compared. These factors include: Soil Composition (SC); Soil Density (SD); Backream Rate (BRR); Borehole Pressure (BP); Reamer Type (RT); Reamer Diameter (RD); Depth of Cover (DC); and Annular Space (AS). The matrix is constructed with eight rows and columns, with the factor description arranged in the same order from left to right across the horizontal column headings, as from top to bottom on the vertical row headings. The resulting matrix formulation is illustrated in Table 3.2.

Table 3.2 AHP Matrix Formulation

	SC	**SD**	**BRR**	**BP**	**RT**	**RD**	**DC**	**AS**
SC	1							
SD		1						
BRR			1					
BP				1				
RT					1			
RD						1		
DC							1	
AS								1

The Analytical Hierarchy Process is based on the pair wise comparison of the factors within the matrix. To demonstrate this, one may compare the first factor (SC) on the vertical axis to the second factor (SD) on the horizontal to determine which one is of greater importance to the development of surface displacements in horizontal directional drilling. The question the responders ask themselves is how much more important is Soil

Composition than Soil Density to the development of ground movements? The answer to the question is based on a predefined numerical scale of values ranging from extremely less important to extremely more important, 1/5 to 5 respectively (Table 3.3). The numeric response is entered into the corresponding cell.

Table 3.3 Scale of Importance

Intensity of Importance	Verbal Definition
1/5	Extremely Less Important
1/3	Slightly Less Important
1	Equally Important
3	Strongly More Important
5	Extremely More Important

If Soil Composition is extremely more important than Soil Density in the development of surface displacement during a horizontal directionally drilled installation, then the cell in the matrix with SC on the vertical and SD on the horizontal would have a value of 5. The comparison would continue horizontally holding Soil Composition as constant and comparing the rest of the factors on the horizontal axis. Once the first row was complete, the comparison of the second factor on the vertical axis would begin against each of the factors on the horizontal in the same manner. In the matrix a diagonal line of cells with a value of 1, meaning equally important, is automatically created when comparing like factors. Values below this line are automatically the reciprocal of the value for the pair of factors above the diagonal line. Thus in the example of the comparison of SC to SD, a value of 1/5 would be assigned to the cell denoted by SC on the horizontal axis and SD on the vertical axis.

To facilitate and ease the gathering of input for the matrix, a questionnaire was developed to assist in determining the weights of the eight factors. A sample of the questionnaire is provided in Appendix A. The questionnaire was developed from the matrix in Table 3.2, with a series of verbalized questions based on the pair wise comparison outlined above. The response was scored based on the verbal definitions outlined in Table 3.3. A total of ten industry experts were polled directly by the Author to ensure the questionnaire was interpreted correctly.

3.4.2 Analysis of Results

An example of the procedure to analyze the data collected from the questionnaire is included in this section. One of the questionnaires with unprocessed responses is shown in Table 3.4, all the questionnaires and analysis is included in Appendix B. Included in this matrix is a row for the summation of each column, which is utilized to normalize the values in each cell. The normalized values are shown in Table 3.5, obtained by dividing each cell in a column by the summation of the particular column.

Table 3.4 Sample Criteria Weights Matrix

	SC	**SD**	**BRR**	**BP**	**RT**	**RD**	**DC**	**AS**
SC	1	3	1/3	1/3	3	3	1/3	3
SD	1/3	1	1/3	1/3	3	5	1/3	3
BRR	3	3	1	1	3	5	1	3
BP	3	3	1	1	5	5	1	3
RT	1/3	1/3	1/3	1/5	1	5	1/3	1
RD	1/3	1/5	1/5	1/5	1/5	1	1/5	1/5
DC	3	3	1	1	3	5	1	1
AS	1/3	1/3	1/3	1/3	1	5	1	1
Sum	11.33	13.87	4.53	4.39	19.20	34	5.19	15.2

Table 3.5 Sample Normalized Criteria Weight Matrix

	SC	**SD**	**BRR**	**BP**	**RT**	**RD**	**DC**	**AS**	**Average**
SC	0.088	0.216	0.073	0.076	0.156	0.088	0.064	0.197	0.120
SD	0.029	0.072	0.073	0.076	0.156	0.147	0.064	0.197	0.102
BRR	0.265	0.216	0.221	0.227	0.156	0.147	0.192	0.197	0.203
BP	0.265	0.216	0.221	0.227	0.260	0.147	0.192	0.197	0.216
RT	0.029	0.024	0.074	0.045	0.052	0.147	0.064	0.066	0.063
RD	0.029	0.014	0.044	0.045	0.010	0.029	0.038	0.013	0.028
DC	0.264	0.216	0.221	0.227	0.156	0.147	0.192	0.066	0.186
AS	0.029	0.024	0.074	0.076	0.052	0.147	0.192	0.066	0.082

The average value of the row in the Normalized Criteria Weight Matrix (Table 3.5) represents the relative weight of that particular factor towards the development of surface movements associated with horizontal directionally drilled installations. This matrix is obtained by dividing each cell in a column by the summation of the particular column. According to the opinion of the respondent to this questionnaire, borehole pressure was the greatest contributing factor to the development of surface movements, while reamer diameter was the least contributing factor. Through the analysis of each respondent, Table 3.6 was compiled indicating the normalized weights for each factor. Table 3.7 summarizes the average weight of each factor in descending order of importance.

Table 3.6 Summary of Normalized Weights by Respondent

	1	2	3	4	5	6	7	8	9	10
SC	0.189	0.120	0.041	0.123	0.131	0.082	0.132	0.077	0.124	0.039
SD	0.103	0.102	0.093	0.047	0.103	0.096	0.164	0.233	0.331	0.118
BRR	0.133	0.203	0.156	0.053	0.106	0.049	0.138	0.166	0.202	0.279
BP	0.220	0.216	0.215	0.272	0.266	0.105	0.090	0.212	0.037	0.189
RT	0.079	0.063	0.068	0.186	0.091	0.055	0.074	0.088	0.096	0.083
RD	0.053	0.028	0.072	0.064	0.060	0.143	0.123	0.057	0.068	0.048
DC	0.189	0.186	0.179	0.162	0.071	0.235	0.228	0.099	0.108	0.193
AS	0.034	0.082	0.176	0.092	0.173	0.235	0.052	0.069	0.033	0.052
CR	0.164	0.098	0.147	0.214	0.115	0.058	0.285	0.172	0.090	0.115

Table 3.7 Summary of Factor Weight

Factor	Weight
Borehole Pressure	0.182
Depth of Cover	0.165
Backream Rate	0.148
Soil Density	0.139
Soil Composition	0.106
Annular Space	0.099
Reamer Type	0.088
Reamer Diameter	0.071

To verify the validity of the Analytical Hierarchy Process, the criteria weight matrix from each of the respondents is checked for consistency by performing a consistency ratio test. It is recommended that the consistency ratio be less than 10%, however, this is not a hard and fast rule (Saaty 1980). The consistency ratio is defined as the consistency index over the random consistency index. As outlined in Taha (1997) the formulation is as follows:

$$[3\text{-}3] \quad CR = \frac{CI}{RI} = \frac{ConsistencyIndex}{RandomConsistencyIndex} \leq 0.1$$

where,

$$[3\text{-}4] \quad CI = \frac{\lambda_{\max} - n}{n-1}$$

$$[3\text{-}5] \quad RI = \frac{1.98(n-2)}{n}$$

In this formulation, n is the total number of factors being compared in the matrix, and λ_{max} is the addition of the resultant product matrix of the multiplication of the criteria weights matrix and the normalized average (in matrix form) of the factors for that specific matrix. The result of this formulation for the criteria weight matrix from each respondent is listed in the bottom row of Table 3.6, the Summary of Normalized Weights by Respondent. The average consistency ratio for all ten respondents was 14.6%, with a standard deviation of 6.7%, and a minimum and maximum of 5.8% and 28.5% respectively. The ratio should be about 10 percent or less for acceptable overall consistency. Otherwise, the quality of the judgmental data should be improved, by revising the manner in which questions are presented to make the pair wise comparisons. This is slightly above the recommended level of 10%, though still relatively acceptable do to the relatively large size of the matrix (Saaty 1980).

3.5 EXPERIMENTAL DESIGN

Early in the investigation, it became evident that some thought would be required to ensure that high quality data be collected with the limited resources available. As a result of financial constraints, there were only enough funds to hire the directional drilling contractor for two days. Subsequently, this eliminated the possibility of installing pipes on multiple sites, as it was only feasible to install two pipes a day over the distance and depth being considered for this investigation. To design the field experiment to be statistically sound, the factors to be considered had to first be selected, and then the level at which these factors were to be investigated be determined. The selection of factors to include in the field experimentation was achieved through the ranking of the factors utilizing the analytical hierarchy procedure. According to the analysis, the factors were ranked from the most likely to influence surface displacement to least. From most influential to the least these factors were; the borehole pressure, depth of cover, backream rate, soil density, soil composition, annular space, reamer type and reamer diameter. If it were required to eliminate factors, the lower ranked factors would be sacrificed to ensure the more highly ranked factors were examined.

Most of the factors were of the quantitative nature, with only the soil composition and reamer type being more qualitative. In the planning of the fieldwork it was essential that the number of borepaths be minimized, while maximizing the quality of data that may be collected. Some of the factors considered were site specific, others were variable on the borepath meaning they could be changed during the installation, while others had to be held constant on an individual borepath. Table 3.8 summarizes the nature of each variable included in the investigation.

Table 3.8 Drilling Factor Relationship with Borepath and Site

Variable or Factor	Site Specific	Bore Specific	Bore Variable
Borehole Pressure			●
Depth of Cover			●
Soil Density	●	●	
Backream Rate			●
Soil Type	●	●	
Annular Space		●	
Reamer Type		●	
Reamer Diameter		●	

Typically, in the investigation of the effects of one or more variables on the response of a system a factorial design is utilized (Finney 1955). To perform a general factorial design, the experimenter selects a fixed number of levels for each of the factors that are under investigation (Box et al. 1978); an experiment is then conducted with all possible combinations of factors at their various levels. The number of runs or data points required to conduct a full factorial experiment is determined by multiplying the number of levels of each of the factors by each other. If the first factor has 2 levels, the second 3 levels and the third 4 levels, then 24 data points or runs would be required for the investigation (2 x 3 x 4 = 24). It is important to limit the number of levels and factors that are considered in a full factorial experiment as too many levels and factors would cause the number of runs to grow exceedingly fast to the point where it would be unfeasible to conduct the research. Though the approach of limiting the number of levels of a factor in the consideration does not allow for the full exploration of the factor space, it can indicate major trends for further research or more detailed runs. The main disadvantage of utilizing a limited number of levels in the design is that the results obtained may not reflect the full extent of the nature of the interaction, or the progression of the change in main effects as the levels are sequentially changed (Finney 1955). However, the factorial design does allow for the consideration of interaction effects of each of the factors with a relatively few runs, and the data collected is well suited for the development of models to explain the observed behaviour of the response in question.

3.5.1 Factor Levels

To facilitate economic efficiency, and because of familiarity with the site due to previous field research, it was decided that this investigation be conducted at the University of Alberta Research Farm. With only one site utilized during the investigation, the soil density and soil composition were eliminated from study, as these factors were relatively constant across the site. Of the remaining factors to consider, borehole pressure and depth of cover were deemed important by the analytical hierarchy procedure, and essential to include. Additionally, the backream rate was also considered to be of interest as this may contribute to the borehole pressure. Of the three remaining factors; annular space, reamer type and reamer diameter; only reamer type was selected to be included. The reamer configuration was selected over the reamer diameter and annular space, as the information gathered relating to the rig operational pressures and ground movements from the different reamers would provide additional data and information for future research. With the exclusion of soil composition and density due to the utilization of only one site, and the selected exclusion of the reamer diameter and annular space factors, only the borehole pressure, depth of cover, backream rate and reamer type factors remained. These four factors formed the basis for the design of the field experiment. Using the suggested two level factorial design, each of the four factors were examined at two levels, thereby resulting in a total of 16 runs or data points to achieve all possible combinations.

The selection of the levels at which the factors would be set was based on previous fieldwork, as well as equipment and tooling limitations. For this examination it was decided that a 200 mm (8 inch) diameter pipe be utilized, as this was the diameter pipe that typical horizontal directional drilling contractors utilize in practice. According to a survey conducted by Allouche et al. (2000), approximately 83% of all pipe installed during the 1999 construction season was of a diameter that was 200 mm (8 inches) or less, subsequently enforcing the selection of this diameter for the research.

Depth of cover was set at the levels of 900 mm and 1200 mm (3 and 4 feet) below the surface monitoring points. For the goal of this research, it was deemed more important to accurately measure the surface heave in response to the various combinations of factors, rather than determining the minimum depth at which surface displacements are minimized. At depths deeper than the ones proposed, there were concerns of the ability to measure any surface effects. The reamers selected for the research were the fluted and spiral compactor type, illustrated in Figure 3.1. Both of these reamer types are routinely utilized in the soil conditions found at the University of Alberta Farm site, though they have very different behaviour during the backream.

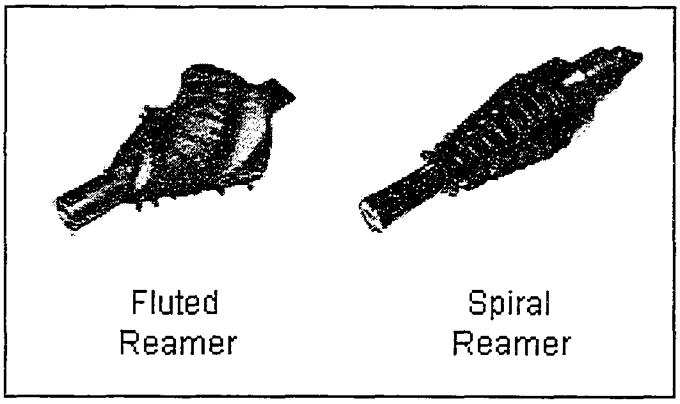

Figure 3.1 Fluted and Spiral Compaction Reamers (Vermeer Manufacturing)

Fluted reamers are designed to cut, mix, and displace the soil as it is pulled towards the drilling rig. This cutting action and the transport of the cuttings by the drill fluid, in combination with a small soil displacement component, provide the necessary borehole enlargement for the installation of the product pipe. Alternatively, a spiral compactor type reamer relies strictly on the displacement of soil to enlarge the borehole for the product pipe. A comparison of these reamer types would provide valuable information on the proper utilization of each type in this soil condition in future research.

Borehole pressure, though ranked as one of the most important factors contributing to the development of surface heave, was also the most difficult to quantify in the research. However, with the very different behaviour of the reamers, inclusion of the backream rate as a separate factor, and the unpredictable nature of the soil structure, it would be very difficult to accurately quantify and in turn maintain a specific pressure level through the length of an individual bore. Consequently, a different perspective on the issue of borehole pressure was required, and this was developed through the utilization of drill mud pumping rates measured with an inline flow meter. The drill rig utilized in the research, a Vermeer D24x40a (Figure 3.2), had only two settings on the mud pump; a high setting rated at 144 litres per minute and a low setting of 72 litres per minute. Adjusted for altitude, the pump on the drill rig operated closer to 100 litres per minute and 50 litres per minute at the high and low settings respectively. Borehole pressure could be adjusted by operating the drill rig at either the high or low pump speed to provide a varied flow to the reamer for differing backream rates, literally creating a high or low pressure that could be maintained through the bore.

Figure 3.2 Vermeer 24X40a Drill Rig

To determine the levels at which to investigate backream rates, calculations were performed based on the flow rate and the geometry of the installation, using equations 1 and 2. Using a 200 mm product pipe, a borehole of 300 mm was required using the recommended practice of sizing the back reamer diameter 1.5 times the diameter of the product (Bennett et al. 2001). By equation 1, with the borehole diameter of 300 mm and the length of drill rod set at 3.0 m, the volume of borehole per length of drill rod is calculated to be approximately 212 liters. At the low volume pumping rate of approximately 50 liters per minute (direct measurement), and a flow factor of 3 for a clay type soil, equation 2 predicts the pull back rate to be approximately 12.7 minutes per rod. For the higher flow rate of 100 liters per minute, the pull back rate is 6.36 minutes per rod. However, the slowest the rig could pull back the drill rod was approximately 6 minutes per rod. It was therefore decided that for the back ream, the two levels would be the slowest the rig could pull back the rod at 6 minutes per rod, and the fastest the rig could pull rod at approximately 2 minutes per rod. These operational levels were the most comfortable for the operator and machine. It is hypothesized that the equations 3-1 and 3-2, are more applicable to larger diameter drill rigs and product pipe installations, accounting for the difference in recommended or predicted pull back rates and the capabilities of the drill rig utilized in this investigation. With the selection of the back ream rates, each of the factors to be considered in this research was now defined. Table 3.9 summarizes the selected factors and levels that were used during this experiment.

Table 3.9 Summary of Factors and Levels

	Depth of Cover	Reamer Type	Flow Rate	Back Ream Rate
Level 1	900 mm	Fluted	50 L/min	6 min/rod
Level 2	1200 mm	Spiral Compactor	100 L/min	2 min/rod

3.5.2 Borepath Design

To achieve a full factorial experimental design, a total of 16 data points were required. Therefore, either a total of 16 installations had to be conducted, or an innovative approach to the design of the experiment had to be conceived. As there was the constraint of two days for drilling time, which only safely allowed for the installation of four pipes, an innovative design had to be pursued. To minimize the number of installations it was necessary to include as many factors as possible in the actual bore profile. Each factor that could be incorporated into the borepath design would decrease the total number of installations by one half – due to each factor having two levels. One factor that was included in the bore profile was the depth of cover as it could be varied during the installation procedure. To further reduce the number of installations each bore was designed in a mirror image such that during the backream the first half could be performed with a low mud flow rate and the second half with the higher flow rate (Figure 3.3). By the inclusion of these factors in the design of the borepath the number of installations was reduced from 16 to 4, effectively reducing the number of installations to a manageable level, while still maintaining experimental integrity.

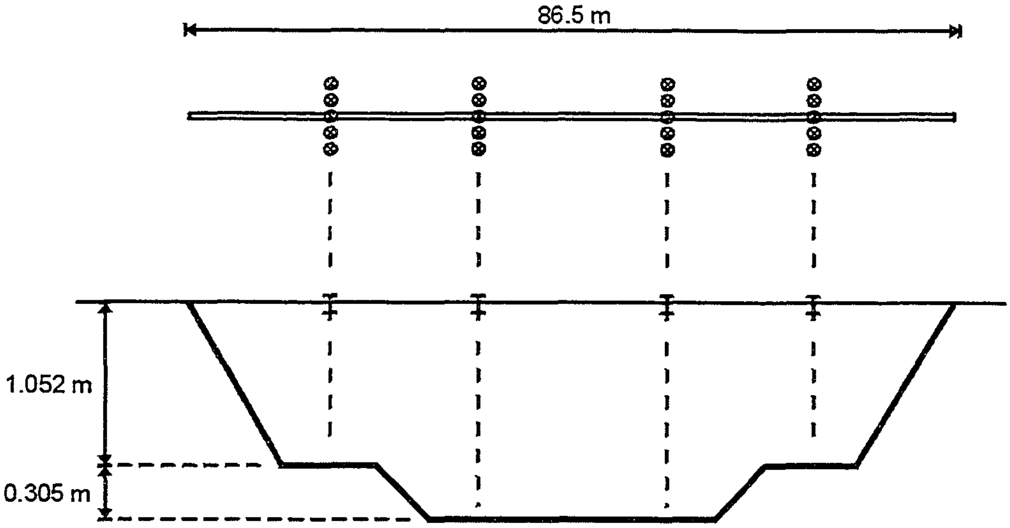

Figure 3.3 Design borepath

The borepath chosen was approximately 86.5 meters in length, with 4 monitoring points along the length indicated by the five small circles in plan view. These circles represent the surface points that were installed to measure the ground displacements. Each monitoring point consisted of five surface points installed perpendicular to the bore path (Figure 3.4). One point was installed on the centerline of the borepath, and two laterally on each side, each separated by 200 mm the equivalent to one product pipe diameter.

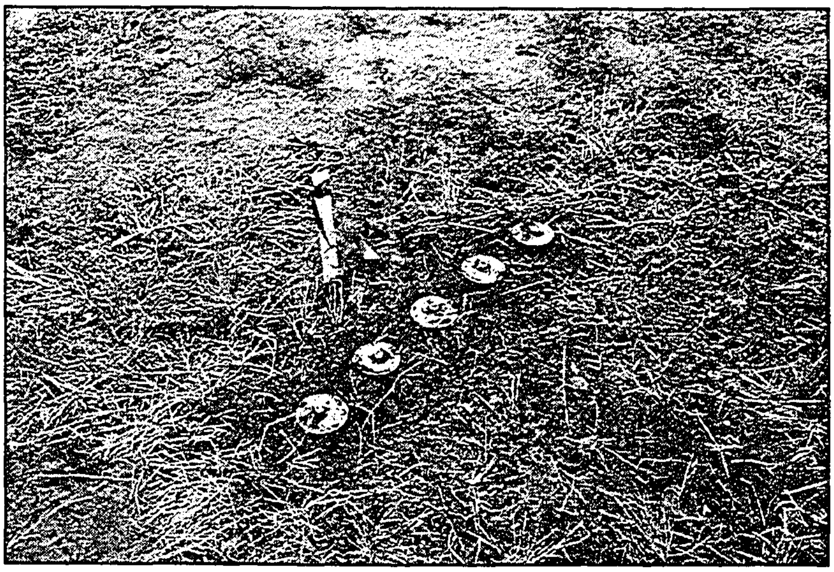

Figure 3.4 Typical Surface Point Configuration at Monitoring Points

Surface point apparatus were constructed of two circular flat plates separated by a section of polyvinyl chloride pipe, slipped over a length of threaded ready rod, all secured in place by standard hexagonal nuts (Figure 3.5). The total length of the surface point apparatus was approximately 300 mm, with a 200 mm separation between the circular flat plates. One flat plate was located at the end of the ready rod length, with the other situated approximately 100 mm from the end of the rod. This created a point that could be pushed into the ground to secure the apparatus in the soil. The polyvinyl chloride pipe with an inside diameter of 19 mm, was selected to slip over the 12 mm diameter ready rod. In this configuration the ready rod could freely travel in an axial direction inside the pipe, free from soil friction.

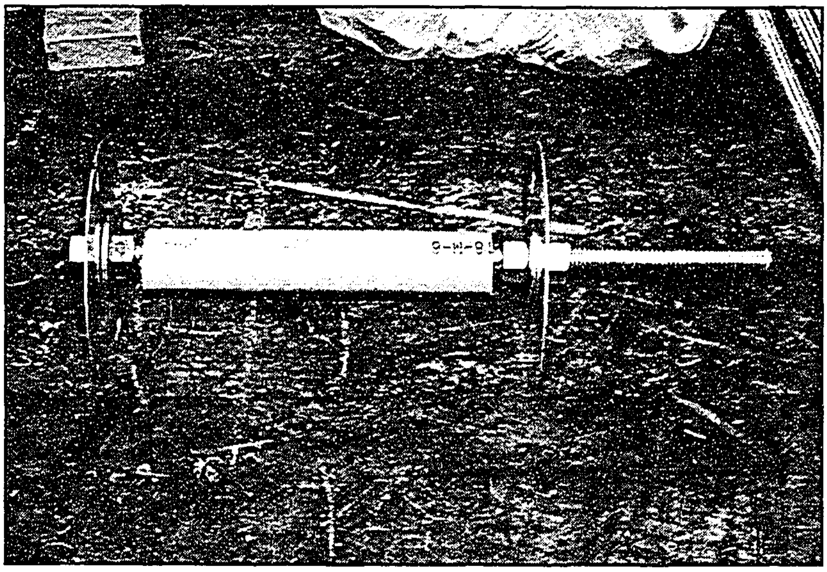

Figure 3.5 Typical Configuration of Surface Point.

Drilling depths were determined by the depth below the surface point as opposed to the ground surface. To negate the effects of the mat of grass on the surface, the base of the surface points were installed approximately 150 mm below the surface. The installation depth for the drilling contractor was therefore 900 and 1200 mm below the base of the surface points, approximately 1050 and 1350 mm below the surface. In the vicinity of the monitoring stations the borepath was brought to the horizontal to ensure proper depth beneath the surface points was maintained. Transition between the depths was conducted over the course of one or two drill rods.

3.5.3 Layout of Investigation

The complete layout for this investigation included a total of four borepaths. At the University of Alberta Research Farms, the test site for this investigation was set up south of the location where the previous research was conducted to ensure that the installations were occurred in undisturbed soil. Each borepath was situated in a North-South orientation, parallel to the service road located on the west side of the test site. Borepaths ran parallel to each other, separated by a 5 m wide isolation strip to prevent soil movement interference across borepaths. Figure 3.6 illustrates the layout of the installations.

Each installation had four monitoring stations identified by the circled numbers beneath the plan view in Figure 3.6. From the location where the rig was setup, the pilot bore was initiated in a southern direction (towards the right in the diagram), reaming occurred in the opposite direction. For each installation, the lower flow rate of 50 liters/minute was maintained in the first half of the ream beneath monitoring stations 1 and 2. At the mid point of the installation (vertical dashed line), the flow rate was increased to 100 liters/minute, beneath monitoring points 3 and 4. The lower flow rate was initiated in the first half of the ream to prevent excess flow into the second half of the installation. Excess drill mud volumes may have affected the ground movement measurements in the second half of the borepath.

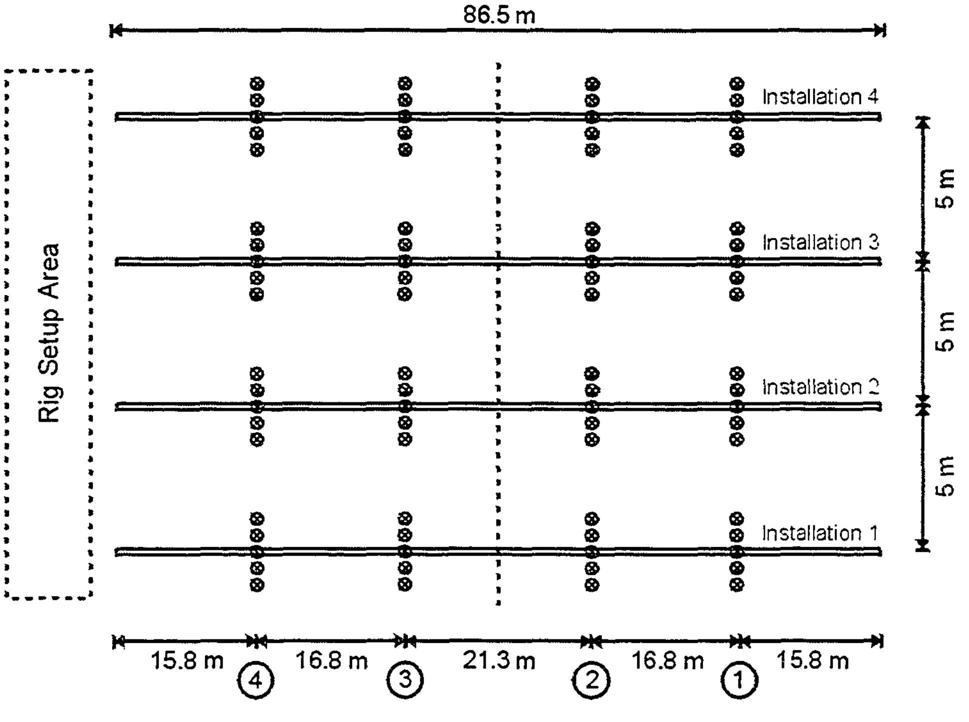

Figure 3.6 Layout of Borepaths

3.5.4 Installation Procedure

Consistency is essential for the full factorial experiment to produce competent results. For any installation only the factors under consideration should be varied, and varied only at the predetermined levels. Every other factor or variable not being studied must be held constant during the investigation. To this extent, the contractor utilized the same directional drill rig on all four installations, along with the same installation procedure and drill mud composition. In this investigation, the actual composition and mixture of the drill fluid was not considered to influence the results of the experiment, and as a result the contractor utilized a mixture that would typically be used in this soil in line with good drilling practices.

For each installation, the contractor set up the rig on the north side of the site for drilling in the southern direction. The entry angle and offset for each installation was held constant to assist in producing similar borepath trajectories. For the drilling of the pilot bore, a Vermeer flat faced drill bit was employed along with a Digitrak walkover locating system. Following the prescribed borepath, the contractor guided the drill bit to the exit location where the reamer and product pipe were attached to the drill stem. Pilot bore drilling procedures were consistent for each installation following generally accepted drilling practices. Once the reamer was attached to the drill stem, the drill rig operator pulled the reamer and product pipe to the rig according to predetermined procedures. Table 3.10 summarizes the procedure followed outlining the factors and levels held on each installation and at each monitoring point.

Table 3.10 Design Installation Summary

Installation	Monitoring Point	Depth	Reamer	Backream Rate	Flow
1	1	900 mm	Fluted	6 min/rod	50 l/min
1	2	1200 mm	Fluted	6 min/rod	50 l/min
1	3	1200 mm	Fluted	6 min/rod	100 l/min
1	4	900 mm	Fluted	6 min/rod	100 l/min
2	1	900 mm	Fluted	2 min/rod	50 l/min
2	2	1200 mm	Fluted	2 min/rod	50 l/min
2	3	1200 mm	Fluted	2 min/rod	100 l/min
2	4	900 mm	Fluted	2 min/rod	100 l/min
3	1	900 mm	Compactor	2 min/rod	50 l/min
3	2	1200 mm	Compactor	2 min/rod	50 l/min
3	3	1200 mm	Compactor	2 min/rod	100 l/min
3	4	900 mm	Compactor	2 min/rod	100 l/min
4	1	900 mm	Compactor	6 min/rod	50 l/min
4	2	1200 mm	Compactor	6 min/rod	50 l/min
4	3	1200 mm	Compactor	6 min/rod	100 l/min
4	4	900 mm	Compactor	6 min/rod	100 l/min

3.6 FIELD RESULTS

Ground movements were recorded after the drilling and the backream phase of each installation utilizing a total station. Surface point displacements were measured using conventional leveling techniques, before, after drilling, and after reaming. The layout devised in the experimental design allowed for the comparison and analysis of ground movements resulting from the various combinations of factors studied. From the installations it was found that in all cases surface heave was exhibited at the surface after both the drilling and reaming phases. During the drilling phase of the installation ground movements ranged from between 0 and approximately 1 mm, for the reaming phase vertical ground displacement ranged between 2 and 6 mm. Several factors were identified and studied during the research including mud flow, backream rate, reamer type, and depth of cover. Included in this paper is part of the analysis of the effect the type of reamer had on the development of surface displacements.

During the installation, fluted and spiral compactor reamers were employed as outlined by the requirements of the full factorial experiment design. Both reamers were used for two boreholes to provide a comparison of how each reamer behaved. Unlike the backream rate and mud flow factors that could be varied during an installation, the reamer type had to be selected prior to the installation commencing, this factor was borehole specific. Figures 3.7 and 3.8 illustrate the results from the four installations for a depth of 1,200 mm with varied backream rates (Lueke and Ariaratnam 2002). The mud flow for a particular installation is identified with the reamer type. The horizontal axis of the graphs indicates the position of the monitoring point in multiples of pipe diameter away from the borepath, in this case 200 mm.

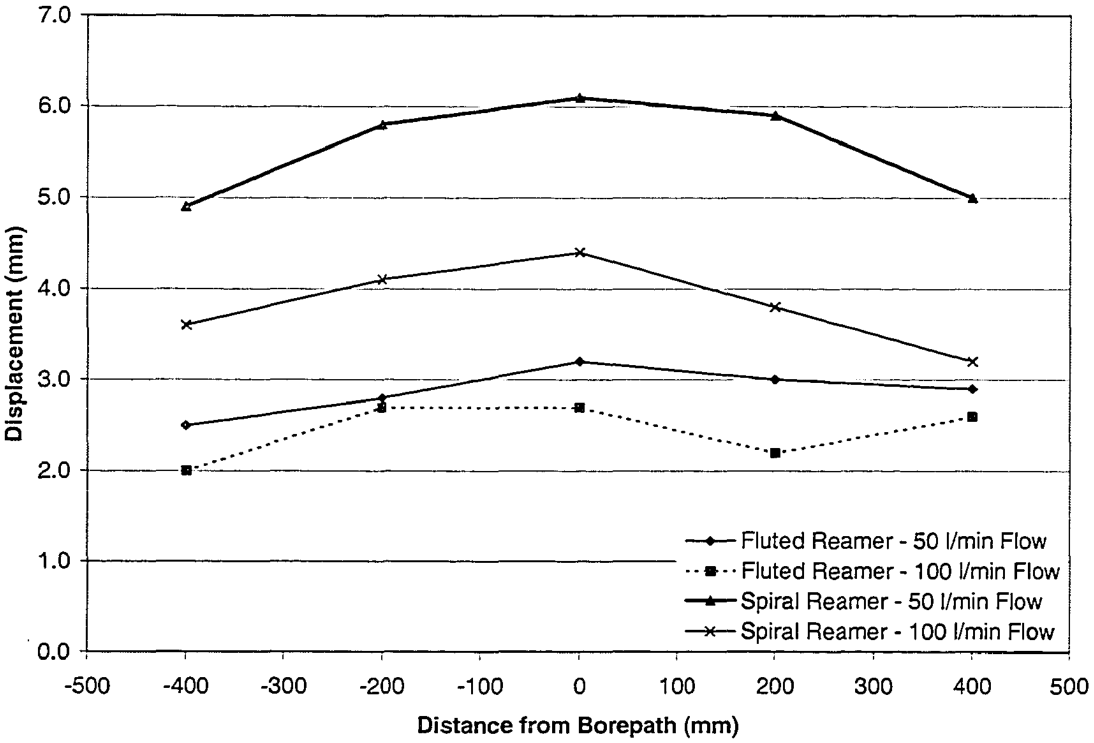

Figure 3.7 Displacements at 1,200 mm Depth with Slow Backream Rate

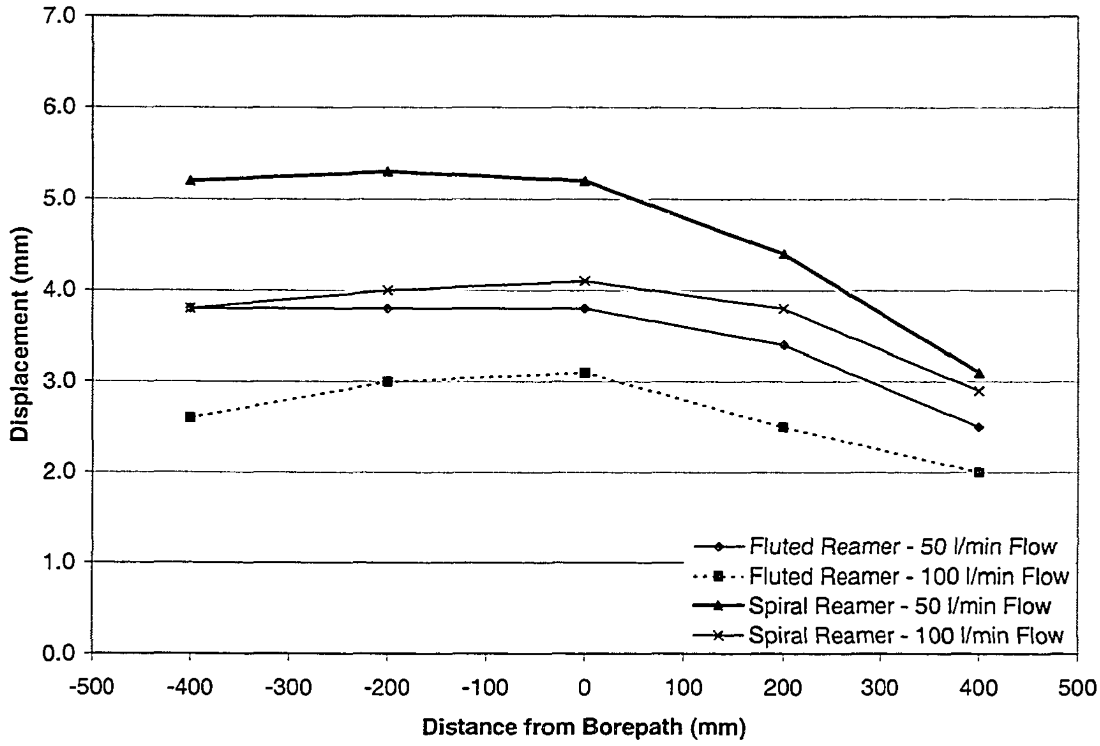

Figure 3.8 Displacements at 1,200 mm Depth with Fast Backream Rate

The results reveal two patterns that are consistent through all the installations. First, that the spiral compactor reamer induces greater surface displacements than the fluted reamer type for either depth and mud flow rate. And secondly, for either reamer type with either mud flow rate, the low mud flow rate for any given combination of factor levels produced greater surface heave than the higher mud flow rate installations. These patterns were consistent for the installations conducted at the 1,200 mm depth and for the 900 mm deep installation with the fast backream rate. The installations conducted at the 900 mm depth with the slower backream had relatively the same amount of surface heave for either reamer type and mud flow rate, with all four installations having a maximum displacement within half a millimeter of each other. While for all other installations, the difference between the fluted and spiral compactor reamer displacements were up to two millimeters.

The greater surface heave exhibited in the installations conducted with the spiral compactor reamer may be accounted for by the design of the reamer itself. As opposed to the fluted reamer, which has slots curved around the circumference of the tool to provide a passage way for cuttings and drilling fluid from the front to the back of the reamer, the spiral compactor has an expanding screw like configuration. The configuration of the spiral reamer does not allow for the transfer of material from the cutting face to the trailing face of the reamer. As a result, that material is compacted into the surrounding soil from the rotation of the reamer as it passes through the ground. Since this material is not removed or transported by the mud to the insertion pit, its volume is compacted into the soil, causing greater surface heave than if that material were removed. Additional information was recorded for the 900 mm depth, as well as differing combinations of factors and factor levels. Chapter 4 summarizes data from all installations and provides additional discussion.

3.7 MODELING

To model the response of the surface displacement data collected in this research program, an artificial neural network model was selected. An artificial neural network refers to a computing paradigm whose central theme is borrowed from the analogy of a biological neural network (Mehrotra et al. 1997). The model may be described as a massive parallel distributed processor made up of many simple highly interconnected processing units or elements, which have an inherent ability to store experimental knowledge and making it available for future use (Haykin 1999). The processing elements are linked together over connections which transfer numerical data from one processing element to the next. These models mimic the brain in that the network acquires knowledge about the environment through a learning or a training process, and that this knowledge is stored in the relative weight, or importance, of links between individual processing elements. The weight of a particular link is ascertained through a learning algorithm which modifies the weights of links between processing elements in a systematic manner to attain a desired design objective (Haykin 1999).

The actual development of a model is an iterative process, as determining the proper model configuration for a given circumstance requires a trial and error approach after some initial mathematical formulation. Input vectors are constructed based on the prescribed drilling practices outlined in Table 3.9, with the resulting surface heave measurements defined as target output. Each drilling factor in the vector had a unique scale meaningful to its domain, with values for the reamer type approximated to account for soil removal efficiency, such that the input was linearly transformed to values between 0 and 1. Of the total 16 input vectors, 4 are withheld from the network to act as a test set, while the remaining vectors are used to train the model. During training, the model compared the target output to its predicted output, and subsequently modified the weights of the links between the processing elements to reduce the average error. Other factors related to the internal configuration of the model may also be adjusted by the developer, to optimize the model.

After the development of several models, with various configurations, a model was created that could predict the magnitude of surface heave based on the input of backream rate, depth of cover, reamer type, and mud flow rate, to within 0.2 mm. This success indicated that it was possible to utilize an artificial neural network as a predictive tool in the determination of the relative magnitude of surface heave. However, in the model's current state, and with the amount of data collected and utilized in its development, the model is not intended, nor is it suggested, that it encompasses all influencing factors to handle all possible drilling situations; rather it provides the framework for further research and development. With additional refinement and data collection, it is anticipated that this model would provide an accurate representation of the relative surface heave generated by varying drilling techniques. The modeling process is discussed in detail in Chapter 5.

3.8 CONCLUSIONS AND RECOMMENDATIONS

This paper presents the initial findings from a research program that was utilized to develop a methodology to evaluate ground displacement factors in horizontal boring operations. There are several factors that contribute to surface heave, of which eight were initially chosen to be studied and an investigation conducted to determine how these factors interact with each other during the installation process, with the ultimate goal of constructing a model to predict the relative magnitude of surface heave one could expect based on a prescribed drilling procedure. Though there are many other factors that may contribute to the development of surface heave, the focus of this research was to develop an experimental methodology and data collection procedure, from which these additional factors may be studied.

Early in the preliminary design of the field experimentation, it became obvious that it would not be feasible to study the effect that each factor had on the development of surface heave associated with the product installation. To gather data suitable to be easily incorporated into a model, a full factorial experimental design was utilized. To adequately study the factor space associated with all eight factors identified in the research, a total of 256 installations would be required based on a full factorial experimental design. Subsequently, through the use of the Analytical Hierarchy Process, factors were ranked and four of the original eight were selected to create a resourceful field experiment achieving 16 data points with only four installations while still maintaining the concept of a full factorial experiment.

Based on the framework presented in this paper, future research could be conducted to expand the explored factor space by the inclusion of the original four factors not selected. Factors such as soil composition and density, as well as reamer diameter and annular space, would enhance the applicability of the model and provide greater insight into factor interaction. Additional factors such as the effect of the water table and drilling fluid composition could also be added to this framework. The next stage of this research is focused on the further development of the model to study the influence of these various factors on the development of surface heave. Through this model, guidelines may be developed based on construction methodology, or drilling practice, to minimize ground movements. Once a competent model is developed it may be adapted to other soil types through the integration of additional field observations and measurements. It is expected that this research will aid in the minimization of damage resulting from surface heave on directionally drilled crossings, and improve drilling practices through proper selection of drilling techniques for particular project conditions.

3.9 REFERENCES

Allouche, E.N., Ariaratnam, S.T., and Lueke, J.S. (2000). "Horizontal directional drilling: a profile of an emerging underground construction industry." Journal of Construction Engineering and Management, ASCE, 126 (1): 68-76.

Bariod Industrial Drilling Products (2000). "Workshop manual: basic drilling fluids." Bariod Industrial Drilling Products, Houston, TX.

Bennett, R.D., Ariaratnam, S.T., and Como, C.E. (2001). "Horizontal directional drilling good practices guidelines." HDD Consortium, Washington, DC.

Box, G.E.P., Hunter, W.G., and Hunter, J.S. (1978). "Statistics for experimenters: and introduction to design, data analysis, and model building." John Wiley & Sons, New York, NY.

Finney, D.J. (1955). "Experimental design and its statistical basis." University of Chicago Press, Chicago, IL.

Haykin, S. (1999). "Neural networks: a comprehensive foundation." Prentice Hall, Upper Saddle River, NJ.

Lueke, J.S. and Ariaratnam, S.T. (2002). "Factors affecting surface heave in horizontal directional drilling operations." Proceedings of No-Dig 2002, Montreal, PQ, April 28-30.

Mehrotra, K., Mohan C.K., and Ranka S. (1997). "Elements of artificial neural networks." Massachusetts Institute of Technology Press, Cambridge, MA.

Saaty, T.L. (1980). "The analytic hierarchy process: planning, priority setting, resource allocation." McGraw-Hill International Book Co., New York, NY.

Saaty, T.L. and Alexander, J.M. (1989). “Conflict resolution: the analytic hierarchy approach.” Praeger, New York, NY.

Taha, H.A. (1997). “Operations research: an introduction - 6th Edition.” Prentice Hall, Upper Saddle River, NJ.

Triantaphyllou, E. and Mann, S.H. (1995). “Using the analytic hierarchy process for decision making in engineering applications: some challenges.” International Journal of Industrial Engineering: Applications and Practice, 2 (1): 35-44.

Chapter 4 FIELD TESTING AND RESULTS

4.1 INTRODUCTION

In recent years, Horizontal Directional Drilling (HDD) has become the preferred construction method for the installation of new underground infrastructure. Being a trenchless method of installation, HDD is particularly suited for locations that are inaccessible by conventional open cut techniques. This may include situations where the proposed installation lies in an environmentally sensitive location; or for the crossing of roads, highways, railway lines, and water courses. The low environmental and social impact of this technology has made directional drilling extremely viable and desirable by municipalities where there is a high investment in surface infrastructure, congestion of existing buried utilities, and where the costs of restricting business or commuter traffic would make open cut alternatives inconvenient. With the utilization of directional drilling, a municipality can reduce the costs associated with restoration, shoring existing utilities, traffic control and detours, as well as the cost of disruption to local business and residential traffic. As a result of this demand for conscientious construction practices, the horizontal directional drilling industry has grown substantially over the past 20 years (Allouche et al. 2000). With this growth, there have been an increased number of contractors utilizing this methodology, and an increased number of incidents where surface heave from an installation has damaged existing surface and subsurface structures. According to a survey conducted by Allouche et al. (2000), 89% of the contractors surveyed were involved in utility installation and 74% in municipal applications. With almost three quarters of all directional drilling contractors involved in municipal applications, there is an increased possibility of contractors drilling within the vicinity of engineered surface or subsurface structures.

A version of this paper entitled "SURFACE HEAVE MECHANISMS IN HORIZONTAL DIRECTIONAL DRILLING" is published by Jason S. Lueke and Samuel T. Ariaratnam in the Journal of Construction Engineering and Management (ASCE) Vol. 131, No. 4, pp. 540-547, May 2005.

Ground disturbance resulting from these installations may occur during the initial pilot bore, prereaming, or the final backream where the product pipe is installed. It is during the reaming and product installation phase where most ground movements occur, due to the action of the reamer either removing soil cuttings or displacing the soil during pullback. Ground movements are becoming a greater concern for municipalities and contractors as horizontal drilling utilization increases and underground right of ways become increasingly crowded. For example, as a result of the increased number of incidents involving contractors that have heaved roadways, in January of 2000, the City of Santa Clara, California, placed a moratorium preventing the use of horizontal directional drilling. It is anticipated that through this research, an understanding of how construction techniques affect the development of ground displacements may be developed, and practitioners of this technology can better plan and implement solutions to minimize the magnitude of ground movements associated with a particular installation.

4.2 HORIZONTAL DIRECTIONAL DRILLING

Horizontal Directional Drilling (HDD) technology evolved from the merging of oil field and water well drilling technologies. The main advantage of this technology over conventional pipe installation techniques is that HDD is a trenchless method, meaning that it requires a minimal amount of excavation to complete an installation. This technique allows for flexibility in the installation of the pipe, as the borepath may be curved or straight, with the path changing direction and depth during installation to avoid surface and subsurface obstacles. First employed in 1971 for a river crossing near Watsonville, California, the horizontal directional drilling industry has grown to encompass 17 manufacturers and several thousand rigs operated by several hundred contractors (Allouche et al. 2000). Directional drilling has been utilized in several industries, first in the oil and gas industries in the early 1980s, then expanded to include utility installation, environmental remediation, and the installation of gravity sewers and forcemains (Allouche et al. 2000).

The installation of pipe and conduit utilizing directional drilling is typically completed in a two-phase operation including the drilling of a pilot hole and its subsequent reaming to install the product pipe (Bennett et al. 2001). Installation of conduit and pipe is conducted from the surface, and commences with the boring of a pilot bore along the path of installation. The pilot bore is launched from the surface at an angle between 8 and 16 degrees, and then gradually becomes horizontal when the required depth is reached. The bore can be steered and tracked from the surface using a walk over or wire line locator system to direct the bore to the exit location (Ariaratnam and Allouche 2000). Once the drill string reaches the surface at the exit location, a reamer is attached to the drill string and pulled back to the entry point. This process enlarges the borehole for the installation of the product line. To achieve the appropriate bore size it may be necessary to perform several reaming operations. Generally, all reams prior to the actual product installation are referred to as pre-reams, and the final ream to which the product pipe is attached is refereed to as the backream. The product line is installed once the borehole is enlarged to a diameter that is generally 1.5 times the outside diameter of the product pipe or conduit (Lueke et al. 2001; Bennett et al. 2001). More detailed descriptions of the HDD process may be found in Ariaratnam and Allouche (2000); Bennett et al. (2001); Allouche et al. (2000); and Knight et al. (2001).

4.3 SURFACE HEAVE FACTORS

The main objective of this research was to study and gain a better understanding of the effects that various construction-related factors have on the development of surface heave during a horizontal directionally drilled installation. The first step towards this goal was to identify the factors that may influence ground movements, and then devise a field based experimental program to measure the effects of these factors. The identified factors include: 1) annular space; 2) backream rate; 3) borehole pressure; 4) depth of cover; 5) reamer type; 6) reamer diameter; 7) soil composition; and 8) soil density.

Identifying and understanding the influence of potential surface heave contributing factors is important to industry practitioners in reducing risks associated with directional drilling installations. The methodology presented in this paper, using field based experimental design, enables both practitioners and researchers to gain a better understanding of the mechanisms that may cause surface heave during this trenchless construction method. This information is particularly important when drilling under paved roads and highways where public safety could be compromised.

4.3.1 Annular Space

The Annular Space is the area that is created between the drill stem or product pipe and the wall of the borehole. This space provides a route for drilling fluid mixed with native soil cuttings (i.e. slurry) to circulate back to the entry or exit locations. Good practices recommend that the diameter of the borehole be 1.5 times that of the product pipe (Bennett et al. 2001). If circulation is lost, soil cuttings may remain in the bore and cause over-pressurizing of the borehole, thereby contributing to the displacement of soil and surface heave, and possibly causing inadvertent returns (Lueke and Ariaratnam 2002).

4.3.2 Backream Rate

During the installation phase, the speed at which the reamer is pulled towards the drill rig through the borehole is commonly referred to as the Backream Rate. The maximum backream rate is a function of the borehole diameter, drilling mud pump capacity and efficiency, drilling fluid viscosity, and a flow factor. The flow factor is a multiplier applied to the volume of the borehole to estimate the amount of drilling fluid required to effectively transport cuttings from the bore to the surface (Bennett et al. 2001). Typically, the backream rate is measured in terms of the length of time required to pull one section of drill pipe or stem.

4.3.3 Borehole Pressure

Borehole Pressure refers to the fluidic pressure developed in the borehole as a result of the drilling process. At the time of this research, there are no readily available methods to measure the actual pressures in the borehole. Subsequently, it was decided that the drilling fluid flow rate be measured instead of borehole pressure. Flow rate provides a measure of the volume of drilling fluid pumped into the borehole during the installation, and could be measured by installing an inline flow meter after the mud pump on the drilling rig.

4.3.4 Depth of Cover

Depth of Cover refers to the distance between the surface and the outside diameter of the product pipe. The amount of soil between the pipe and the surface has a direct influence on the expected amount of surface heave. The greater the cover, the less risk of surface heave occurring due to increasing over burden pressure and arching occurring in the soil matrix.

4.3.5 Reamer Type

There are various types of reamers utilized in directional drilling. The selection of a suitable reamer is generally based on the composition and nature of the soil formation where the installation is occurring. Reamers are typically classified into three main categories: 1) compaction; 2) mixing; and 3) all-purpose. In this research, a spiral (compaction) and a fluted (all-purpose) reamer were utilized. The behavior of the reamer within a specific soil medium determines the potential of ground displacements in the vicinity of the borehole (Lueke and Ariaratnam 2002).

4.3.6 Reamer Diameter

Reamer Diameter refers to the largest diameter bore that the reamer cuts into the soil medium during reaming. The ratio between the diameter of the bore and depth of cover may have an influence on the magnitude of surface heave exhibited on a given installation.

4.3.7 Soil Composition

Soil Composition refers to the classification of the soil by its material characteristics. This classification is made utilizing particle size distribution and plasticity. The composition of the soil determines its behavior during an induced strain event.

4.3.8 Soil Density

Soil density is simply defined as the ratio of mass to unit volume of the soil. The density of the soil may relate to the ease of compaction or dislodging of the soil during the reaming phase of the installation.

4.4 EXPERIMENTAL DESIGN

Surface heave exhibited during a horizontal directionally drilled installation is the output response of a system affected by the aforementioned factors. Typically, in the investigation of the effects of one or more variables on the response of a system, a factorial design is utilized (Finney 1955). In a general factorial design, a fixed number of levels are selected for each of the factors that are under investigation (Box et al. 1978). An experiment is then conducted with all possible combinations of factors at their various levels. This factorial design considers the interaction effects between the factors with relatively few observations, and the data collected is suitable for the development of models to explain the observed behavior of the response in question. The following sections briefly describe the design of the field experiment, further discussion can be found in Lueke and Ariaratnam (2003).

4.4.1 Analytical Hierarchy Process

To conduct a field examination utilizing all eight factors would require 256 observations, assuming 2 levels per factor. This number of observations would exceed the available resources for this research. The Analytical Hierarchy Process (AHP) was utilized to select factors for inclusion in the experiment. AHP is a multi-criteria decision-making approach that was developed by Saaty in the 1970s as a method to aid decision makers in the solving of complex problems (Triantaphyllou and Mann 1995, Saaty 1980). The process is commonly conducted utilizing the direct questioning of people who may or may not be experts in the problem, but who at least are familiar with the problem. This process would rank the factors in their perceived order of importance towards the development of surface heave.

Ten industry experts were solicited from the areas of contracting, consulting, manufacturing, and academia, with each respondent answering a questionnaire based on the pair wise comparison of each identified drilling factor. The respondents were asked to assess the relative importance each factor to another for every possible combination of factors using a predetermined scale. Table 4.1 presents the average results from all respondents. Borehole pressure was found to be the factor perceived to contribute the most to surface heave, while the factor thought to contribute the least was reamer diameter. Details of this analysis can be found in Lueke and Ariaratnam (2003).

Table 4.1 Relative Factor Weight

Factor	Weight
Borehole Pressure	0.182
Depth of Cover	0.165
Backream Rate	0.148
Soil Density	0.139
Soil Composition	0.106
Annular Space	0.099
Reamer Type	0.088
Reamer Diameter	0.071

4.4.2 Selecting Factor Levels

To assist in limiting the number of factors investigated, the study was limited to one site, that being the University of Alberta Research Farms. Soil density and soil composition factors were eliminated from the examination as these factors were relatively constant across the site. The elimination of soil considerations allowed the investigation to focus primarily on construction factors. Based on the results of the Analytical Hierarchy Process; borehole pressure, depth of cover, and backream rate were included in the experimental design due to their high ranking. Of the three remaining factors; annular space, reamer type, and reamer diameter; reamer type was selected to be included in the study. The reamer type was selected to obtain data relating to the rig operational pressures and ground movements to contribute to future research. Using the two level factorial design, with each of the four factors examined at two levels, 16 observations were required to achieve all possible combinations (2 x 2 x 2 x 2 = 16).

Factor levels were determined from previous field experimentation as well as the limitations of the drilling equipment utilized (Ariaratnam et al. 2000). It was decided to use a 200 mm diameter pipe, as this represented a typical size of product pipe used in practice (Allouche et al. 2000). The depth of installation was set at 900 mm and 1200 mm below the surface to simulate shallow utility installation. For reamers, a spiral compactor reamer and a fluted reamer were selected. These were best suited for the soil conditions found at the field site and typical of the type of tooling that an HDD contractor would use under the field conditions found at the University of Alberta Farm site. With borehole pressure being difficult to measure, mud flow was used as a substitute and set at 50 liters/minute and 100 liters/minute, adjusted for altitude. And lastly, backream rate was set at the maximum (2 minutes/rod or 1.524 m/min) and minimum (6 minutes/rod or 0.508 m/min) pullback rates that the drilling rig could maintain.

4.4.3 Field Investigation

To further minimize the number of installations required in the experimental procedure, an innovative method of borepath design was considered. If a factor could be included in the actual bore profile, the number of installations would be reduced by half. One factor that was included in the bore profile was the depth of cover, as it could be varied along the borepath. To further reduce the number of installations, each bore was designed in a mirror image such that during the backream the first half could be performed with a low mud flow rate and the second half with the higher flow rate. By the inclusion of these factors in the design of the borepath, the number of installations was reduced from sixteen to four, effectively reducing the number of installations to a manageable level, while still maintaining experimental integrity. The final borepath design is shown in Figure 4.1. The borepath is approximately 86.5 meters in length, with four measurement locations along its length. Each measuring location was composed of five surface points that provided vertical heave measurements above the center line of the installation as well as two points to the left and right separated by 200 mm perpendicular to the borepath. A total of four installations were conducted utilizing this borepath; parallel to each other with a 5 m separation between each installation to minimize displacement contamination. Each borepath was drilled utilizing similar techniques according to HDD best practices (Bennett et al. 2001), with specifically assigned levels to each section of the path to obtain every possible combination of factor levels. Installations were conducted utilizing the Vermeer D24x40A Navigator horizontal directional drill, by a contractor that was experienced working with the soil conditions found at the test site. Installations were completed over two days in summer of 2001, at the University of Alberta Research Farm. Soil composition of the upper 4 m at this site consists of a uniform lacustrine Lake Edmonton Clay with a unit weight of approximately 18 kN/m^3 (Zhang 1999).

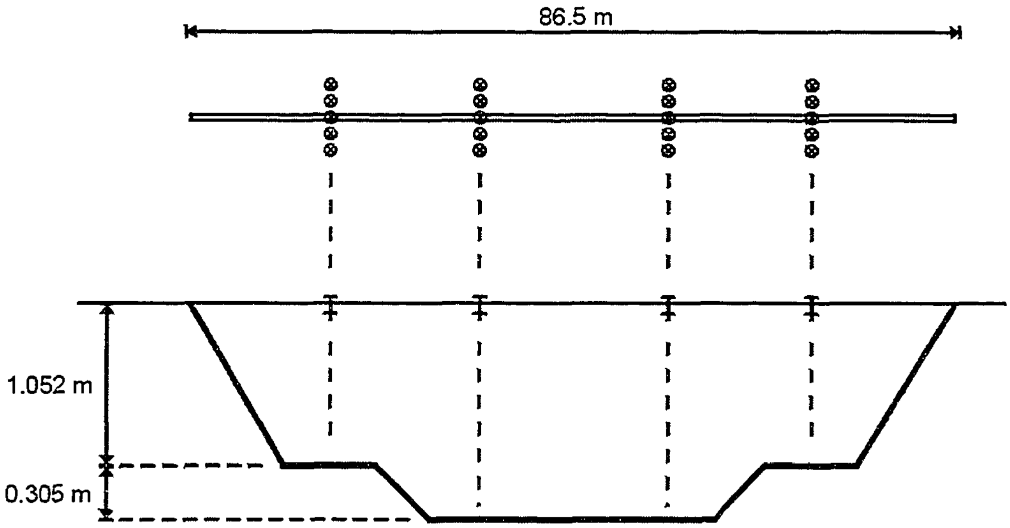

Figure 4.1 Borepath Design

4.5 GROUND MOVEMENT RESULTS

Ground movements were recorded after the drilling and backreaming phase of each installation. The layout devised in the experimental design allowed for the comparison of ground movements resulting from all combinations of factors studied. Each installation was conducted using generally accepted drilling practices to ensure that the data collected reflected not only good drilling practices, but captured the techniques utilized by the greatest number of contractors.

Surface displacements were monitored though the use of surface points (Lueke and Ariaratnam 2003). Surface points functioned as survey hubs. The surface points were measured prior to drilling, after the drilling, and after the reaming phase of the installation. Previous research work at the test location utilized linear potentiometers to measure the displacements, however, after analysis it was determined that conventional leveling techniques could be utilized to obtain similar quality data at a reduced cost and turn around time (Ariaratnam et al. 2000). From the installations, it was discovered that, in all cases, surface heave was exhibited after both the drilling and reaming phases. Ground movements during the drilling phase of the installation ranged between 0 and 1 mm, while for the reaming phase, vertical ground displacement were measured between 2 and 6 mm. Table 4.2 summarizes surface heave after drilling and reaming for installations at 900 mm, Table 4.3 for installations at 1,200 mm. Appendix C includes the raw survey data obtained during the investigation. The following sections discuss results by factor examined during the field installations.

Table 4.2 Surface Heave at 900 mm Installation Depth

	Installation-Point	1-1	1-4	2-1	2-4	3-1	3-4	4-1	4-4
	Reamer	Fluted	Fluted	Fluted	Fluted	Spiral	Spiral	Spiral	Spiral
	BRR (min/rod)	6	6	2	2	2	2	6	6
	Flow (l/s)	50	100	50	100	50	100	50	100
	Surface Point								
Drilling (mm)	-400	0.5	0.4	0.5	0.1	0.1	0.1	0.0	0.0
	-200	0.7	0.5	0.3	0.1	0.2	0.2	0.0	0.1
	0	0.7	0.3	0.2	0.3	0.2	0.5	0.2	0.2
	200	0.4	0.6	0.2	0.2	0.2	0.1	0.2	0.0
	400	0.2	0.3	0.1	0.1	0.1	0.1	0.2	0.0
	Surface Point								
Reaming (mm)	-400	4.6	3.8	2.0	3.9	4.7	4.2	5.2	5.6
	-200	5.3	4.5	4.0	4.0	5.5	5.2	6.0	6.0
	0	6.0	5.7	4.1	3.6	5.5	4.9	5.8	5.8
	200	5.7	5.0	4.0	3.0	4.7	3.9	5.3	5.2
	400	5.0	3.6	3.4	2.0	3.7	2.9	4.2	2.9

Table 4.3 Surface Heave at 1,200 mm Installation Depth

	Installation-Point	1-2	1-3	2-2	2-3	3-2	3-3	4-2	4-3
	Reamer	Fluted	Fluted	Fluted	Fluted	Spiral	Spiral	Spiral	Spiral
	BRR (min/rod)	6	6	2	2	2	2	6	6
	Flow (l/s)	50	100	50	100	50	100	50	100
	Surface Point								
Drilling (mm)	-400	0.2	0.1	0.1	0.0	0.1	0.1	0.1	0.1
	-200	0.2	0.2	0.2	0.0	0.2	0.2	0.0	0.1
	0	0.1	0.1	0.2	0.1	0.3	0.2	0.1	0.1
	200	0.4	0.1	0.2	0.2	0.3	0.0	0.0	0.1
	400	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.0
	Surface Point								
Reaming (mm)	-400	2.5	2.0	3.8	2.6	5.2	3.8	4.9	3.6
	-200	2.8	2.7	3.8	3.0	5.3	4.0	5.8	4.1
	0	3.2	2.7	3.8	3.1	5.2	4.1	6.1	4.4
	200	3.0	2.2	3.4	2.5	4.4	3.8	5.9	3.8
	400	2.9	2.6	2.5	2.0	3.1	2.9	5.0	3.2

4.5.1 Backream Rate

As previously discussed, backream rate (BRR) refers to the speed at which the reamer is pulled through the borehole to the drill rig, measured in time required to pull one length of drill stem or rod. For this investigation the backream rate was set, by default of the machine's operating envelope, to have a slow pullback rate of 6 minutes per rod (0.508 m/min), and a fast pullback rate of 2 minutes per rod (1.524 m/min). Figures 2.2 through 4.5 illustrate the displacements recorded for different backream rates and mud flow, compared by depth and reamer type. Each figure indicates the vertical surface displacement exhibited for both slow and fast backream rates and high and low mud flow rates. Displacements were measured above the centerline of the borehole and at four locations perpendicular to the installation. Two monitoring points were located on each side of the borepath separated by 200 mm, or one product pipe diameter.

Results from the field installations conducted at the 900 mm depth, illustrated in Figures 4.2 and 4.3, indicate that the slower backream rate of 6 minutes per rod (0.508 m/min) induced greater surface heave than those conducted with the fast backream rate of 2 minutes per rod (1.524 m/min). For installations with the fluted reamer, the difference in maximum surface heave magnitude between the slow and fast backream rates was almost 2 mm. Alternatively, for installations performed with the spiral reamer, the difference between the slow and fast backream rates was only 0.3 mm to 1.0 mm depending on mud flow rate.

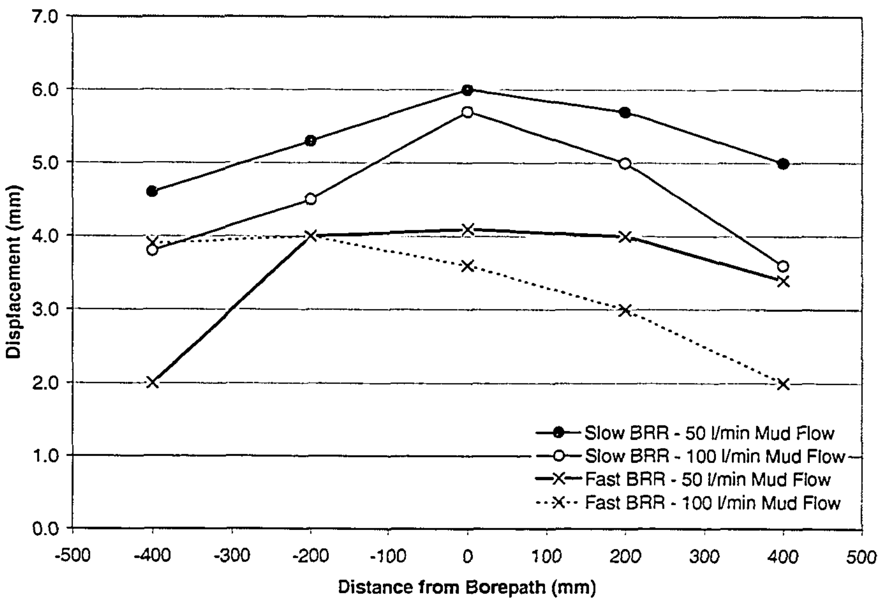

Figure 4.2 Displacements from 900 mm Depth with Fluted Reamer

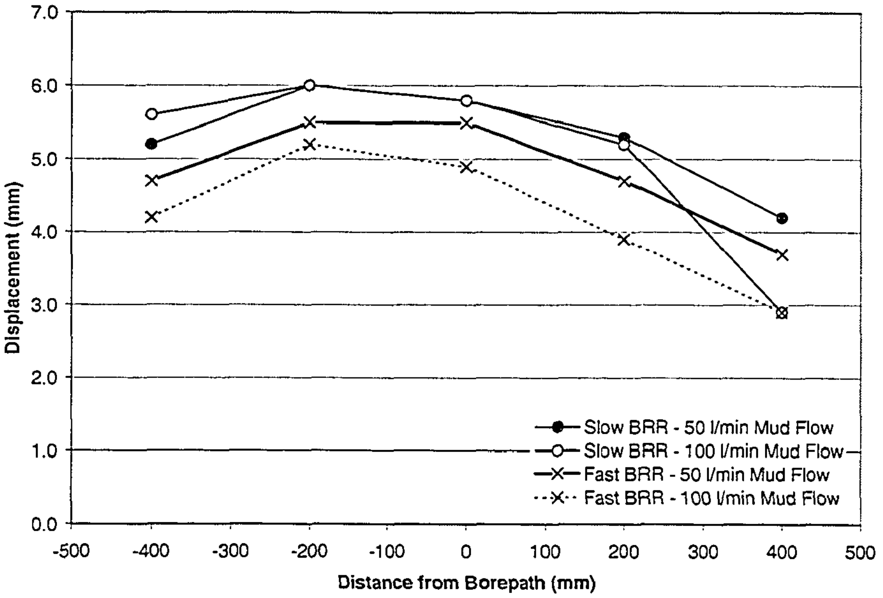

Figure 4.3 Displacements from 900 mm Depth with Spiral Reamer

Installations conducted at the 1,200 mm depth are shown in Figures 4.4 and 4.5. For the installations conducted with the fluted reamer, the faster backream rate produced greater surface heave than the slower backream rate regardless of mud flow. The differences between surface heave magnitudes were between 0.5 mm and 0.7 mm when comparing backream rate and the associated mud flow. The spiral reamer at 1,200 mm depth behaved as the other installations conducted at the 900 mm depth, with the slower backream rate producing greater surface heave than the faster rate. Additionally, there was a consistent pattern of lower flow rates associated with greater surface heave, from data series with the same backream rate and depth of installation.

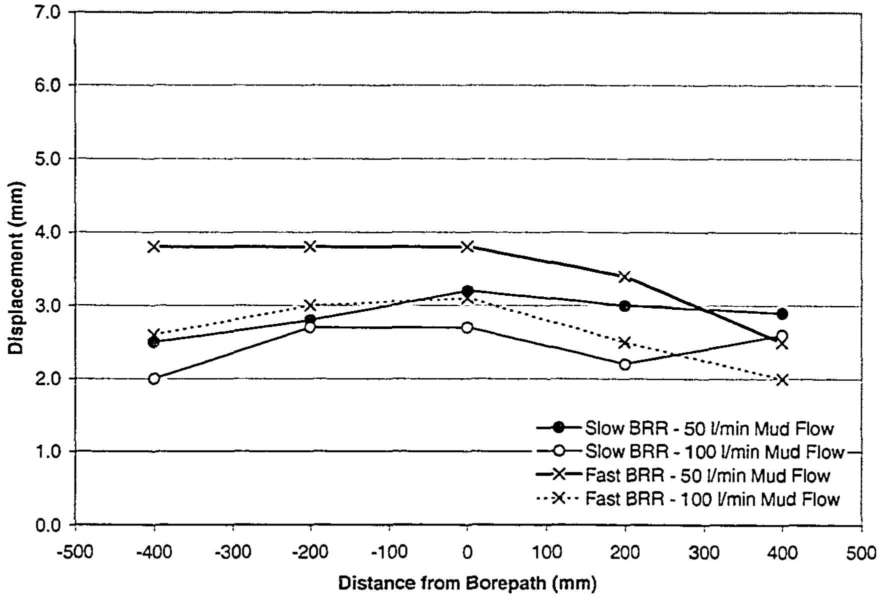

Figure 4.4 Displacements from 1,200 mm Depth with Fluted Reamer

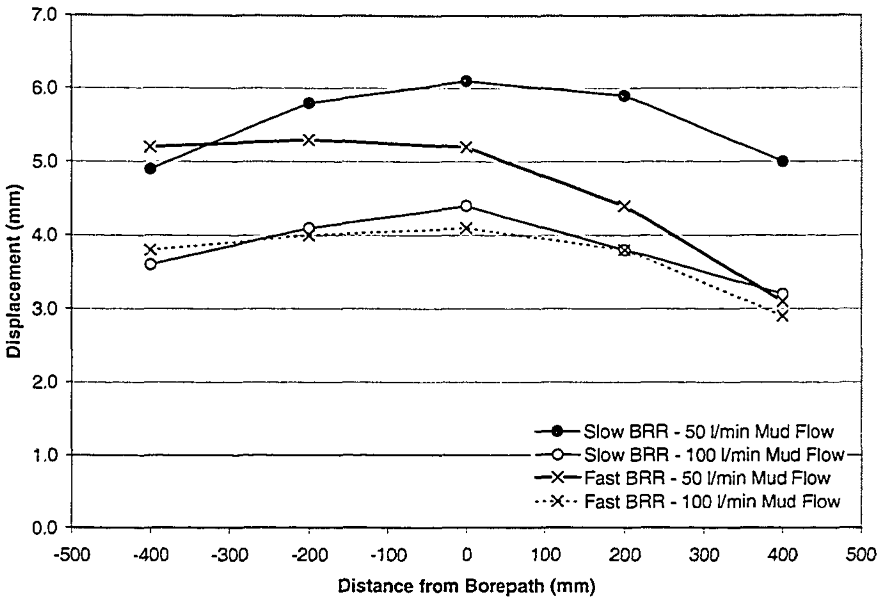

Figure 4.5 Displacements from 1,200 mm Depth with Spiral Reamer

The observed results are opposite to what may be expected. Intuitively, slower backream rates may be associated with less ground disturbance as there would be an increased volume of drilling fluid to sweep cuttings out of the bore, thereby reducing the volume of soil that may be displaced into the surrounding soil stratum. However, the only observation that demonstrated this premise was that of the fluted reamer at the 1,200 mm depth, otherwise the ground displacements were less with the faster backream rate. This would suggest that the mechanism at work might be related to the volume of drilling fluid in the bore, or the borehole pressure.

Best practice indicates that the backream is related to the soil medium, diameter of the installation, and the rate at which mud can be pumped into the borehole. Based on the equations presented in Chapter 3 from Bennett et al. 2001, for a backream rate of 6 min/rod (0.508 m/min) the appropriate mud flow rate is 131 l/min, and 393 l/min for the faster 2 min/rod (1.524 m/min) backream rate. These calculations assume a 300 mm diameter borehole, 3 m long drill rods, a flow factor of 3 for clay soil, and a pump efficiency of 0.81. The pump efficiency is assumed using a typical drilling mud viscosity. Based on the drill rig's maximum mud flow rate of 100 l/min, this would indicate that the installation was outrunning the pump, otherwise not providing enough drilling fluid to adequately clean the spoil from the borehole. At the faster backream rate, only a quarter of the drilling fluid application rate theoretically required is available for that installation rate. This may indicate that for this size of product, the drill rig is unable to provide an adequate mud flow rate to adequately clean out the borehole.

4.5.2 Reamer Type

Fluted and spiral compactor reamers were used for the field installation as previously discussed. Each reamer was used for two boreholes, with similar installation procedures to provide a comparison of the behavior of each reamer. Unlike the backream rate and mud flow factors that could be varied during an installation, the reamer type had to be selected prior to the installation commencing, as this factor was borehole specific. Figures 4.6 through 4.9 illustrate the results from the four installations by depth and backream rate. The mud flow for a particular installation is identified with the particular reamer type.

Figures 4.6 and 4.7 illustrate resulting surface heave from installations conducted at the 900 mm depth of cover for slow and fast backream rates. Installations using the slower backream rate all had relatively high maximum displacements of approximately 5.5 to 6.0 mm. Maximum displacements for the fast backream rate ranged between 4.0 and 5.5 mm. There was little difference in level of surface heave produced for the slow backream rate between the different reamers. However, at the faster backream rate it was clearly observed that the spiral compactor type reamer created greater surface heave than the fluted reamer.

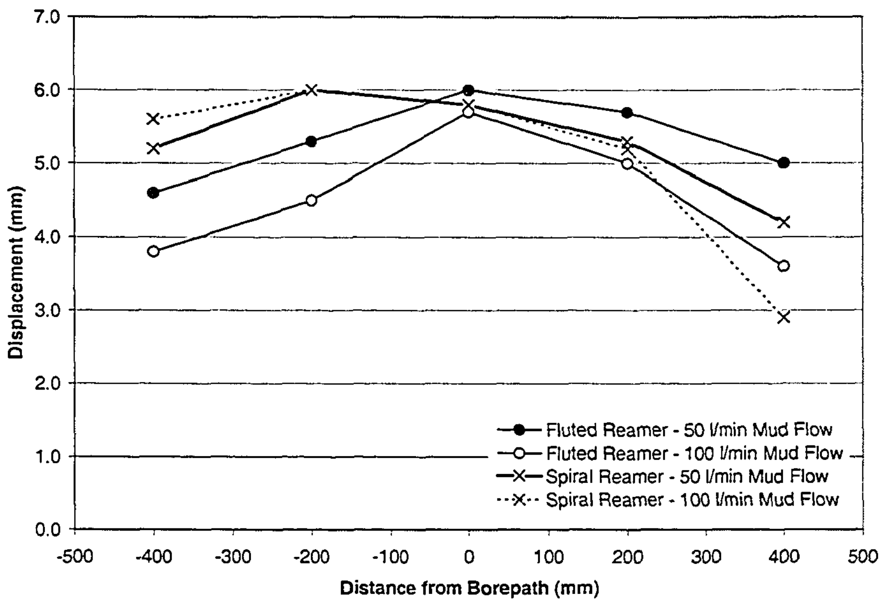

Figure 4.6 Displacements from 900 mm Depth with Slow Backream Rate

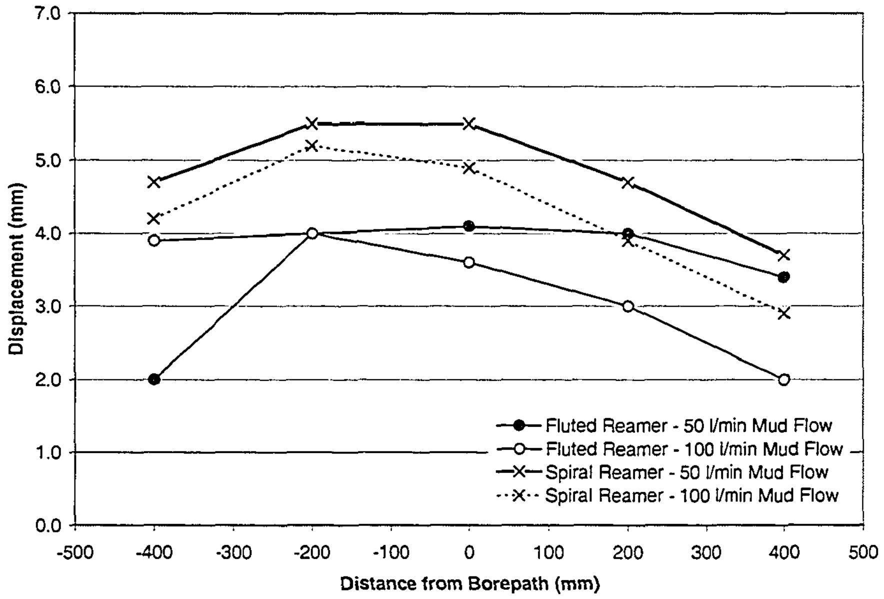

Figure 4.7 Displacements from 900 mm Depth with Fast Backream Rate

For installations observed at a depth of cover of 1,200 mm depicted in Figures 4.8 and 4.9, the greatest surface heave was observed from installations conducted at a slow backream rate. Surface displacements ranged between 2.6 and 6.2 mm for the slow backream rate, and 3.1 and 5.2 for installations conducted with the fast backream rate. Regardless of backream rate, the spiral compactor reamer produced greater surface heave than the fluted reamer.

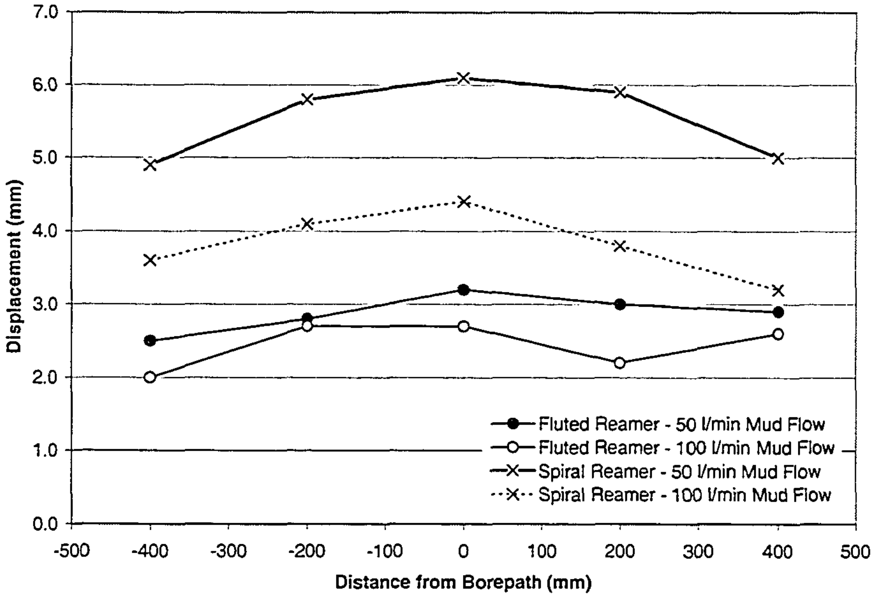

Figure 4.8 Displacements from 1,200 mm Depth with Slow Backream Rate

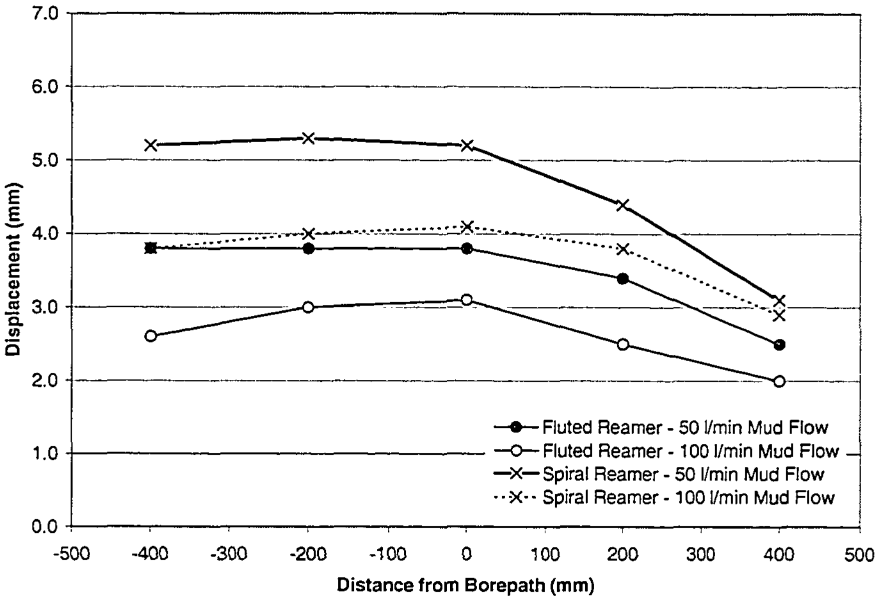

Figure 4.9 Displacements from 1,200 mm Depth with Fast Backream Rate

The results reveal two patterns that are consistent through most of the installations. Firstly, the spiral compactor reamer caused greater surface displacements than the fluted reamer for various depths and mud flow rates. And secondly, the low mud flow rate for any given combination of depth and backream rates produced greater surface heave than the higher mud flow rate installations for either reamer type. These patterns were consistent for the installations conducted at the 1,200 mm depth and for the 900 mm depth installation with the fast backream rate. The installations conducted at the 900 mm depth with the slower backream had relatively the same amount of surface heave for either reamer type and mud flow rate, with all four installations having a maximum displacement within half a millimeter of each other. For all other installations, the difference between the fluted and spiral compactor reamer displacements was much greater, up to approximately 3 mm.

The greater surface heave exhibited in the installations conducted with the spiral compactor reamer may be accounted for by the design of the reamer itself. As opposed to the fluted reamer, which has slots curved around the circumference of the tool to provide a passage way for cuttings and drilling fluid to flow from the front to the back of the reamer, the spiral compactor has an expanding screw like configuration. The configuration of the spiral reamer does not allow for the transfer of material from the cutting face to the trailing face of the reamer. As a result, that material is compacted into the surrounding soil from the rotation of the reamer as it passes through the ground. If this material is not removed or transported to the entrance or exit pit, its volume will compact into the soil, thereby creating greater surface heave than if it were removed. Again, the lower mud flow application rate created greater surface displacements than those installations conducted with the higher application rate. This pattern is also demonstrated in the different reamer types, as ground movements for installations conducted with either reamer type are greater with the lower mud flow rate, when compared to the same installation conducted with the same reamer with a higher mud application rate. These patterns may be related to borehole cleaning and soil cutting transportation effectiveness.

4.5.3 Depth of Cover

The depth of cover factor levels were set to 900 mm and 1,200 mm. Depth of cover refers to the distance between the surface and the borepath at which drilling and reaming were conducted. In general, HDD installations of this diameter are typically not conducted at this shallow of a depth; however, for the purpose of this investigation it was necessary to have some discernable surface heave. Subsequently, the slightly shallower cover depths were chosen to provide a comparison of the effect of the various factors on surface heave during a horizontal directionally drilled installation. Figures 4.10 through 4.13 compare the effects of installation depths and mud flow rate to the magnitude of surface displacement developed during the reaming phase of the installation.

Figures 4.10 and 4.11 illustrate the resulting surface heave from installations conducted with fluted reamers at slow and fast backream rates. For installations conducted with the fluted reamer and a slow backream rate, greatest surface heave occurred with the shallower 900 mm depth of cover. At the slow backream rate the maximum displacements ranged between 2.6 and 6.0 mm, and the maximum observed surface heave dropped by approximately 50% when depth of cover was increased from 900 mm to 1,200 mm. For the installations conducted with the fast backream rate maximum surface heave ranged between 3.1 and 4.1 mm. There was also a drop in surface heave produced when depth of cover was increased; however, it was not as pronounced as that observed at the slower backream rate.

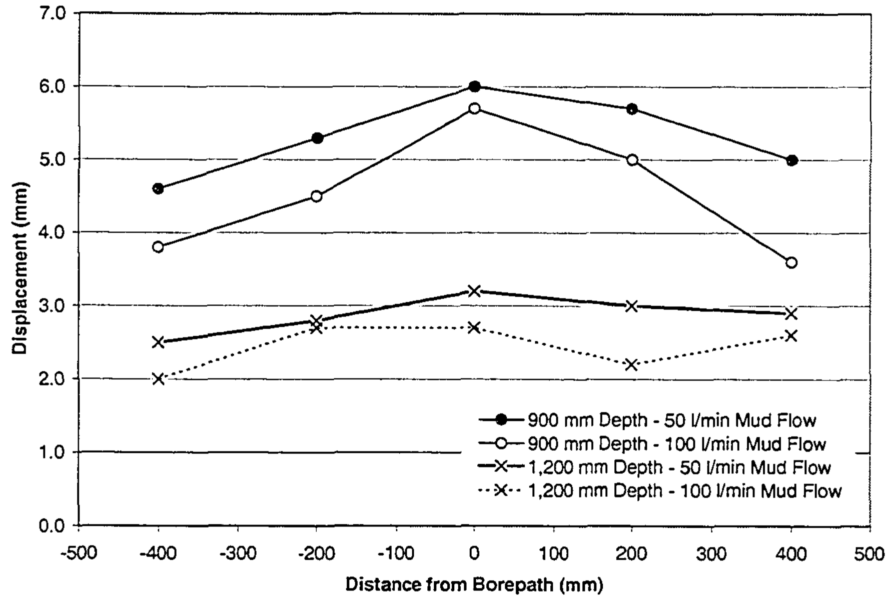

Figure 4.10 Displacements from the Fluted Reamer with Slow Backream Rate

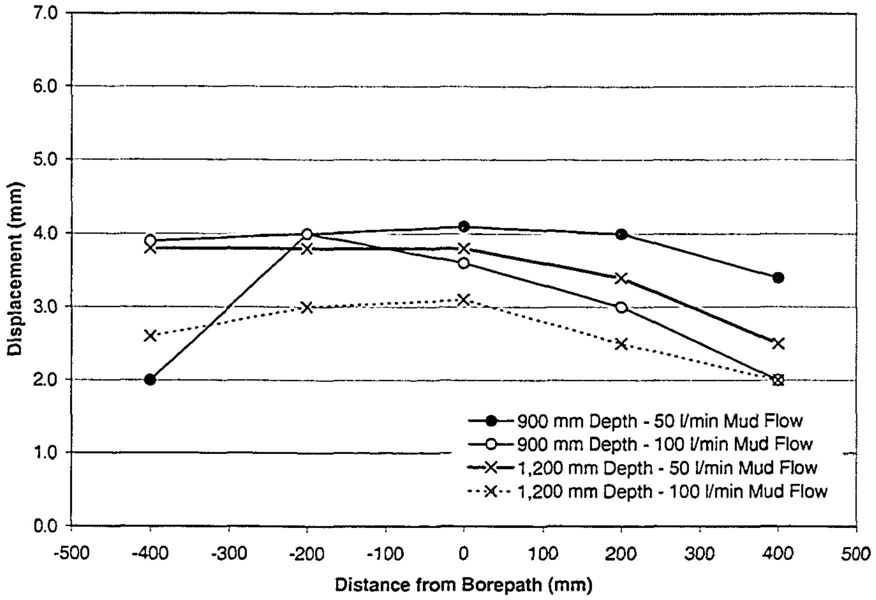

Figure 4.11 Displacements from the Fluted Reamer with Fast Backream Rate

For installations conducted with the spiral compactor type reamer (Figures 4.12 and 4.13) the effect of depth of cover was less discernable. The slow backream rate produced surface heave that ranged between 4.4 and 6.1 mm, and 4.1 to 5.5 for those done with the faster backream rate. It could be observed that surface heave decreased with increase in depth of cover. The installation conducted at 1,200 mm created similar surface heave to that conducted at a 900 mm depth for the same mud flow rate. This example did not follow the pattern of surface heave diminishing with depth.

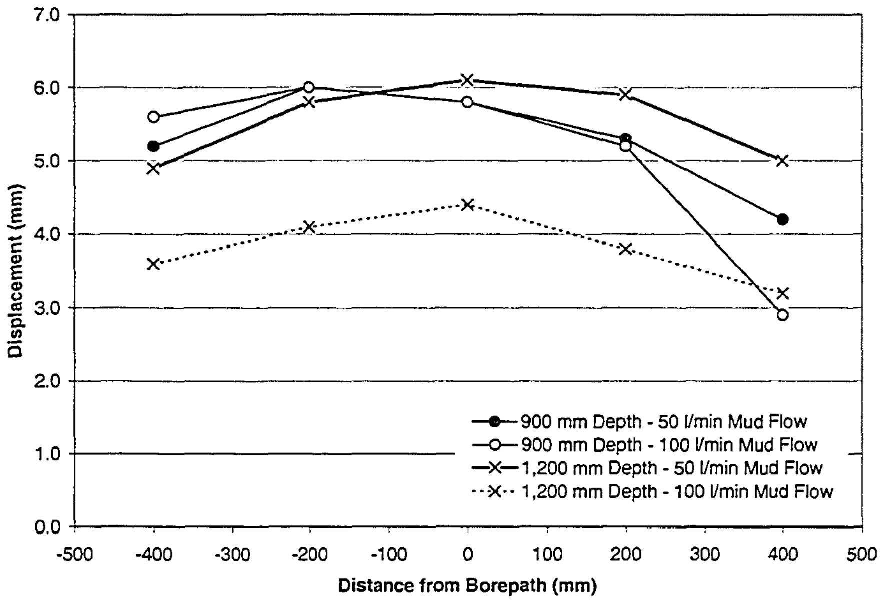

Figure 4.12 Displacements from the Spiral Reamer with Slow Backream Rate

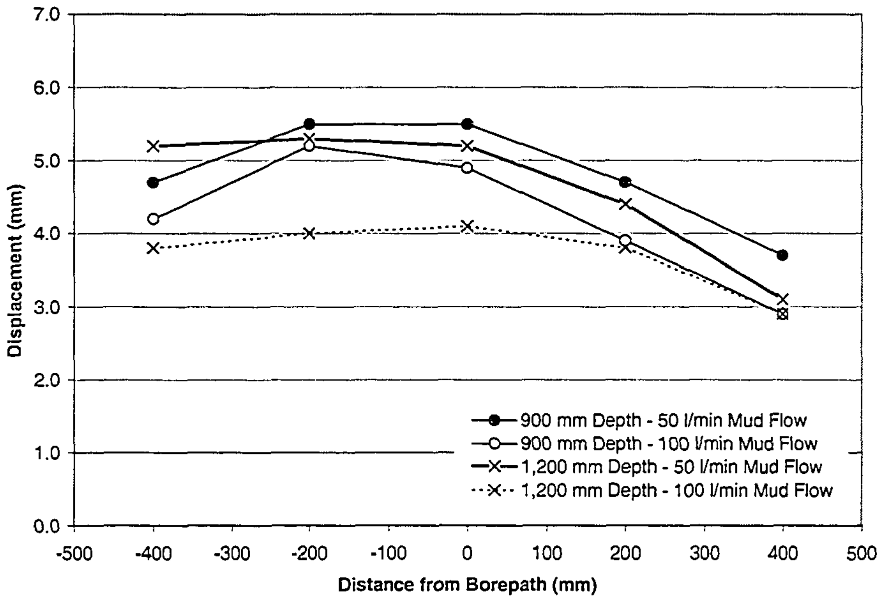

Figure 4.13 Displacements from the Spiral Reamer with Fast Backream Rate

In general, the data indicates that installations conducted at shallower depths induce greater surface heave than those conducted at deeper depths. For most installations, surface heave for the shallow installations were greater than the deeper installations when comparing installations with similar mud application rates. Additionally, for any given installation, lower mud flow rates produced greater surface heave when comparing results from the same installation depth, reamer, and backream rate. When considering the effect of the backream rate, a smaller spread was observed between the maximum and minimum surface heave values for installations conducted with the fast backream rate when comparing similar reamers. Additionally, there is less surface heave for installations conducted with a fast backream rate and similar reamers. This pattern is not as evident for the installations conducted with the spiral reamer and a slow backream rate, as there was not as great of a difference in the surface displacements between the two installation depths.

Intuition suggests that deeper installations would produce less surface heave than those conducted at shallower depths. This is due to the effect of soil arching on deeper installations, and the ratio of the change in borehole diameter (or soil displaced) to the depth of the installation being smaller. At deeper depths, there is a greater volume of soil to absorb the effects of displaced soil cuttings and dissipate the volume change. As the depth of cover increases, the magnitude of surface displacements decreases. This is particularly evident when comparing Figure 4.2 and 4.4. Though the data collected examining the depth of cover appears to be intuitive, the data collected is essential to not only proves this assumption but to provides the data sets required to fully examine the system for modeling purposes.

4.5.4 Mud Flow

The rate at which drilling fluid is injected into the bore during the pullback is referred to as the mud flow. Mud flows were varied between the two predetermined levels during the reaming phase of the installation. Low flow was measured to be 50 liters/min, while high flow was 100 liters/min. In Figures 4.2 through 4.13, each result is plotted with reference to mud flow. In general, the low flow rate level produced the greatest displacement in almost all situations and consistently had larger displacements than those installations performed with the higher flow rate. The only exception is illustrated in Figure 4.3 at the 900 mm depth with a spiral reamer pulled at a slower backream rate. In this situation, the maximum surface heave was the same for both mud flow levels. As there appears to be no correlation between installation parameters, this may be accounted for by normal natural experimental variation.

The observed behavior may be explained through the process of cuttings transport and borehole cleaning efficiency. During the reaming phase of the installation, the reamer cuts or displaces the soil along the borepath in an effort to provide sufficient space for the product pipe. The method in which the borehole is enlarged depends primarily on the type of reamer, though, in most situations, cuttings from the soil formation are produced and remain in the borehole unless removed. Cutting removal is accomplished by displacing the cuttings that are produced with an equal or greater volume of drilling fluid to provide the transport mechanism. The volume of drilling fluid required to flush the borehole and transport the cuttings is dependant on the nature and consistency of the soil formation.

For these installations, HDD best practices indicate that a volume three to five times that of the volume of bore produced is required for adequate borehole cleaning and cuttings transport (Bennett et al. 2001). With the 300 mm diameter bore (i.e. 1.5 times the product pipe diameter), and 3 m rods (3.048 m) the calculated volume of the borehole is approximately 212 liters of soil per section of rod. Using a clean out factor of 3, the total volume of drilling fluid required to provide adequate borehole cleaning is approximately 636 liters. With mud flow rates of 50 and 100 l/min set at the maximum and minimum mud flow that could be produced by the drill rig, backream rates in the order of 15.7 and 7.8 min/rod were theoretically required to adequately remove the volume of soil necessary to install the product pipe. This backream rate is much slower than that which could be achieved with the drill rig.

Based on the results of the research, the larger displacements associated with the lower flow rate may be explained by the displacement of materials left in the borehole as a result of inadequate cleaning and cuttings transport. This is supported by the smaller displacements recorded at the points where a higher mud flow rate was utilized, perhaps doubling the effectiveness of cuttings transport and borehole cleaning in some situations.

4.5.5 Centerline Heave Observations

Centerline heave observations are plotted for all installations by reamer and backream rate, organized by depth and mud flow rate in Figure 4.14. Each line represents a borepath used during the field investigation. This figure provides an overview of all observations and allows some general trends to be observed and reconfirmed from previous discussions:

1. There is an inverse relationship between surface heave and mud flow rate.
2. There is an inverse relationship between surface heave and depth of cover.
3. Generally, the spiral reamer created greater surface heave.
4. Reamers may behave differently depending on installation practices.
5. Depth of cover determines the order of magnitude of displacements when all other factors are equal, suggesting depth of installation to be a major factor in the development of surface heave on HDD installations.

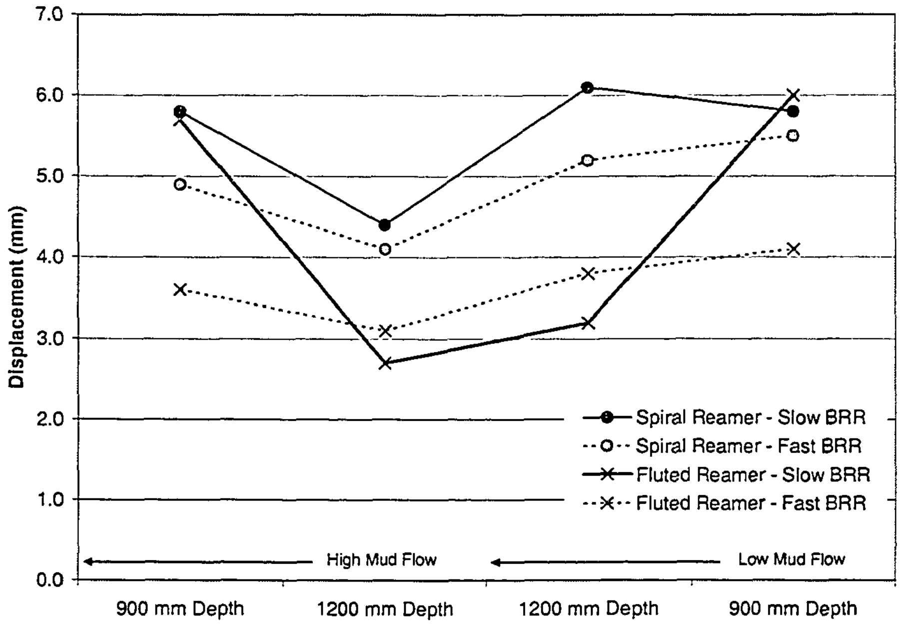

Figure 4.14 Summary of Centerline Displacements by Borepath

4.6 CONCLUSIONS

This paper presented an analysis of several factors that contribute to the development of surface heave during horizontal directional drilling installations. These include: 1) mud flow; 2) backream rate; 3) reamer type; and 4) depth of cover. A full factorial experiment was designed and implemented based on these contributing factors. From this study the following conclusions can be drawn:

1. Low drilling fluid application rates, or mud flow, produced greater surface displacement with almost all combinations of factor levels, and had larger displacements than those installations conducted with the higher flow rate. There is an inverse relationship between mud flow and surface heave.

2. Installations conducted at the 900 mm depth with the slower backream rate had greater surface displacements than those conducted at the faster backream rate. With increasing depth, the difference between the magnitudes of displacements exhibited between the slow and faster backream rate diminished. An exception to

this pattern was the 1,200 mm deep installation utilizing the fluted reamer, as it produced greater surface heave at the faster backream rate.

3. Regardless of depth and mud flow rate, the spiral compactor type reamer generally induced greater surface displacements than the fluted reamer.

4. In general, shallow installations produce greater surface heave than deeper installations. For installations conducted with a slow backream rate, the difference between the magnitude of the installations at 900 and 1,200 mm depths were smaller than those installed with the faster backream rate. There is an inverse relationship between surface heave and depth of cover.

5. Reamers may behave differently depending on drilling practices utilized.

The findings presented in the research indicate the major trends in surface heave development associated with various construction practices in horizontal directional drilling, in the particular soil found at the University of Alberta Research Farm. It also sets a framework from which future research may be conducted to examine surface heave development in other soil compositions, as well as the development of a model to examine the interaction effects of the various drilling techniques to minimize the magnitude of surface heave on directional crossings.

4.7 REFERENCES

Ariaratnam, S.T. and Allouche, E.N. (2000). "Suggested practices for installations using horizontal directional drilling." Practice Periodical on Structural Design and Construction, ASCE, 5(4), 142-149.

Ariaratnam, S.T., Lueke, J.S., Beljan, I.J., and Colwell D.A.F. (2000). "Insitu monitoring and evaluation of horizontal directional drilling installations." Proceedings of the 4th CSCE Construction Specialty Conference, Victoria, British Columbia, April 9-12.

Allouche, E.N., Ariaratnam, S.T., and Lueke, J.S. (2000). "Horizontal directional drilling: a profile of an emerging underground construction industry." Journal of Construction Engineering and Management, ASCE, 126(1), 68-76.

Bennett, R.D., Ariaratnam, S.T., and Como, C.E. (2001). "Horizontal directional drilling good practices guidelines." HDD Consortium, Washington, DC.

Box, G.E.P., Hunter, W.G., and Hunter, J.S. (1978). "Statistics for experimenters: an introduction to design, data analysis, and model building." John Wiley & Sons, New York.

Finney, D.J. (1955). "Experimental design and its statistical basis." University of Chicago Press, Chicago, IL.

Knight, M., Duyvestyn, G., and Gelinas, M. (2001). "Excavation of surface installed pipeline." Journal of Infrastructure Systems, ASCE, 7(3), 123-129.

Lueke, J.S. and Ariaratnam, S.T. (2003). "Experimental procedure for evaluating ground displacement factors in directional drilling." Canadian Journal of Civil Engineering, CSCE, Vol 30, 830-840.

Lueke, J.S. and Ariaratnam, S.T. (2002). "Factors affecting surface heave in horizontal directional drilling operations." Proceedings of No-Dig 2002 Conference, North American Society for Trenchless Technology, Montreal, PQ, April 28-30.

Lueke, J.S., Ariaratnam, S.T., Colwell, D.A.F. (2001). "Towards the development of horizontal directional drilling depth of cover guidelines." Proceedings of No-Dig 2001 Conference, North American Society for Trenchless Technology, Nashville, Tennessee, April 1-4.

Saaty, T.L. (1980). "The analytic hierarchy process: planning, priority setting, and resource allocation." McGraw-Hill International Book Co., New York.

Triantaphyllou, E. and Mann, S.H. (1995). "Using the analytic hierarchy process for decision making in engineering applications: some challenges." International Journal of Industrial Engineering: Applications and Practice, 2(1), 35-44.

Zhang, D.J.Y. (1999). "Predicting capacity of helical screw piles in Alberta soils." M.Sc. Thesis, University of Alberta, Department of Civil and Environmental Engineering, Edmonton, Alberta.

Chapter 5 MODELING AND TREND ANALYSIS

5.1 INTRODUCTION

Horizontal directional drilling is a trenchless technique that has been successfully utilized for the installation of a variety of pipes, conduits, and utilities for several years. It has gained popularity over conventional open cut installation methodologies, due to its non-disruptive operation and flexible installation design. However, this technique has also contributed to instances where structures and utilities directly above the path of installation have been damaged from surface heave. It is proposed that with correct drilling practices and procedures, the potential to cause damage from surface heave may be reduced. Currently, there is no established numerical method to determine the relationship between drilling practices and resulting surface heave for a horizontally drilled installation. Neural network (NN) modeling provides the methodology to determine if a relationship exists and to develop a model to predict surface heave. The model discovers the relationship between various drilling factors based on a learning technique, without the need to establish a hypothesis or make assumptions about the system's behavior during its construction. Additionally, through the utilization of neural networks a variety of factors may be examined which may be difficult to account for in conventional numeric and geometric analysis. Neural networks have seen application in the prediction of surface settlements due to tunneling, and have several advantages in this type of application compared to traditional geotechnical analysis (Kim et al. 2001).

A version of this paper entitled "NUMERICAL CHARACTERIZATION OF SURFACE HEAVE ASSOCIATED WITH HORIZONTAL DIRECTIONAL DRILLING" authored by Jason S. Lueke and Samuel T. Ariaratnam was accepted in the Tunnelling and Underground Space Technology Journal on April 4, 2004.

The goal of this research was to determine the feasibility of utilizing NN to predict surface heave, develop an implementation procedure, and evaluate the model based on trend examination. Several factors were identified as contributing to surface heave development in horizontal directional drilling, from which four factors: 1) depth of cover, 2) reamer efficiency, 3) mud flow rate, and 4) backream rate, were selected to develop a full factorial experiment. Data collected from this field implemented installation experiment, were utilized to develop a preliminary neural network model. Statistical methods associated with regression analysis were utilized to confirm the correlation between the four factors and surface heave, as well as to confirm that each variable was relevant to predicting heave. Additionally, an analysis was conducted to determine the relative importance of each factor in its contribution to heave development. The trained network model was utilized to conduct a sensitivity analysis to determine how varying drilling practices influence surface heave. With a better understanding of this behavior, construction techniques may be adapted in situations where there is a potential to inflict damage on nearby structures or utilities from surface heave.

5.2 BACKGROUND

Horizontal directional drilling (HDD) is a trenchless method of construction utilized in the installation of underground utilities, pipe, and conduit. Trenchless construction methods are those that minimize or eliminate the need for excavation during the installation or rehabilitation of new or existing utilities. This technique provides practitioners with increased installation options, as the drill path may be straight or curved, and the direction of the drill path may be changed at any time during the installation to negotiate surface and subsurface obstacles. Horizontal directional drilling has become the preferred method of installation for municipalities when crossing roads, rivers, nature preserves and parks, rivers, or locations of high utility congestion due to the design flexibility and minimal surface disruption. Typical product installations range in diameter from 50 to 1200 mm, and up to 2,000 m in length; with applications in gas distribution, fiber-optic lines, electrical conduit, sewer (gravity and force-main), and water distribution systems (Ariaratnam and Allouche 2000). Typical pipe materials used in HDD include high-density polyethylene (HDPE), polyvinyl chloride (PVC), steel, and ductile iron (Ariaratnam and Allouche 2000). Born from the merging of technologies from the water well and oil field industries, the first HDD installation was conducted in 1971 for a river crossing near Watsonville, California. After the first commercial HDD rigs became available in 1985 (Stangl 1990), the industry has experienced rapid growth with several thousand rigs being operated by several hundred contractors worldwide (Allouche et al. 2000).

Directional drilling installations are generally conducted in three distinct phases: 1) drilling of the pilot bore; 2) the project; and 3) the pullback (DCCA 1998). The pilot bore phase consists of using a small diameter drill head to drill a borehole from the entry location to the desired exit location. During the pilot bore phase (Figure 5.1), the drill proceeds downward from the entry location to the desired depth where the drill will continue along a horizontal path, or sloped in the case of a gravity sewer installation, before following a curvilinear path to the exit location. Once the pilot hole has been completed, the drill head is removed and a reamer is attached. During the reaming stage, the reamer is pulled through the borehole, typically sized 1.5 times the diameter of the product pipe being installed. For larger diameter pipes, several reaming passes, known as pre-reaming, may occur with increasing reamer sizes to achieve this 1.5 diameter upsizing. The pipe pullback operation (Figure 5.2) can either be performed in conjunction with the reaming phase; commonly known as a “continuous” installation, or after the reaming has been completed. During a “continuous” operation, the product pipe is attached to the back of the reamer with a swivel link to prevent the rotation of the product pipe during installation.

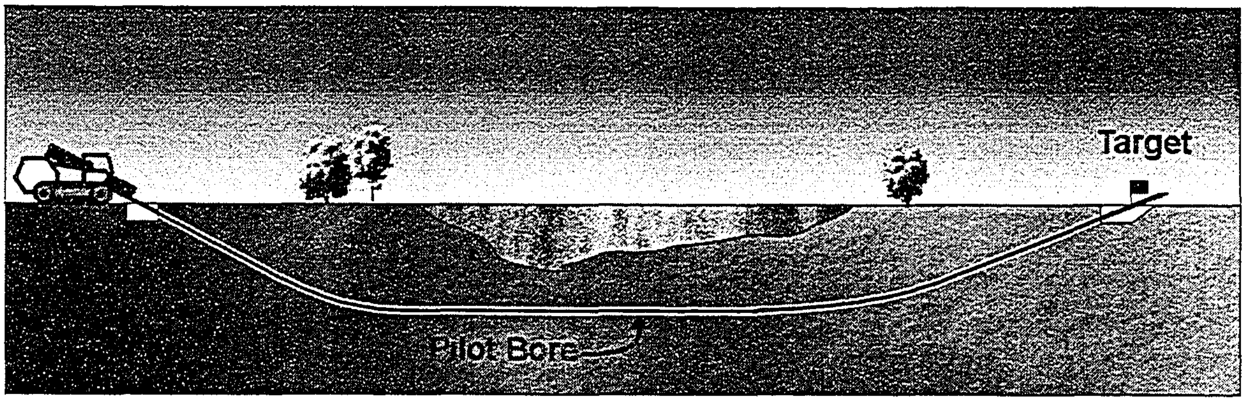

Figure 5.1 HDD Pilot Bore Phase

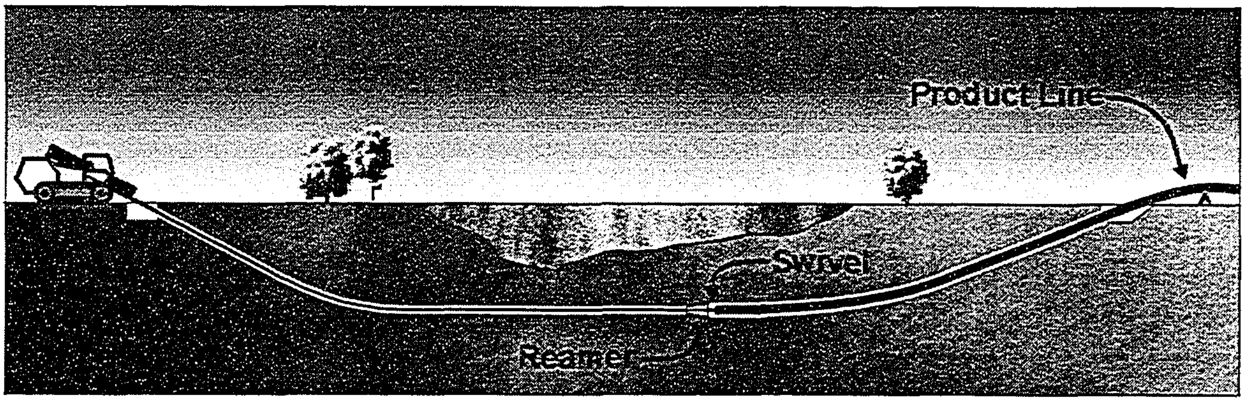

Figure 5.2 HDD Pipe Pullback Operation

5.3 MONITORING SURFACE HEAVE IN HORIZONTAL DRILLING

In order to collect data to develop the neural network model, a monitoring program was developed based on a full factorial design. A factorial design is typically utilized to examine the effects of one of more variables or factors on the response of a system (Finney 1955). To conduct a full factorial experiment, the factors investigated must first be selected with each factor assigned at least two values or levels that are specific to its domain. The response of the system is monitored during runs that are described by unique combinations of the factors and levels such that every combination is examined. Eight factors were identified as contributing to surface heave development: 1) annular space, 2) backream rate, 3) borehole pressure, 4) depth of cover, 5) reamer type, 6) reamer diameter, 7) soil composition, and 8) soil density. Additional information on drilling factors that contribute to surface heave and the experimental design can be found in Lueke and Ariaratnam (2002 a).

To examine the factor-space created by eight factors with a minimum of two levels, a total of 256 of monitoring points would be required ($2^8 = 256$). However, based on logistics and resources available, it would have been difficult to conduct an experiment of this scope. Therefore, the number of factors was reduced through a combination of industry rankings and focusing on drilling techniques as opposed to site conditions. Factors were ranked utilizing the analytical hierarchy process and the following factors were selected for field trials: 1) backream rate, 2) depth of cover, 3) reamer type, and 4) borehole pressure (Lueke and Ariaratnam 2002 b). Borehole pressure was subsequently changed to mud flow due to difficulties in measuring borehole pressure during the installation. In examining only four factors at two levels, the number of “experiments”, or installations, was reduced to sixteen.

Factor levels were set based on previous experience on the University of Alberta Research Farm site, as well as the operational envelope of the Vermeer 24x40A horizontal directional drilling rig which was utilized for this research. Soil composition of the upper 4 m at this site consists of a uniform lacustrine Lake Edmonton Clay with a unit weight of approximately 18 kN/m^3 (Zhang 1999). Local contractors typically use either the spiral compactor or fluted style of reamer when drilling in these conditions; subsequently these reamers were selected as the two levels for reamer type. All installations were conducted with 200 mm diameter high density polyethylene pipe, as this represented a typical size of product pipe used in shallow utility installations (Allouche et al. 2000). To ensure that surface heave could be measured, installation depths were set at 900 and 1200 mm below the surface. With borehole pressure difficult to measure accurately, the mud flow was used as a substitute and set at 50 liters/minute and 100 liters/minute, adjusted for altitude based on the drill rigs pump capacity. And lastly, backream rate was set at the maximum (2 min/rod) and minimum (6 min/rod) pullback rates that the drilling rig could maintain. On the particular drill rig utilized for this investigation, drill rods were approximately 3.05 m in length.

The borepath was designed to include depth of cover and mud flow as factors in each individual borepath in order to reduce the number of installations required to four. Constructed in a mirror image, each borepath was approximately 86.5 m in length and began at the surface and proceeded to be on grade at 900 mm at chain 15.8 m, 1,200 mm at 32.6, maintain 1,200 mm at 53.9 m, rise to 900 mm at 70.7 m, and exit the surface at 86.5 m. The chain lengths of 15.8 m, 32.6 m, 53.9 m, and 70.7 m indicate the location of the monitoring points on the borepath and represent one of the sixteen combinations of factors and levels. During the backream phase of the installation, the mud flow was varied such that on the first half (exit to the mid point) the lower mud flow was utilized, and on the second half (mid point to the rig) the higher mud flow.

A total of four installations were conducted utilizing this borepath, parallel to each other with a 5 m separation between each installation to minimize displacement contamination. Figure 5.3 illustrates the layout of the investigation site. Monitoring points consisted of five surface heave measurement points installed perpendicular to the borepath, with one on centerline and two on either side separated by 200 mm, approximately one pipe diameter. During the drilling and reaming phases the top of the surface points were surveyed utilizing conventional leveling techniques, after the drill head or reamer had past the monitoring point. From previous field experimentation done at this site, it was observed that there was no appreciable settlement or heave between the drilling and reaming phases of an installation.

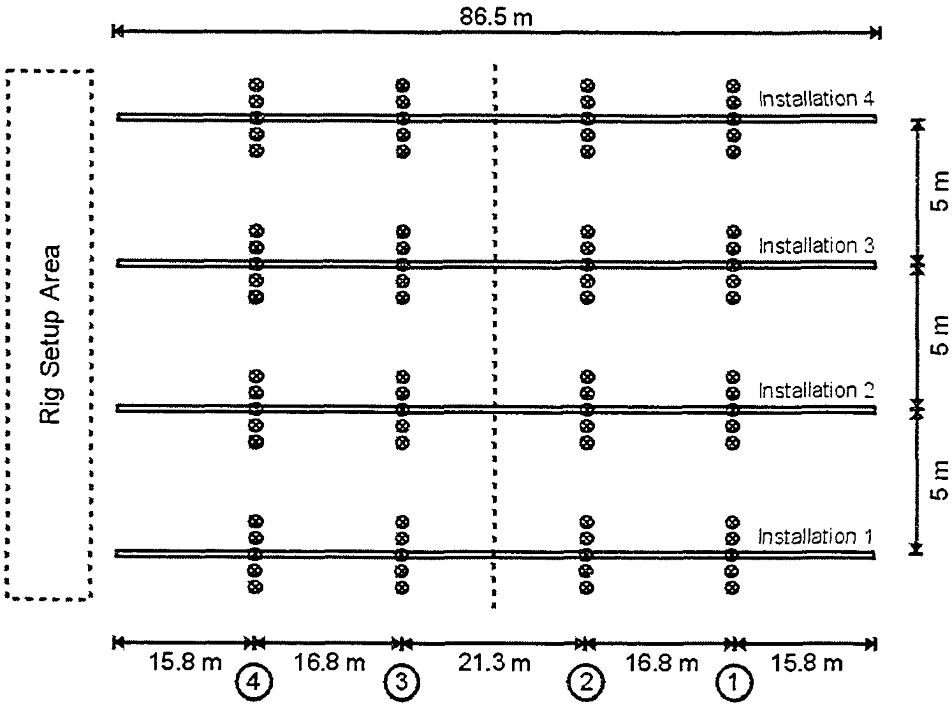

Figure 5.3 Layout of Borepaths for Field Investigation

From the installations, it was discovered that, in all cases, surface heave was exhibited at the surface after both the drilling and reaming phases. Ground movements during the drilling phase of the installation ranged between 0 and 1 mm, while for the reaming phase, vertical ground displacements were measured between 2 and 6 mm. Factor levels and the associated surface heave are summarized in Table 5.1; surface heave values are shown for centerline values, as well as 200 mm perpendicular on either side of the borepath for that particular combination of factors during the backream. The specific surface value(s) coupled with the associated factor levels for that surface heave magnitude, create a vector.

Table 5.1 Summary of Factors and Associated Surface Heave

Installation	Reamer	Depth (mm)	BRR (min/rod)	Flow (l/min)	Surface Heave (mm)		
					-200 mm	Center	+200 mm
1-1	Fluted	900	6	50	5.3	6.0	5.7
1-2	Fluted	1,200	6	50	2.8	3.2	3.0
1-3	Fluted	1,200	6	100	2.7	2.7	2.2
1-4	Fluted	900	6	100	4.5	5.7	5.0
2-1	Fluted	900	2	50	4.0	4.1	4.0
2-2	Fluted	1,200	2	50	3.8	3.8	3.4
2-3	Fluted	1,200	2	100	3.0	3.1	2.5
2-4	Fluted	900	2	100	4.0	3.6	3.0
3-1	Spiral	900	2	50	5.5	5.5	4.7
3-2	Spiral	1,200	2	50	5.3	5.2	4.4
3-3	Spiral	1,200	2	100	4.0	4.1	3.8
3-4	Spiral	900	2	100	5.2	4.9	3.9
4-1	Spiral	900	6	50	6.0	5.8	5.3
4-2	Spiral	1,200	6	50	5.8	6.1	5.9
4-3	Spiral	1,200	6	100	4.1	4.4	3.8
4-4	Spiral	900	6	100	6.0	5.8	5.2

5.4 NEURAL NETWORK BASED MODELING

Artificial neural network modeling refers to a computing theme that is borrowed from the analogy of a biological neural network. Though there are many different types, a neural network may be described as a massive parallel distributed processor made up of many simple highly interconnected processing units or elements, which have an inherent ability to store experimental knowledge and making it available for future use (Haykin 1999). These models mimic the brain in that the network acquires knowledge about the environment through learning or a training process, and that this knowledge is stored in the relative weight, or importance, of links between individual processing elements. While conventional statistical methods are model driven, where the structure of the model has to be known or created before data is applied, neural networks are data driven;

and as such the model is constructed based on the data with no preconceived assumptions made in its development. Neural networks have seen several successful applications in the field of geotechnical and rock engineering, and this success may be attributed to their ability to compensate for the inherent uncertainties and imperfections found in geotechnical engineering problems (Kim et al. 2001).

The basic building block of a neural network is the processing element, illustrated in Figure 5.4. Processing elements are synonymous to the neurons found in biological nervous systems, and operate only on the input they receive from connections and the localized data they contain. Each processing element may have several inputs represented by links from other processing elements or raw input from the environment. The magnitude of a signal received by the processing element along a specific link is multiplied by the weight of that link. The processing element sums the weighted input it receives, and passes it on to an activation function which acts to limit the amplitude of the output from the processing element. Networks are typically constructed in layers, with each layer containing at least one processing element. Each layer is connected to the previous and next layer, unless it is the input or output layer, as this is where data enters and leaves the network. All other layers are termed hidden, as these layers do not receive or transmit information to the outside world. The weight of a particular link is determined by a learning algorithm which modifies the weights of the links between processing elements in a systematic manner to achieve a desired design objective.

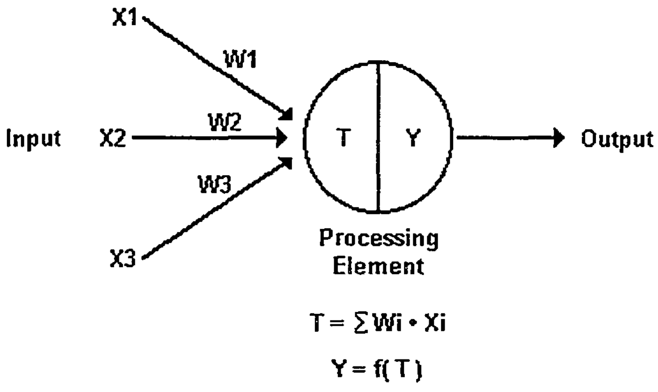

Figure 5.4 Typical Processing Element

In this paper, a multi-layered neural network trained using the back-propagation algorithm was developed utilizing commercially available software program to analyze the relationship between the various drilling factors and surface heave. The back-propagation algorithm is a generalization of the least mean squared algorithm that modifies the weights of the links between processing elements to minimize the mean squared error between the desired and actual outputs of the network (Mehrotra et al. 1997). Though there are other learning algorithms, back-propagation is well suited for the type of system modeling and prediction problem that is presented by this research. Model development includes data preprocessing, determining the network architecture, and evaluation. In general, the process involves some trial and error, as there is no methodology to determine the best model configuration, as there may be several configurations that would be suitable for a given system.

5.4.1 Data Preprocessing

Input is presented to the neural network as a series of preprocessed vectors. Preprocessing assists the network to learn by having the vectors presented in a fashion which allows the learning algorithm to handle it more efficiently. Generally, the input and output variables of the vector are normalized over a range between zero and one (Gurney 1997). One common method of data normalization is to scale the variables, both input and output, over a range which is relative to the specific variable. Prior to scaling, the minimum and maximum values of the variables must be determined, either being actual or theoretical values. For this application, theoretical values were used as the network was to be constructed to predict values outside the range of collected field data. Utilizing Equation 5-1, input variables were scaled over the modeling range indicated in Table 5.2. Output variables were simply divided by 10, maximizing the theoretical surface heave prediction for this network as 10 mm.

[5-1] $$Sv = \frac{(V - R_{\min})}{(R_{\max} - R_{\min})}$$

where: Sv = Scaled variable magnitude

V = Original variable magnitude

R_{min} = Minimum value of scaled range

R_{max} = Maximum value of scaled range

Table 5.2 Surface Heave Factor Levels and Modeling Range

Factor	Level A	Level B	Modeling Range
Mud Flow	50 l/min	100 l/min	0 – 200 l/min
Depth of Cover	900 mm	1,200 mm	0 – 2,000 mm
Backream Rate	2 min/rod	6 min/rod	0 – 10 min/rod
Reamer Type (Efficiency)	Spiral Compactor (15%)	Fluted (60%)	0 – 100%

Factor ranges were selected based on previous field experiments conducted in the area, operational limits of the drilling equipment, and to examine the behavior of the factor over the range on the development or surface heave. Normalization of the reamer required a slightly different technique, involving a change of perspective to transform the qualitative variable to a numeric form. Reamer type could not be scaled as the other variables, as there is no numeric method to compare one reamer to the next. Most reamers are designed with a specific functionality in the borehole; either to cut the formation, mix the cuttings with the drilling fluid, to displace the soil in the pipe zone into the surrounding formation, or some combination of these actions. Subsequently, it was suggested that the most appropriate method to transform the reamer type factor for input to the network would be to approximate the volume of soil that is removed from the pipe zone as opposed to displaced into the formation. By associating reamer type with a removal efficiency, the model would be able approximate the effect of different reamer configurations. However, there are no references alluding to this quantification technique, no manufacturers have determined this ratio for their reamers, and no research has been done on the efficiency of reamers based on design and configuration. Based on previous field research observations and experience, the reamer soil removal efficiency was approximated as being 15% for the spiral compactor reamer, and 60% for the fluted reamer. These values allowed for the scaling of reamer efficiency during sensitivity analysis. The magnitude of values selected for reamer efficiency should not have an affect on the development of relationships between the various factors.

When training the network, typically 20% of the available data is withheld from the network to evaluate or test its performance. Based on this testing set, the network can be evaluated to see how it generalizes to input patterns which it has not seen before. To develop a competent model, it is essential that during the training phase the model is exposed to all possible patterns contained in the data set. Additionally, since the testing set is to be used to evaluate the model's performance, it must also be representative of the patterns in the data and the training set. Based on the 16 observations, it would be impossible to construct effective training and testing sets as each pattern is only represented once in the overall data population; consequently, not every input pattern could be presented to the network during training.

To compensate for this problem, virtual data points were created by using the average value of the centerline magnitude with that of the surface point one pipe diameter to the left and right. This created two values for surface heave at each monitoring location and input pattern, centerline and left surface point, and centerline and right surface point. Though, in the overall scheme of network development, this still was not enough data to work with, it overcame the problem of not having each pattern represented in the training and testing sets. The adoption of utilizing the virtual data points in the development of the model was based on the following:

1) Statistical analysis of the 16 centerline data points, with the virtual 32 averaged data points; indicate that the two populations were similar in terms of overall surface heave magnitude (Table 5.3).

2) Surface heave profiles indicated that for some installations, the reamer may not have passed directly under the centerline point, subsequently offsetting the maximum surface heave magnitude, this averaging technique considered these situations.

3) Utilization of the additional data points in the training and testing sets improved overall performance of the network.

Table 5.3 Statistics of Data Point Configuration

Statistic	Centerline Data	Combined Data
Average	4.62 mm	4.46 mm
Standard Deviation	1.14 mm	1.11 mm
Minimum	2.7 mm	2.5 mm
Maximum	6.1 mm	6.0 mm
Range	3.4 mm	3.5 mm
Median	4.6 mm	4.3 mm

Utilizing the 32 vectors created by the averaging procedure, training and testing sets were constructed to be statistically representative of the overall data population. Appendix D lists data sets utilized in development of the final neural network model. Multiple training and testing sets were developed ensuring that the average backream rate, depth of cover, reamer efficiency, mud flow rate, and to a lesser extent surface heave, were similar to the overall population statistically. During the training and testing set selection, 20%

of the data was designated for testing, resulting in the training set consisting of 28 vectors, and the remaining 6 vectors for testing.

5.4.2 Model Development

One of the first tasks associated with the development of the network, is to determine its architecture. The architecture of the network refers to the number of layers as well as the number of processing elements in each layer. For this application, the number of elements on the input layer is predetermined at four, one for each factor studied (backream rate, reamer efficiency, depth of cover, and mud flow), and one output element representing the resulting surface heave. What requires determination are the number of hidden layers and number of elements on each. This is typically accomplished through trial and error, though in general two hidden layers are suitable for most problems, while one is actually preferred. If there are too many elements and layers in the network, it may tend to memorize the data and perform badly on test data which it has not seen. This would result in the network losing its ability to generalize. However, if there are not enough elements, the network may not be powerful enough to understand the patterns presented in the training data.

In the development of the network, the number of hidden layers was limited to one, while the number of hidden elements was determined through a systematic process of experimentation. In addition to determining the number of hidden elements, other modeling parameters had to be determined including momentum, and a coefficient of learning. Using the training and testing data sets listed in Appendix D, numerous modeling runs were conducted to determine the optimum model configuration. All models were developed utilizing the delta-rule learning rule and sigmoid transfer functions (Mehrotra et al. 1997, Gurney 1997).

To evaluate the performance of the network to the test data, three different error evaluation equations were utilized. These included the mean absolute error (MAE), root mean square error (RMS), and average system error (ASE). MAE measures the average error between the observed and forecasted values; RMS measures the average error magnitude giving greater impact to the larger magnitude errors than MAE; and ASE simply measures the percent difference between the forecasted and observed values.

[5-2] $$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|F_i - O_i\right|$$

[5-3] $$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(F_i - O_i)}$$

[5-4] $$ASE = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|O_i - F_i\right|}{O_i}$$

where: n = number of vectors (input-output pairs)
F_i = forecasted or predicted value
O_i = observed or target value

Utilizing these error measurement techniques, forecasted surface heave values from the test data were compared to the observed value for that input pattern, and by minimizing the error, the best model configuration was determined. In situations where there were conflicting minimum error values, the root mean square error was followed as it was most critical of large errors between the observed and forecasted values; as having a model that overall produced low error was the goal of its development.

NeuralWorks Professional II Plus, a commercially available neural network software package by NeuralWare Inc., was utilized to train and develop the neural network model. Utilizing this application various configurations of models were developed and evaluated by varying the number of hidden processing elements, momentum, and learning rates, as shown in Figures 5.5 through 5.7. Appendix E summarizes the development process for the final model. Through this trial and error approach, it was determined that the best model performance was achieved with 3 hidden processing elements on the hidden layer, a momentum of 0.7, and a learning ratio of 0.3. All evaluation runs were performed with the delta-rule learning rule and the sigmoid transfer function, for 50,000 iterations, with the same training and test sets. Results for runs greater than 50,000 iterations produced negligible improvements in forecasting and error reduction. In this configuration, the model averaged 0.22 mm RMS error, 0.16 mm MAE, and 4.2% ASE, for 10 testing set evaluations utilizing randomly initialized weights for all connections in the network.

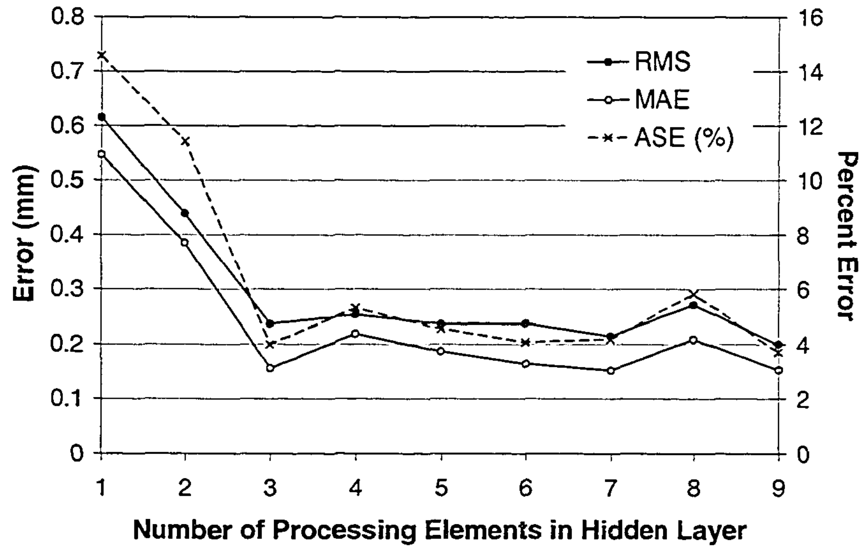

Figure 5.5 Network Output for Different Hidden Elements

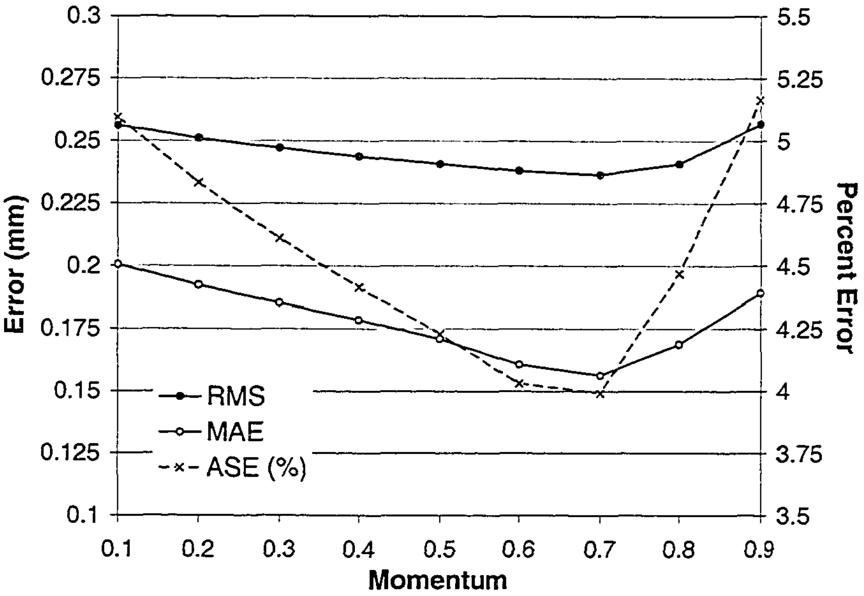

Figure 5.6 Effect of Momentum on Network Error

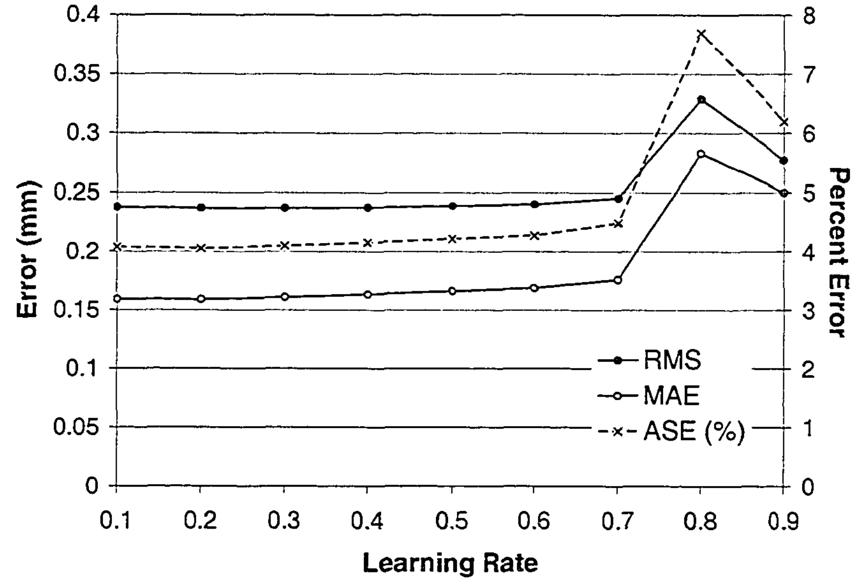

Figure 5.7 Effect of Learning Rate on Network Error

When evaluating the model's response to the number of hidden processing elements in the single hidden layer, there was a substantial drop in error as the hidden elements were increased from one to three as shown in Figure 5.5. However, after three hidden elements there was no significant change in error. Though, there was less overall error with seven hidden elements, a case could be made that the model had merely memorized input patterns, and that utilizing the minimum number of hidden elements possible would allow the model to generalize better. Networks developed with a momentum of 0.7, performed slightly better than other networks as illustrated in Figure 5.6. Though there is no significant change in error over the range of 0.1 to 0.9, all three error indicators were minimized at the 0.7 value. Momentum is a modeling parameter that controls the learning; it assists learning by changing connection weights in the same direction that had previously improved the error. Figure 5.7 illustrates the effect of the learning rate on the performance of the network. The learning rate (the rate at which errors modify weights) effect on the overall performance of the model remained relatively constant until a learning rate of 0.7 was utilized. At this value to error indices spiked and started to decline again at the 0.9 value. As there was negligible change in error from 0.1 to 0.7, the NeuralWorks default value of 0.3 was maintained and utilized in the final model configuration. The optimal model configuration, illustrated in Figure 5.8, was determined to have three hidden processing elements, a momentum of 0.7, and a learning rate of 0.3. This configuration was used in all comparisons and trend investigations.

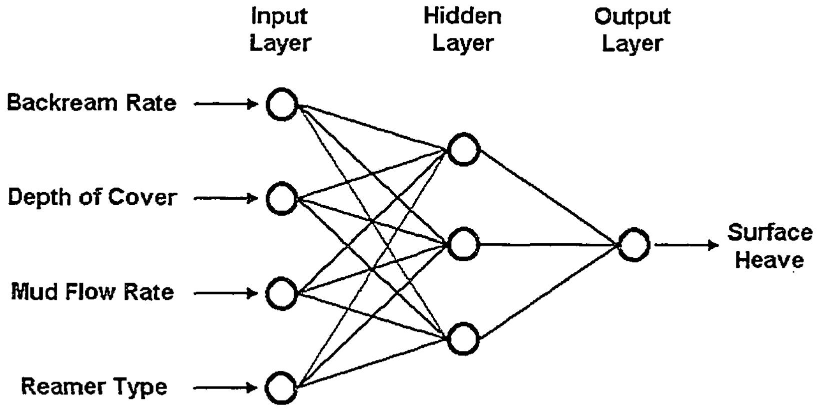

Figure 5.8 Network Model Configuration

Analysis of input vectors utilized in the development of the neural network model, was conducted utilizing the Microsoft Excel LINEST function. The results of this statistical analysis are included in Appendix F. The analysis indicated that the data had a coefficient of determination, or r^2 value, of 0.7364, which indicates there is a correlation between the input factors and resulting surface heave measured in the field. To confirm that there was actually a relationship in the data between the input factors and resulting surface heave, an F statistic was employed. Since the F observed value of 14.28 (degrees of freedom $v_1 = 4$ and $v_2 = 21$), is greater than the F critical (0.05) value of 2.84, there is a 95% chance that there is a definite relationship between the installation practice and the development of surface heave.

To determine if each factor was significant enough to contribute to the development of surface heave, T statistics were derived based on the output provided by the Excel LINEST function. For each factor a T observed value was calculated, resulting in values of 2.64 for flow rate, 2.40 for backream rate, 5.02 for depth of installation, and 4.40 for reamer efficiency. Based on an alpha of 0.05, or a 95% confidence level, the T critical value based on 4 degrees of freedom is 1.72. Since the observed value of T is greater than the critical value for all four factors, it indicates that all the prescribed factors were useful in the prediction of surface heave, for the specified field conditions measured in this study. Appendix F summarizes the F and T statistics produced by the LINEST function. Linear regression was not utilized in the modeling of the surface heave mechanism as this relationship is non-linear in nature.

Table 5.4 compares the error measurements of test data set alone, as well as presenting the trained neural network model with the complete set of 32 data vectors, the training and testing set combined.

Table 5.4 Summary of Neural Network Model Prediction Error

Model and Data	RMS (mm)	MAE (mm)	ASE (%)
Neural Network – Test Data (10)	0.223	0.162	4.2
Neural Network – All Data (10)	0.211	0.172	3.9

The error decreased when the model predicted surface heave for all the data, though this would be accounted for by the fact that 80% of the data was utilized in model construction, therefore increasing the number of accurate predictions. Error values for the neural network were based on the average error of ten runs, with each run starting with randomly initialized connection weights prior to training and testing. Figure 5.9 plots the predicted surface heave values against the measured or observed field values for the neural network model. The high r^2 value of 0.9639 for the neural network indicates a high correlation between predicted and actual surface heave measurements.

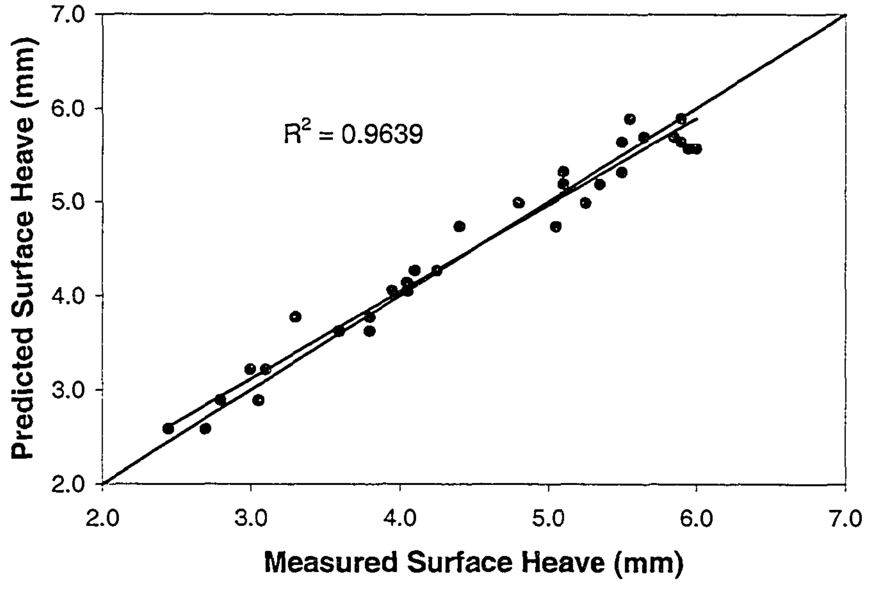

Figure 5.9 Predicted and Observed Surface Heave Utilizing Neural Network

5.5 RELATIVE IMPORTANCE OF FACTORS

An analysis was conducted to determine which factor had the greatest influence on the development of surface heave. The computation technique utilized in this analysis is from Garson (1991) and the process and computations are outlined in Appendix G. The relative importances of the input variables are determined using the trained connection weights between processing elements. Summary results from this analysis are presented in Table 5.5. A total of ten runs were performed with the same training data set, though with randomly initialized connection weights at the start of training for each run.

Table 5.5 Relative Importance of Input Variables (Percentage)

Trial	Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow Rate
1	35.3	23.9	28.6	12.3
2	18.1	45.9	25.9	10.1
3	25.7	41.9	20.8	11.7
4	17.3	47.2	24.7	10.8
5	15.9	47.9	25.6	10.5
6	23.9	31.1	29.2	15.8
7	29.3	37.8	21.7	11.1
8	36.9	27.0	23.4	12.7
9	23.9	33.2	28.0	15.0
10	18.7	42.7	27.7	10.9
Average	24.5	37.8	25.6	12.1

The most significant factor to the development of surface heave in this system was determined to be the depth of cover with a value of 37.8%, based on the average of ten runs. On individual runs, the relative importance of each input variable changed slightly, however on average the depth of cover remained the most important factor. On analysis of the ordinal placement, or the number of times each factor secured a positioning, listed by this notation (1^{st}:2^{nd}:3^{rd}:4^{th}), the following is determined; depth of cover (8:1:1:0), backream rate (0:7:3:0), reamer efficiency (2:2:6:0), and mud flow (0:0:0:10). Backream rate and reamer efficiency were both very similar in terms of importance with 25.6% and 24.5% respectively, with backream rate having slightly greater importance to the development of surface heave based on the average and the ordinal placement. In all cases the mud flow rate was determined to have the least effect on the development of surface heave, and presented only a 12.1% rating of importance and ten fourth place ordinals.

Compared to the findings of the survey conducted utilizing the analytical hierarchy process (AHP) in Chapter 3, there is a slight correlation between the perceived importance of a factor and that determined by the neural network. It is difficult to compare the relative importance to the AHP analysis as some of the factors were changed in meaning during their implementation in the field experiment. Depth of cover and backream rate were ranked 2 and 3 by the AHP, while analysis of the relative importance of the factors using the trained neural network model weights ranked depth of cover as the most important, followed by backream rate, in the development of surface heave.

5.6 SENSITIVITY ANALYSIS

To determine how the model predicted trends based on the field data used in its development, a series of data sets were constructed in a systematic manner to examine the model's behavior as a factor varied over a range. Analysis of the effect of flow rate on surface heave indicated that mud flow had the least influence; therefore in the examination of the other factors an average mud flow of 75 l/min was used in the construction of other trend graphs, to reflect its negligible contribution, though to keep its value within the explored factor-space. Examinations were performed on depth of cover, reamer efficiency, and backream rate.

Using normalized input vectors, the primary factor under examination was varied between 0.1 and 0.9, while the remaining factors were either held constant at a value which was utilized in the experimental design, or examined at 0.2, 0.4, 0.6, and 0.8 input values. The factor which was varied during the examination of the primary factor was termed the secondary factor – for that specific examination. For each primary factor that was examined, 16 configurations were constructed ensuring each of the other factors was examined as a secondary factor, at each design factor level. Each configuration created a curve which indicated the trend in surface heave as the primary factor varied from 0.1 to 0.9. To compare the configurations for each primary factor, the slope of the curve was determined based on a linear fitting, and the minimum, maximum, and average surface heave predicted was gathered. The effect of the secondary factor for a specific configuration was determined by averaging the slopes at a specific experimental factor level (listed as Secondary Effect in Tables 5.6 to 5.8), while the effect of the primary factor on the development of surface heave was determined by averaging the slopes of all examined configurations (listed as the name of the Primary Factor in Tables 5.6 to 5.8). Appendix H contains the input vectors and the output from the neural network model.

Table 5.6 summarizes the investigation of the contribution of depth of cover towards the development of surface heave. As the depth of cover increased, there was a strong negative relationship towards the development of surface heave (-0.73), indicating that surface heave decreased as the depth of cover increased. The effect of the secondary factor is best observed by comparing the surface heave statistics; which indicate that as the reamer efficiency increased the average surface heave produced decreased, and as the backream speed decreased the average surface heave increased. Predictably, as the depth of cover increased surface heave decreased largely due to arching effects of the soil, and the geometry of the installation. As the depth of cover increased, displacements resulting from installation would dissipate over the distance to the surface.

Table 5.6 Depth of Cover Trends

Reamer	Depth	BRR	Slope	Surface Heave (mm)			Secondary Effect	Depth
				Min	Max	Ave		
20%	200 - 1,800 mm	6 min/rod	-0.69	2.2	7.5	5.2	-0.81 Reamer	-0.73
40%	200 - 1,800 mm	6 min/rod	-0.81	1.8	7.7	4.9		
60%	200 - 1,800 mm	6 min/rod	-0.87	1.6	7.7	4.6		
80%	200 - 1,800 mm	6 min/rod	-0.86	1.5	7.6	4.2		
20%	200 - 1,800 mm	2 min/rod	-0.53	2.3	6.6	4.6	-0.67 Reamer	
40%	200 - 1,800 mm	2 min/rod	-0.65	1.8	6.8	4.4		
60%	200 - 1,800 mm	2 min/rod	-0.74	1.5	6.9	4.1		
80%	200 - 1,800 mm	2 min/rod	-0.77	1.4	7.0	3.7		
60%	200 - 1,800 mm	2 min/rod	-0.74	1.5	6.9	4.1	-0.83 BRR	
60%	200 - 1,800 mm	4 min/rod	-0.82	1.5	7.4	4.3		
60%	200 - 1,800 mm	6 min/rod	-0.87	1.6	7.7	4.6		
60%	200 - 1,800 mm	8 min/rod	-0.89	1.7	7.9	4.8		
15%	200 - 1,800 mm	2 min/rod	-0.50	2.5	6.6	4.7	-0.61 BRR	
15%	200 - 1,800 mm	4 min/rod	-0.58	2.4	7.1	5.0		
15%	200 - 1,800 mm	6 min/rod	-0.66	2.3	7.5	5.3		
15%	200 - 1,800 mm	8 min/rod	-0.71	2.3	7.8	5.6		

Figures 1 and 2 in Appendix H illustrate the general trend of decrease in surface heave as the depth of cover increases is observed. Additionally, the effect of the secondary effect of reamer efficiency can be noted. As reamer efficiency is increased, there is a significant drop in the level of surface heave as the depth of cover increases. Figures 3 and 4 also illustrate the general trend in decreasing surface heave with increased depth of cover, however the secondary factor of backream rate does not have as significant effect.

The investigation of reamer efficiency and its contribution to surface heave is summarized in Table 5.7. As reamer efficiency increased, there was a weaker negative relationship to surface heave (-0.24), indicating that surface heave decreased as reamer efficiency increased. From examination of secondary factors, it can be determined that as the depth of cover increased, the average surface heave decreased, and as the backream speed decreased, the surface heave increased. These trends are similar to what was determined in examination of the effect of depth. Reamer efficiency as defined in the model attempts to quantify a reamer's configuration on the basis of soil removed to soil displaced when expanding the borehole. This assumption correctly approximated the differences between the spiral and fluted reamers.

Table 5.7 Reamer Efficiency (RE) Trends

Reamer	Depth	BRR	Slope	Surface Heave (mm)			Secondary Effect	RE
				Min	Max	Ave		
10 - 90%	400 mm	2 min/rod	0.03	6.1	6.4	6.3	-0.17 Depth	-0.24
10 - 90%	800 mm	2 min/rod	-0.16	3.9	5.3	4.9		
10 - 90%	1,200 mm	2 min/rod	-0.32	2.1	4.5	3.4		
10 - 90%	1,600 mm	2 min/rod	-0.23	1.5	3.3	2.2		
10 - 90%	400 mm	6 min/rod	-0.02	6.9	7.3	7.2	-0.19 Depth	
10 - 90%	800 mm	6 min/rod	-0.20	4.5	6.2	5.7		
10 - 90%	1,200 mm	6 min/rod	-0.34	2.4	5.0	3.7		
10 - 90%	1,600 mm	6 min/rod	-0.20	1.7	3.3	2.2		
10 - 90%	900 mm	2 min/rod	-0.22	3.3	5.1	4.5	-0.25 BRR	
10 - 90%	900 mm	4 min/rod	-0.23	3.6	5.4	4.8		
10 - 90%	900 mm	6 min/rod	-0.26	3.8	5.9	5.2		
10 - 90%	900 mm	8 min/rod	-0.30	4.1	6.4	5.6		
10 - 90%	1,200 mm	2 min/rod	-0.32	2.1	4.5	3.4	-0.34 BRR	
10 - 90%	1,200 mm	4 min/rod	-0.33	2.2	4.7	3.5		
10 - 90%	1,200 mm	6 min/rod	-0.34	2.4	5.0	3.7		
10 - 90%	1,200 mm	8 min/rod	-0.35	2.7	5.3	4.0		

Figures 5 and 6 from Appendix H effectively show the effect of change in depth of cover during the examination of reamer efficiency. Based on the results of the neural network model, for each 400 mm increase in depth of cover there is a corresponding 0.5 up to 2.0 mm decrease in the magnitude of surface heave. In general, the level of surface heave predicted by the model does not change significantly as the reamer efficiency increases. Depth of cover in this situation has the greatest influence on the surface heave produced. Figures 7 and 8 of Appendix H indicate a negligible difference in surface heave produced as the secondary factor backream rate was changed. There is only a 0.3 to 0.5 mm increase in surface heave for each increment of 2 min/rod decrease in backream rate.

Table 5.8 summarizes the examination of the effect backream rate has on surface heave. As backream speed decreased in general, there was a weak positive relationship to surface heave (0.14), indicating that surface heave increased. Additionally, following previous trends, as depth of cover increased, surface heave decreased, and as reamer efficiency increased, surface heave decreased. The trend in the development of surface heave in relation to backream rate is opposite to what may intuitively be expected. Where one might expect that slower reaming speeds would provide greater opportunity for the reamer to cut and mix the soil cuttings with the drilling fluid, the opposite occurs with the development of greater surface heave.

Table 5.8 Backream Rate (BRR) Trends

Reamer	Depth	BRR	Slope	Surface Heave (mm)			Secondary Effect	BRR
				Min	Max	Ave		
60%	400 mm	1 - 9 min/rod	0.20	6.1	7.7	7.0	0.13 Depth	0.14
60%	800 mm	1 - 9 min/rod	0.20	4.8	6.3	5.5		
60%	1,200 mm	1 - 9 min/rod	0.08	3.0	3.7	3.3		
60%	1,600 mm	1 - 9 min/rod	0.04	1.8	2.1	1.9		
15%	400 mm	1 - 9 min/rod	0.23	5.9	7.7	6.9	0.15 Depth	
15%	800 mm	1 - 9 min/rod	0.23	5.1	6.9	6.0		
15%	1,200 mm	1 - 9 min/rod	0.14	4.3	5.4	4.8		
15%	1,600 mm	1 - 9 min/rod	0.01	3.1	3.2	3.1		
20%	900 mm	1 - 9 min/rod	0.22	4.9	6.6	5.7	0.18 Reamer	
40%	900 mm	1 - 9 min/rod	0.21	4.7	6.4	5.5		
60%	900 mm	1 - 9 min/rod	0.17	4.4	5.7	5.0		
80%	900 mm	1 - 9 min/rod	0.13	3.7	4.6	4.2		
20%	1,200 mm	1 - 9 min/rod	0.13	4.2	5.3	4.7	0.10 Reamer	
40%	1,200 mm	1 - 9 min/rod	0.10	3.8	4.6	4.1		
60%	1,200 mm	1 - 9 min/rod	0.08	3.0	3.7	3.3		
80%	1,200 mm	1 - 9 min/rod	0.09	2.3	3.0	2.6		

From examination of the graphs illustrated in Figures 9, 10, 11, and 12 of Appendix H, there is a consistent trend that as backream rate is decreased, or slowed, surface heave gently increases. Again, as seen in other graphs, the general trends indicating that surface heave decreased significantly with increase in depth are illustrated in Figures 9 and 10, and a decrease in surface heave as reamer efficiency increases in Figures 11 and 12. The behavior of the model is confirmed as it consistently predicts similar trends in output as the input factors are varied. For the most part, the effect on surface heave as the input variables are changed can be rationalized by actual field observations.

5.7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Results from this research indicate that there is a direct relationship between the development of surface heave and drilling practices employed on shallow small diameter utility installations conducted by horizontal directional drilling. This was confirmed from statistical analysis, a sensitivity analysis conducted utilizing the trained neural network model, and field observations. Statistical analysis indicated that there was a correlation between the four factors: depth of cover, backream rate, mud flow, and reamer efficiency, and the development of surface heave, and that all four factors were useful to predict surface heave. Based on an analysis of the trained neural network model the importance of the various factors was determined, and concluded that the depth of installation was the most important factor towards the development of surface heave under the conditions of the field experiment, followed by backream rate and reamer efficiency, with mud flow having the least influence. Sensitivity analysis indicates that as depth of cover increased, the magnitude of surface heave decreased; as the backream speed decreased, surface heave increased; and as reamer efficiency increased, surface heave decreased. The analysis indicates that the relationship between drilling practice and surface heave is not a linear relationship, but a dynamic system where changes in factors generally produce non-linear responses.

The use of virtual data points, as described in this paper, was necessary to create additional data points to use in model development to compensate for limited field data. The authors acknowledge that based on the limited volume of available data to construct the neural network model, in its current state, the application and validity of the model is limited to the conditions in which the field installations were performed. Typical neural network modeling utilizes a very large number of data points to provide suitable training and validation populations. However, with limited resources available for this preliminary research, the utilization of virtual data points to determine the feasibility of the neural network modeling technique for this application was deemed acceptable.

The neural networking modeling approach as utilized in this research provided a useful mechanism to examine the relationship between the various factors contributing to surface heave. Based on the results, even with the limited data, the model confirmed there was a relationship between construction practices and resulting surface heave in horizontal directional drilling. The relationships determined by the model match the hypothesis of what would be reasonably expected on a typical installation. Additional data would refine the model and enhance its predictive ability; however, it is the opinion of the author that additional data would not change the conclusions of this research. The trained neural network model provided an experimental tool to analyze the affect of changing the various factors that influence surface heave.

To further develop the model and expand its field of application, the following recommendations for future work are provided:

1) Additional drilling factors should be considered in subsequent field experimentation including but not limited to annular space sizing, reamer diameter, soil composition, and soil density. Inclusion of additional factors would increase the applicability of the model.

2) The implementation of additional field installations and monitoring to increase the data available for model development.

3) The neural network model was developed based on the data collected from a full factorial experiment conducted under specific field parameters. Increasing the range or number of levels at which the drilling factors were examined would train the model to account for different soil characteristics, pipe and reamer diameters, depth of cover and installation lengths not examined in this preliminary work.

4) Development of a universal quantification technique to account for reamer cutting removal or mixing efficiency to use as input in the model, and to account for varying reamer geometry and configuration. Redefine the concept of reamer efficiency to more accurately describe the affect of the type of reamer utilized.

5) Incorporation of borehole pressure as a factor that relates to the development of surface heave. Recent developments in downhole tooling, now makes it possible to accurately measure borehole pressure on horizontal drilling installations. The relationship between borehole pressure, backream rate, and drilling fluid pumping rate can now be further examined to determine its influence on ground movement.

6) Examination of the effect the length of installation in relation to the location of the reamer and length of pipe installed has on the development of surface heave. To better understand the system, one would need to account for the distance the drilling fluid travels inside the borehole from the reamer to the exit pit during the backream.

It is suggested that a model which accurately depicts the relationship between drilling practices and ground movements could have applications in planning, training, education, and diagnostic investigation. Contractors could estimate the ground displacement behavior associated with different downhole tooling configurations to plan installations in sensitive situations. Academics, consultants, and inspectors could use this tool to better understand field observations and simulate different configurations and drilling techniques. And lastly, when problems occur during the installation process, this tool could potentially be used to suggest alternative methods to adjust drilling techniques to achieve project objectives.

5.8 REFERENCES

Allouche, E.N., Ariaratnam, S.T., and Lueke, J.S. (2000). "Horizontal directional drilling: a profile of an emerging underground construction industry." Journal of Construction Engineering and Management, ASCE, 126 (1): 68-76.

Ariaratnam, S.T. and E.N. Allouche (2000). "Suggested practices for installations using horizontal directional drilling." Practice Periodical on Structural Design and Construction, ASCE, 5 (4): 142-149.

Directional Crossing Contractors Association (DCCA) (1998). "Guidelines for successful mid-sized directional drilling projects," Directional Crossing Contractors Association, Dallas, Texas.

Finney, D.J. (1955). "Experimental design and its statistical basis." University of Chicago Press, Chicago, IL.

Garson, G.D. (1991). "Interpreting neural network connection weights." AI Expert, (6)7: 47-51.

Gurney, K.N. (1997). "An introduction to neural networks." UCL Press, London.

Haykin, S. (1999). "Neural networks: a comprehensive foundation." Prentice Hall, Upper Saddle River, NJ.

Kim, C.Y., G.J. Bae, S.W. Hong, C.H. Park, H.K. Moon, H.S. Shin (2001). "Neural network based prediction of ground surface settlements due to tunneling." Computers and Geotechnics, Volume 28, 517-547.

Lueke, J.S. and S.T. Ariaratnam (2002 a). "Modeling of surface heave contributing factors in directional boring operations." Proceedings of the Annual Conference of the Canadian Society for Civil Engineering, Montreal, Quebec, June 5-8.

Lueke, J.S. and S.T. Ariaratnam (2002 b). “Factors affecting surface heave in horizontal directional drilling operations.” Proceedings of No-Dig 2002, Montreal, Quebec, April 28-30.

Mehrotra, K., Mohan C.K., and Ranka S. (1997). “Elements of artificial neural networks.” Massachusetts Institute of Technology Press, Cambridge, MA.

Stangl, G.A. (1990). “Historical development of mini-directional horizontal boring methods.” Proceedings of Microtunneling and Horizontal Directional Drilling Symposium, Trenchless Technology Center, Louisiana Tech University, Ruston, La.

Zhang, D.J.Y. (1999). “Predicting capacity of helical screw piles in Alberta soils.” M.Sc. Thesis, University of Alberta, Department of Civil and Environmental Engineering, Edmonton, Alberta.

Chapter 6 CONCLUSIONS AND DISCUSSION

6.1 CONCLUSIONS

The main objective of this research was to develop an understanding of how various factors related to horizontal directional drilling contribute to the development of surface heave during the backream phase of phase of the installation. Three subcomponents were derived to achieve this objective. The first component was to identify the factors that contribute to surface heave during a horizontal directionally drilled installation, and to use these factors to design an experiment to determine how these construction practices affect surface heave. The second component was to conduct a full scale experiment to observe the effect of construction methodology through the systematic manipulation of variables during an actual field installation. The final component of this objective was to develop a model to quantify surface heave and how the identified factors relate to each other towards the development of surface heave. The conclusions of this research are summarized by the three subcomponents: surface heave factors, field installations, and surface heave modeling.

6.1.1 Surface Heave Factors

Several factors were identified as contributing to the development of surface heave on directionally drilled installations. The identified factors included: 1) annular space, 2) backream rate, 3) borehole pressure, 4) depth of cover, 5) reamer type, 6) reamer diameter, 7) soil composition, and 8) soil density. Due to resource constraints, only four of the factors were selected to be included in a full factorial based field experiment. These factors were selected utilizing an analytical hierarchy procedure and the interviewing of industry practitioners. This selection process narrowed the field of factors investigated to depth of cover, backream rate, borehole pressure, and reamer type. Based on the results of the field experiment, a neural network model of the surface heave system and associated factors was developed. Observations and findings from the model are discussed by factor examined.

Depth of Cover

For most of the field installations conducted in this research, the magnitude of surface heave recorded during the shallow installations were greater than those observed on the deeper installations when comparing installations with similar mud flow applications rates. This was also reflected in the trained neural network model, which indicated there was a strong negative relationship between the magnitude of surface heave and depth of cover, as depth of cover increased. For this investigation, the effect of depth of cover was examined at 900 and 1200 mm below the surface. Shallow depth of cover variables were specifically selected to promote the development of surface heave, and to allow for accurate measurement during the data collection process.

Reamer Type

In the design of the field experiment, fluted and spiral compactor type reamers were selected for comparison. The results of the field installations revealed that the spiral compactor reamer induced greater magnitudes of surface heave than the fluted reamer for almost all the installations. Since there was no method to compare the behavior of the reamers in the borehole, in the neural network model the concept of reamer efficiency was devised. Reamer efficiency estimated the effectiveness of removing soil from the path of the reamer as it creates space to accommodate the product pipe. The fluted reamer was designed to cut and mix the soil with the circulated drilling fluid to transport the soil out of the borehole. Alternatively, the spiral compactor reamer was designed to displace the soil, hence was not as efficient as the fluted reamer in removing soil from the borehole. Utilizing the concept of reamer borehole soil removal efficiency, the model indicated that as reamer efficiency increased there was a weak negative relationship towards surface heave, indicating that surface heave decreased as reamer efficiency increased. The concept of reamer efficiency reasonably approximated the differences between the design and behavior of the spiral compactor and fluted reamer.

Backream Rate

The backream rate for the investigation was set at 2 and 6 minutes per drill rod, determined by the operational characteristics of the drill rig. Field observations illustrated that the faster backream rate of 2 minutes per rod reduced the magnitude of surface heave observed for installations conducted with the spiral compactor reamer. The effect of backream rate on the fluted reamer was less conclusive. The neural network model trend analysis suggested that there was a weak positive relationship between the magnitude of surface heave and backream rate, indicating that as backream rate decreased surface heave increased. It should be noted that based on generally accepted best practices, the volume of drilling fluid pumped into the bore during the installation was insufficient for the diameter of installation, this was determined by mud volume calculations after the installations were completed. The drill rig utilized for this installation was essentially too small to handle the installation of the 200 mm diameter product pipe. However, this size of drill rig is commonly utilized by many contractors to install product of this size. Additional investigation to examine the relationship between backream rate and surface heave may be required with the proper mud application rate to better explore this interaction.

Mud Flow

The rate at which drilling fluid was injected through the drill stem into the borehole during the backream stage of an installation is referred to as the rate of mud flow. In the initial stages of the investigation, mud flow replaced borehole pressure as the factor to be included in the experimental design. The technology to accurately and economically measure borehole pressure during the installation was not available at the time the field investigations were conducted. Mud flow was varied between 50 and 100 litres per minute, set by the operational capabilities of the drilling rig. In general, low mud flow rates produced greater surface heave than installations performed with higher mud flow rates for all combinations of factors examined. Sensitivity analysis with the neural network model also supported this observation. The higher mud flow rate used in the field installations is closer to what is theoretically required to clean cuttings from the borehole during the backream stage of the installation.

6.1.2 Field Investigations

This research developed a methodology to systematically explore the interaction of the various factors that contribute to the development of surface heave through the use of a full factorial experimental design. A field-monitoring program was implemented utilizing surface points to measure the heave developed at particular points along prescribed borepaths. Borepaths were designed to incorporate construction factors such as depth of cover and mud flow to reduce the number of installations required to fully explore the factor space. The design of the borepaths allowed for the full factorial examination to be completed with the least number of horizontal directionally drilled installations.

6.1.3 Surface Heave Modeling

A neural network was successfully applied in the modeling of the surface heave system, proving the feasibility of this modeling technique to the horizontal directional drilling process. The neural network modeling technique provided the methodology to determine that there is a relationship between the development of surface heave and construction practices utilized on shallow small diameter utility installations conducted by horizontal drilling. The benefit of utilizing the neural network modeling approach was that the model could discover the relationship between the various drilling factors based on a learning technique, without the need to establish a starting hypothesis or make assumptions about the system's behavior during its construction. Additionally, through the utilization of the neural network model a variety of factors were examined which were difficult to account for in conventional numeric or geometric analysis.

Results from this research indicate that there is a direct relationship between the development of surface heave and the drilling practices employed on a given installation. This was confirmed with statistics performed from a regression analysis, a sensitivity analysis from designated input patterns, and field observations. Regression analysis indicated there was a correlation between the drilling factors of depth of cover, backream rate, mud flow, and reamer type; and that all four factors were useful to predict surface heave development. Depth of cover was determined to be the most influential factor in the development of surface heave based on a sensitivity analysis conducted of the weights of the links between nodes on the trained neural network model.

In the model's current state, it has very limited predictive capability. This is due to the limited number of data points utilized in its development. In this research, the application of a neural network was primarily for the understanding of the relationships between the factors contributing to surface heave.

6.2 RELEVANCE OF RESEARCH

This research studied construction techniques associated with horizontal directional drilling and their effect on the development of surface heave under actual field conditions. The following discusses how this research improved on previous work conducted in the field of surface heave associated with directional drilling.

- Most of the previous research in ground movements associated with horizontal directional drilling focused on geotechnical parameters. This research considered construction related factors such as rate of mud flow, type of reamer, and backream rate, and depth of cover.

- Previous research in this area utilized laboratory simulation of borehole pressure to induce ground movements, alternatively this research was based on actual field installations providing accurate behavior of drilling fluid flow in the borehole.

- The field data collection program was designed to gather multiple surface heave measurements with various combinations of construction techniques on the same site. Previous research recorded ground movements from unique projects, on various sites, and under different installation conditions. In some cases, previous research focused on proving that ground movements do not occur with a particular technique. Having multiple installations on the same site allows for the understanding of how construction techniques affect surface heave development. In addition, the field program was designed with the purpose of creating ground movements during the installation process.

- Numerical methods of determining ground movements require several assumptions regarding borehole behavior, and typically focus on accurately defining soil parameters. Assumptions may include symmetrical behavior, accounting for volume of soil removed or compacted, borehole pressure, and change in borehole diameter. These assumptions are difficult to accurately quantify and apply to real world installations. Actual field installations minimize the number of assumptions required. The utilization of neural network modeling requires no assumptions of how the system will behave during its development. The model develops its own understanding of how the system behaves by learning from the data provided from the field installations.

- Some ground movement research has been conducted on large scale horizontal directionally drilled installations. These installations are typically large diameter, have a relatively large depth of cover, and may require many weeks to complete the installation. On these installations, borehole pressures were recorded and related to the overburden pressure provided by the soil for the particular project. By maintaining borehole pressure beneath the over burden pressure on a particular project, the previous researchers concluded that ground movements should not occur. This does not account for ground movements caused by the displacement of soil by the reamer during the backreaming phase of the installation. The research conducted in this thesis, focuses on utility type installations which are characterized as relatively small diameter, shallow installation depths, short in duration, and typically in an urban setting. Utility projects generally are too short in duration and have limited budgets to have the contractor study and record borehole pressure as well as determine overburden pressure through geotechnical investigation. Thus the research in this thesis focuses on understanding construction techniques such that they may be modified by the utility contractor to minimize the development of surface heave, as a general method of practice.

- Previous work focused on the pressurization of the borehole as the primary factor contributing to the development of surface heave. Though this may be a contributing factor, soil displacement may also contribute to surface heave. The methodology utilized in this research accounted for ground movements caused by displacements by including the reamer design as a factor in the investigation.

6.3 RECOMMENDED HDD CONSTRUCTION PRACTICES

This research examined how construction practices are related to the development of surface heave on a horizontal directionally drilled installation. The following recommendations for the directional drilling industry are suggested based on examination of the field observations and the results of the neural network model. These recommendations are only for installation conducted in soil similar to that which was examined in this research.

- The primary factor affecting surface heave on a directionally drilled installation is depth of cover. It has been shown that increasing the depth of cover can significantly reduce the magnitude of surface heave developed during an installation. Increasing the depth of cover, or distance between the borepath and any structure that may be affected by ground movements, is the primary tool the contractor and engineer may utilize to minimize the potential of damage occurring on projects where surface heave may be a concern.

- Proper utilization of drilling fluid is an important factor in controlling the development of surface heave. Circulating the proper volume of drilling fluid through the borehole for the size of product and backream rate used during the installation assists in reducing the magnitude of surface heave developed. Contractors should ensure that for a particular installation, the capabilities of the drill rig are suitable for the size of product installed and the rate at which the product is installed. Calculations should be performed in the planning stage of the project to assist in the proper selection of equipment. Utilizing higher volumes of drilling fluid reduces the magnitude of surface heave developed when comparing installations conducted under similar conditions.

- Reamer design has a significant effect on the development of surface heave. Designs which are more efficient at removing soil from the proposed borepath reduce the magnitude of surface heave observed on an installation. Reamer efficiency significantly influences the order of magnitude of surface heave developed on an installation when all other factors are equal. Reamers designed to cut and mix the soil with the circulated drilling fluid should be utilized if soil conditions permit.

6.4 AREAS FOR FUTURE RESEARCH

This section presents some areas where future research can be directed to further understand the horizontal directional drilling process and particularly, how surface heave relates to construction techniques utilized during the installation process. This section will also discuss aspects of the research in this thesis which require further examination based on the results obtained during the analysis and modeling.

First and foremost, the effect of surface heave in relation to construction practices should be explored in other soil mediums and soil parameters. In this research, only one site was instrumented and studied for the factorial experiment, that being the University of Alberta Research Farms. By conducting the same field study used in this research in sand or gravel soil medium, valuable information related to the surface heave mechanism would be attained. In addition to different soil mediums, soils of differing parameters such as moisture content and consistency should also be examined in a field setting. This would allow direct comparison of how soil classification affects the development of surface heave on a horizontal directional drilled installation.

During the development of the field experiment, it became apparent that to perform a detailed examination of the behavior of the surface heave mechanism, only a limited number of factors could be examined due to limited resources and the relatively high financial cost of performing actual field examinations. This lead to the necessity of selecting only what was perceived as being the most important factors affecting surface heave development. These factors were then used to design a factorial experiment. However, several other factors exist that could contribute to the behavior of the system. Factors that were discussed but did not rank high during the selection process, were soil composition and density (previously noted above), as well as reamer diameter and annular space. Reamer diameter relates to the actual diameter of the installation, while the annular space factor refers to how the reamer diameter is selected. Current industry rules of thumb indicate that the reamer diameter should be 1.5 times that of the product pipe diameter. This oversize creates the annular space. Changing the size of the annular space would affect the volume of drilling fluid required for an installation as well as the backream rate. Additional factors such as the effect of water table and drilling fluid composition could also be added to this framework. Inclusion of these additional factors would enhance the applicability of the model and provide greater insight into factor interaction.

The scope of this research was limited to product pipe sizes typical of shallow subsurface utility installations conducted in an urban setting. This is where the effects of surface heave would be most noticeable and cause potential damage. During the field installations, only a 200 mm diameter high density polyethylene product pipe was used. Additional diameters should be incorporated into future work in this area to allow a relationship to be developed between diameter and depth of cover towards the potential of surface heave development. This could potentially lead to the establishment of simple guidelines for minimum depth of cover in relation to product diameter.

Additional HDD installations should be conducted to allow collection of additional data to train and refine the neural network model. It was apparent in the development of the neural network model that there was insufficient data to allow use of the model to situations outside of the parameters studied. With additional data from other installations, the model could be developed to generalize and predict surface heave for situations beyond that covered in this research. Additionally, the number of levels for each factor could be expanded in the model development and training.

The length of an installation has a direct effect on the pressures created in the borehole. In general, the highest borehole pressures are developed at the mid point of the installation. This is due to the length drilling fluid must be pumped to circulate back to the entry or exit pits. The pressure in the borehole increases as an installation increases in length. In this research, all installations were conducted over a length of approximately 86.5 m. To explore the effect the length of the installation has on the development of surface heave; future research should include installations of varying lengths. To better understand the system, one would need to account for the distance the drilling fluid travels inside the borehole from the reamer to the exit pit during the backream. In this manner, length of installation could become another modeling factor.

The development of a universal quantification technique to account for reamer cutting removal or mixing efficiency to use as input in the model that accounts for varying reamer geometry and configuration should be investigated. In this research, it was difficult to quantify reamer behavior; therefore, the concept of reamer efficiency was developed. Reamer efficiency was a value assigned to the reamer that rated its ability to remove cuttings from the borehole in terms of percentage of soil removed as opposed to displaced into the surrounding soil medium. There are several reamer configurations and each one functions differently in the borehole. However, they all serve the same purpose; that being to make space to accommodate the product pipe. In relation to the development of surface heave, a method of quantifying reamer behavior would allow a more effective comparison and selection of reamers to limit ground displacement for a given set of installation or project parameters.

Additional research should be conducted into the relationship between surface heave and borehole pressure. During the field investigation stage of this research, it was difficult to effectively measure borehole pressure; therefore mud flow rate was incorporated as substitute factor. Recent developments in downhole tooling now make it possible to accurately measure borehole pressure on directionally drilled installations. This would allow the inclusion of borehole pressure as a factor, in addition to mud flow rate. Borehole pressure could also be related to overburden stresses as another means to predict or understand the surface heave mechanism.

Further research should be conducted into refining the method of determining the proper backream rate based on the mud pump rate, soil classification, and reamer diameter. The speed at which the reamer is pulled back to the drill rig directly affects pressure in the borehole and the ability of the mud system to effectively remove or circulate cuttings or soil within the borehole. In examination of the industry accepted formula for determination of backream rate on completion of the field installations, it was determined that the backream rate suggested by the formula could not be achieved based on the parameters of the given installation. Therefore, suggesting that for shallow small diameter installations conducted with smaller drilling rigs a different method of determining backream rate may be required. By examining the relationship between backream rate, borehole pressure, reamer diameter, and reamer configuration, a better understanding of an effective backream rate may be found.

APPENDIX A

UNIVERSITY OF ALBERTA
CONSTRUCTION ENGINEERING AND MANAGEMENT

UNDERSTANDING FACTORS AFFECTING GROUND MOVEMENTS IN HORIZONTAL DIRECTIONAL DRILLING

There are several factors that may affect ground movements resulting from horizontal directionally drilled installations including; soil type, soil density, back ream penetration rate, borehole pressure, reamer type, reamer diameter, depth of cover, and annular space. The purpose of this questionnaire is to determine which factors are considered to have the most influence on the magnitude of ground movements associated with horizontal directionally drilled installations.

Please rate the following factors against each other utilizing the following scale:

EL = Extremely Less Important
SL = Slightly Less Important
EI = Equally Important
SM = Strongly More Important
EM = Extremely More Important

	EL	SL	EI	SM	EM
1. How would you rate *soil type* against *soil density*?	☐	☐	☐	☐	☐
2. How would you rate *soil type* against *back ream penetration rate*?	☐	☐	☐	☐	☐
3. How would you rate *soil type* against *borehole pressure*?	☐	☐	☐	☐	☐
4. How would you rate *soil type* against *reamer type*?	☐	☐	☐	☐	☐
5. How would you rate *soil type* against *reamer diameter*?	☐	☐	☐	☐	☐
6. How would you rate *soil type* against *depth of cover*?	☐	☐	☐	☐	☐
7. How would you rate *soil type* against *annular space*?	☐	☐	☐	☐	☐
8. How would you rate *soil density* against *back ream penetration rate*?	☐	☐	☐	☐	☐
9. How would you rate *soil density* against *borehole pressure*?	☐	☐	☐	☐	☐

	EL	SL	EI	SM	EM
10. How would you rate *soil density* against *reamer type*?	☐	☐	☐	☐	☐
11. How would you rate *soil density* against *reamer diameter*?	☐	☐	☐	☐	☐
12. How would you rate *soil density* against *depth of cover*?	☐	☐	☐	☐	☐
13. How would you rate *soil density* against *annular space*?	☐	☐	☐	☐	☐
14. How would you rate *back ream penetration rate* against *borehole pressure*?	☐	☐	☐	☐	☐
15. How would you rate *back ream penetration rate* against *reamer type*?	☐	☐	☐	☐	☐
16. How would you rate *back ream penetration rate* against *reamer diameter*?	☐	☐	☐	☐	☐
17. How would you rate *back ream penetration rate* against *depth of cover*?	☐	☐	☐	☐	☐
18. How would you rate *back ream penetration rate* against *annular space*?	☐	☐	☐	☐	☐
19. How would you rate *borehole pressure* against *reamer type*?	☐	☐	☐	☐	☐
20. How would you rate *borehole pressure* against *reamer diameter*?	☐	☐	☐	☐	☐
21. How would you rate *borehole pressure* against *depth of cover*?	☐	☐	☐	☐	☐
22. How would you rate *borehole pressure* against *annular space*?	☐	☐	☐	☐	☐
23. How would you rate *reamer type* against *reamer diameter*?	☐	☐	☐	☐	☐
24. How would you rate *reamer type* against *depth of cover*?	☐	☐	☐	☐	☐
25. How would you rate *reamer type* against *annular space*?	☐	☐	☐	☐	☐
26. How would you rate *reamer diameter* against *depth of cover*?	☐	☐	☐	☐	☐
27. How would you rate *reamer diameter* against *annular space*?	☐	☐	☐	☐	☐
28. How would you rate *depth of cover* against *annular space*?	☐	☐	☐	☐	☐

APPENDIX B

Questionnaire Number 1

Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS
SC	1	1	3	1/3	3	5	3	3
SD	1	1	1/3	1/3	3	3	1/3	3
BRR	1/3	3	1	1	3	1	1/5	5
BP	3	3	1	1	3	5	1	5
RT	1/3	1/3	1/3	1/3	1	5	1/3	3
RD	1/5	1.3	1	1/5	1/5	1	1	1
DC	1/3	3	5	3	3	1	1	5
AS	1/3	1/3	1/5	1/3	1/3	1	1/5	1

Sums	6.534	12.001	11.867	4.400	16.534	22.000	7.067	26.000

Normalized Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS	Average
SC	0.153	0.083	0.253	0.076	0.181	0.227	0.425	0.115	0.189
SD	0.153	0.083	0.028	0.076	0.181	0.136	0.047	0.115	0.103
BRR	0.051	0.250	0.084	0.227	0.181	0.045	0.028	0.192	0.133
BP	0.459	0.250	0.084	0.227	0.181	0.227	0.142	0.192	0.220
RT	0.051	0.028	0.028	0.076	0.060	0.227	0.047	0.115	0.079
RD	0.031	0.028	0.084	0.045	0.012	0.045	0.142	0.038	0.053
DC	0.051	0.250	0.421	0.227	0.181	0.045	0.142	0.192	0.189
AS	0.051	0.028	0.017	0.045	0.020	0.045	0.028	0.038	0.034

Multiplication of Criteria Weight Matrix and Average Weights:

	1.935
	0.972
	1.223
	2.091
	0.726
	0.541
	1.904
	0.319
λ_{max} =	9.710

$$CI = \frac{9.710 - 8}{8 - 1} = 0.244$$

$$RI = \frac{1.98\,(8 - 2)}{8} = 1.485$$

$$CR = \frac{CI}{RI} = \frac{0.244}{1.485} = 16.5\%$$

Questionnaire Number 2

Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS
SC	1	3	1/3	1/3	3	3	1/3	3
SD	1/3	1	1/3	1/3	3	5	1/3	3
BRR	3	3	1	1	3	5	1	3
BP	3	3	1	1	5	5	1	3
RT	1/3	1/3	1/3	1/5	1	5	1/3	1
RD	1/3	1/5	1/5	1/5	1/5	1	1/5	1/5
DC	3	3	1	1	1	5	1	1
AS	1/3	1/3	1/3	1/3	1/3	5	1	1

Sums	11.334	13.868	4.533	4.400	19.200	34.000	5.200	15.200

Normalized Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS	Average
SC	0.088	0.216	0.074	0.076	0.156	0.088	0.064	0.197	0.120
SD	0.029	0.072	0.074	0.076	0.156	0.147	0.064	0.197	0.102
BRR	0.265	0.216	0.221	0.227	0.156	0.147	0.192	0.197	0.203
BP	0.265	0.216	0.221	0.227	0.260	0.147	0.192	0.197	0.216
RT	0.029	0.024	0.074	0.045	0.052	0.147	0.064	0.066	0.063
RD	0.029	0.014	0.044	0.045	0.010	0.029	0.038	0.013	0.028
DC	0.265	0.216	0.221	0.227	0.156	0.147	0.192	0.066	0.186
AS	0.029	0.024	0.074	0.076	0.052	0.147	0.192	0.066	0.082

Multiplication of Criteria Weight Matrix and Average Weights:

	1.147
	0.920
	1.847
	1.972
	0.533
	0.238
	1.682
	0.685
λ_{max} =	9.024

$$CI = \frac{9.024 - 8}{8 - 1} = 0.146$$

$$RI = \frac{1.98\,(8-2)}{8} = 1.485$$

$$CR = \frac{CI}{RI} = \frac{0.146}{1.485} = 9.8\%$$

Questionnaire Number 3

Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS
SC	1	1	1/5	1/5	1/3	1	1/5	1/3
SD	1	1	1	1	1	1/3	1	1/5
BRR	5	1	1	1	5	1	1	1
BP	5	1	1	1	5	5	1	3
RT	3	1	1/5	1/5	1	3	1/5	1/3
RD	1	3	1	1/5	1/3	1	1/5	1/5
DC	5	1	1	1	5	5	1	1
AS	3	5	1	1/3	3	5	1	1

Sums	24.001	14.000	6.400	4.933	20.667	21.333	5.600	7.067

Normalized Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS	Average
SC	0.042	0.071	0.031	0.041	0.016	0.047	0.036	0.047	0.041
SD	0.042	0.071	0.156	0.203	0.048	0.016	0.179	0.028	0.093
BRR	0.208	0.071	0.156	0.203	0.242	0.047	0.179	0.142	0.156
BP	0.208	0.071	0.156	0.203	0.242	0.234	0.179	0.425	0.215
RT	0.125	0.071	0.031	0.041	0.048	0.141	0.036	0.047	0.068
RD	0.042	0.214	0.156	0.041	0.016	0.047	0.036	0.028	0.072
DC	0.208	0.071	0.156	0.203	0.242	0.234	0.179	0.142	0.179
AS	0.125	0.357	0.156	0.068	0.145	0.234	0.179	0.142	0.176

Multiplication of Criteria Weight Matrix and Average Weights:

	0.398
	0.811
	1.435
	2.077
	0.670
	0.685
	1.725
	1.736
$\lambda_{max} =$	9.537

$$CI = \frac{9.537 - 8}{8 - 1} = 0.219$$

$$RI = \frac{1.98\,(8 - 2)}{8} = 1.485$$

$$CR = \frac{CI}{RI} = \frac{0.219}{1.485} = 14.8\%$$

Questionnaire Number 4

Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS
SC	1	5	3	1	1	1	1/3	1
SD	1/5	1	1/5	1/5	1/5	1	1	1
BRR	1/3	5	1	1/5	1/5	1/3	1/5	1/3
BP	1	5	5	1	5	5	5	1
RT	1	5	5	1/5	1	5	3	3
RD	1	1	3	1/5	1/5	1	1/5	1
DC	3	1	5	1/5	1/3	5	1	3
AS	1	1	3	1	1/3	1	1/3	1

Sums	8.534	24.000	25.201	4.000	8.267	19.333	11.067	11.333

Normalized Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS	Average
SC	0.117	0.208	0.119	0.250	0.121	0.052	0.030	0.088	0.123
SD	0.023	0.042	0.008	0.050	0.024	0.052	0.090	0.088	0.047
BRR	0.039	0.208	0.040	0.050	0.024	0.017	0.018	0.029	0.053
BP	0.117	0.208	0.198	0.250	0.605	0.259	0.452	0.088	0.272
RT	0.117	0.208	0.198	0.050	0.121	0.259	0.271	0.265	0.186
RD	0.117	0.042	0.119	0.050	0.024	0.052	0.018	0.088	0.064
DC	0.352	0.042	0.198	0.050	0.040	0.259	0.090	0.265	0.162
AS	0.117	0.042	0.119	0.250	0.040	0.052	0.030	0.088	0.092

Multiplication of Criteria Weight Matrix and Average Weights:

	1.187
	0.492
	0.506
	3.049
	1.948
	0.610
	1.557
	0.874
λ_{max} =	10.225

$$CI = \frac{10.225 - 8}{8 - 1} = 0.318$$

$$RI = \frac{1.98\,(8 - 2)}{8} = 1.485$$

$$CR = \frac{CI}{RI} = \frac{0.318}{1.485} = 21.4\%$$

Questionnaire Number 5

Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS
SC	1	3	3	1/3	1	3	1	1/3
SD	1/3	1	3	1/3	1	3	1	1/3
BRR	1/3	1/3	1	1/3	1	3	3	1
BP	3	3	3	1	3	3	3	3
RT	1	1	1	1/3	1	3	1	1/3
RD	1/3	1/3	1/3	1/3	1/3	1	1	1
DC	1	1	1/3	1/3	1	1	1	1/3
AS	3	3	1	1/3	3	1	3	1

Sums	10.001	12.667	12.667	3.333	11.334	18.000	14.000	7.333

Normalized Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS	Average
SC	0.100	0.237	0.237	0.100	0.088	0.167	0.071	0.045	0.131
SD	0.033	0.079	0.237	0.100	0.088	0.167	0.071	0.045	0.103
BRR	0.033	0.026	0.079	0.100	0.088	0.167	0.214	0.136	0.106
BP	0.300	0.237	0.237	0.300	0.265	0.167	0.214	0.409	0.266
RT	0.100	0.079	0.079	0.100	0.088	0.167	0.071	0.045	0.091
RD	0.033	0.026	0.026	0.100	0.029	0.056	0.071	0.136	0.060
DC	0.100	0.079	0.026	0.100	0.088	0.056	0.071	0.045	0.071
AS	0.300	0.237	0.079	0.100	0.265	0.056	0.214	0.136	0.173

Multiplication of Criteria Weight Matrix and Average Weights:

	1.243
	0.951
	0.928
	2.468
	0.827
	0.536
	0.637
	1.613
$\lambda_{max} =$	9.202

$$CI = \frac{9.202 - 8}{8 - 1} = 0.116$$

$$RI = \frac{1.98\,(8 - 2)}{8} = 1.485$$

$$CR = \frac{CI}{RI} = \frac{0.116}{1.485} = 11.6\%$$

Questionnaire Number 6

Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS
SC	1	1	3	1	1	1/3	1/3	1/3
SD	1	1	3	1	3	1/3	1/3	1/3
BRR	1/3	1/3	1	1/3	1	1/3	1/3	1/3
BP	1	1	3	1	3	1	1/3	1/3
RT	1	1/3	1	1/3	1	1/3	1/3	1/3
RD	3	3	3	1	3	1	1/3	1/3
DC	3	3	3	3	3	3	1	1
AS	3	3	3	3	3	3	1	1

Sums	13.334	12.668	20.001	10.667	18.001	9.334	4.000	4.000

Normalized Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS	Average
SC	0.075	0.079	0.150	0.094	0.056	0.036	0.083	0.083	0.082
SD	0.075	0.079	0.150	0.094	0.167	0.036	0.083	0.083	0.096
BRR	0.025	0.026	0.050	0.031	0.056	0.036	0.083	0.083	0.049
BP	0.075	0.079	0.150	0.094	0.167	0.107	0.083	0.083	0.105
RT	0.075	0.026	0.050	0.031	0.056	0.036	0.083	0.083	0.055
RD	0.225	0.237	0.150	0.094	0.167	0.107	0.083	0.083	0.143
DC	0.225	0.237	0.150	0.281	0.167	0.321	0.250	0.250	0.235
AS	0.225	0.237	0.150	0.281	0.167	0.321	0.250	0.250	0.235

Multiplication of Criteria Weight Matrix and Average Weights:

	0.689
	0.799
	0.403
	0.894
	0.457
	1.250
	2.060
	2.060
$\lambda_{max} =$	8.610

$$CI = \frac{8.610 - 8}{8 - 1} = 0.087$$

$$RI = \frac{1.98\,(8 - 2)}{8} = 1.485$$

$$CR = \frac{CI}{RI} = \frac{0.087}{1.485} = 5.8\%$$

Questionnaire Number 7

Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS
SC	1	1/3	1/5	1/5	3	1	3	3
SD	3	1	3	3	3	1	1	1
BRR	5	1/3	1	3	3	1	1/5	3
BP	5	1/3	1/3	1	1/3	1/3	1/3	3
RT	1/3	1/3	1/3	3	1	1/3	1/3	3
RD	1	1	1	3	3	1	1/5	3
DC	1/3	1	5	3	3	5	1	3
AS	1/3	1	1/3	1/3	1/3	1/3	1/3	1

Sums	16.000	5.333	11.200	16.534	16.667	10.000	6.400	20.000

Normalized Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS	Average
SC	0.062	0.062	0.018	0.012	0.180	0.100	0.469	0.150	0.132
SD	0.188	0.188	0.268	0.181	0.180	0.100	0.156	0.050	0.164
BRR	0.312	0.063	0.089	0.181	0.180	0.100	0.031	0.150	0.138
BP	0.312	0.063	0.030	0.060	0.020	0.033	0.052	0.150	0.090
RT	0.021	0.063	0.030	0.181	0.060	0.033	0.052	0.150	0.074
RD	0.062	0.188	0.089	0.181	0.180	0.100	0.031	0.150	0.123
DC	0.021	0.188	0.446	0.181	0.180	0.500	0.156	0.150	0.228
AS	0.021	0.188	0.030	0.020	0.020	0.033	0.052	0.050	0.052

Multiplication of Criteria Weight Matrix and Average Weights:

	1.415
	1.868
	1.666
	1.146
	0.761
	1.249
	2.388
	0.477
$\lambda_{max} =$	10.970

$$CI = \frac{10.970 - 8}{8 - 1} = 0.424$$

$$RI = \frac{1.98\,(8-2)}{8} = 1.485$$

$$CR = \frac{CI}{RI} = \frac{0.424}{1.485} = 28.6\%$$

Questionnaire Number 8

Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS
SC	1	1/3	1	1/3	1/5	1/3	3	1/3
SD	3	1	3	1	3	5	3	3
BRR	1	1/3	1	1	5	3	3	3
BP	3	1	1	1	5	5	3	3
RT	5	1/3	1/5	1/5	1	1	1/3	1
RD	3	1/5	1/3	1/5	1/3	1/3	1/3	1
DC	1/3	1/3	1/3	1/3	3	3	1	3
AS	3	1/3	1/3	1/3	1	1	1/3	1

Sums	19.335	3.867	7.200	4.400	18.534	21.334	14.000	15.333

Normalized Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS	Average
SC	0.052	0.086	0.139	0.076	0.011	0.016	0.214	0.022	0.077
SD	0.155	0.259	0.417	0.227	0.162	0.234	0.214	0.196	0.233
BRR	0.052	0.086	0.139	0.227	0.270	0.141	0.214	0.196	0.166
BP	0.155	0.259	0.139	0.227	0.270	0.234	0.214	0.196	0.212
RT	0.259	0.086	0.028	0.045	0.054	0.141	0.024	0.065	0.088
RD	0.155	0.052	0.046	0.045	0.018	0.047	0.024	0.065	0.057
DC	0.017	0.086	0.046	0.076	0.162	0.141	0.071	0.196	0.099
AS	0.155	0.086	0.046	0.076	0.054	0.047	0.024	0.065	0.069

Multiplication of Criteria Weight Matrix and Average Weights:

	0.748
	2.224
	1.646
	2.068
	0.897
	0.563
	0.969
	0.681
$\lambda_{max} =$	9.795

$$CI = \frac{9.795 - 8}{8 - 1} = 0.256$$

$$RI = \frac{1.98\,(8 - 2)}{8} = 1.485$$

$$CR = \frac{CI}{RI} = \frac{0.256}{1.485} = 17.3\%$$

Questionnaire Number 9

Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS
SC	1	1/3	1/3	5	1	3	1	5
SD	3	1	3	5	5	5	5	5
BRR	3	1/3	1	3	5	5	1	5
BP	1/5	1/5	1/3	1	1/3	1/3	1/3	1
RT	1	1/5	1/5	3	1	3	1	3
RD	1/3	1/5	1/5	3	1/3	1	1	3
DC	1	1/5	1	3	1	1	1	5
AS	1/5	1/5	1/5	1	1/3	1/3	1/5	1

Sums	9.734	2.667	6.267	24.001	14.000	18.667	10.533	28.000

Normalized Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS	Average
SC	0.103	0.125	0.053	0.208	0.071	0.161	0.095	0.179	0.124
SD	0.308	0.375	0.479	0.208	0.357	0.268	0.475	0.179	0.331
BRR	0.308	0.125	0.160	0.125	0.357	0.268	0.095	0.179	0.202
BP	0.021	0.075	0.053	0.042	0.024	0.018	0.032	0.036	0.037
RT	0.103	0.075	0.032	0.125	0.071	0.161	0.095	0.107	0.096
RD	0.034	0.075	0.032	0.125	0.024	0.054	0.095	0.107	0.068
DC	0.103	0.075	0.160	0.125	0.071	0.054	0.095	0.179	0.108
AS	0.021	0.075	0.032	0.042	0.024	0.018	0.019	0.036	0.033

Multiplication of Criteria Weight Matrix and Average Weights:

	1.063
	3.023
	1.893
	0.320
	0.851
	0.568
	0.943
	0.278
$\lambda_{max} =$	8.939

$$CI = \frac{8.939 - 8}{8 - 1} = 0.134$$

$$RI = \frac{1.98\,(8-2)}{8} = 1.485$$

$$CR = \frac{CI}{RI} = \frac{0.134}{1.485} = 9.0\%$$

Questionnaire Number 10

Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS
SC	1	1/5	1/5	1/5	1	1	1/5	1/5
SD	5	1	1/3	1/3	1	3	1	3
BRR	5	3	1	5	3	5	1	5
BP	5	3	1/5	1	3	5	1	5
RT	1	1	1/3	1/3	1	3	1/3	3
RD	1	1/3	1/5	1/5	1/3	1	1/5	3
DC	5	1	1	1	3	5	1	5
AS	5	1/3	1/5	1/5	1/3	1/3	1/5	1

Sums	28.000	9.867	3.467	8.267	12.667	23.333	4.933	25.200

Normalized Criteria Weight Matrix:

	SC	SD	BRR	BP	RT	RD	DC	AS	Average
SC	0.036	0.020	0.058	0.024	0.079	0.043	0.041	0.008	0.039
SD	0.179	0.101	0.096	0.040	0.079	0.129	0.203	0.119	0.118
BRR	0.179	0.304	0.288	0.605	0.237	0.214	0.203	0.198	0.279
BP	0.179	0.304	0.058	0.121	0.237	0.214	0.203	0.198	0.189
RT	0.036	0.101	0.096	0.040	0.079	0.129	0.068	0.119	0.083
RD	0.036	0.034	0.058	0.024	0.026	0.043	0.041	0.119	0.048
DC	0.179	0.101	0.288	0.121	0.237	0.214	0.203	0.198	0.193
AS	0.179	0.034	0.058	0.024	0.026	0.014	0.041	0.040	0.052

Multiplication of Criteria Weight Matrix and Average Weights:

	0.336
	1.041
	2.712
	1.732
	0.759
	0.441
	1.719
	0.460
$\lambda_{max} =$	9.198

$$CI = \frac{9.198 - 8}{8 - 1} = 0.171$$

$$RI = \frac{1.98\,(8 - 2)}{8} = 1.485$$

$$CR = \frac{CI}{RI} = \frac{0.171}{1.485} = 11.5\%$$

APPENDIX C

Field Survey Data: Installation 1

Reamer	Fluted							
Depth	900 mm		1,200 mm		1,200 mm		900 mm	
BRR	6 minutes/rod							
Mud	50 liters/rod				100 liters/rod			
	Point 1		**Point 2**		**Point 3**		**Point 4 - Drill**	
	(m)	(mm)	(m)	(mm)	(m)	(mm)	(m)	(mm)
Initial	1.505		1.421		1.418		1.644	
	1.515		1.436		1.421		1.663	
	1.506		1.435		1.422		1.669	
	1.498		1.437		1.413		1.662	
	1.499		1.442		1.435		1.646	
		Movement		Movement		Movement		Movement
Drill	1.500	0.500	1.419	0.200	1.417	0.100	1.640	0.400
	1.508	0.700	1.434	0.200	1.419	0.200	1.658	0.500
	1.499	0.700	1.434	0.100	1.421	0.100	1.666	0.300
	1.494	0.400	1.433	0.400	1.412	0.100	1.656	0.600
	1.497	0.200	1.441	0.100	1.434	0.100	1.643	0.300
Ream	1.454	4.600	1.394	2.500	1.397	2.000	1.602	3.800
	1.455	5.300	1.406	2.800	1.392	2.700	1.613	4.500
	1.439	6.000	1.402	3.200	1.394	2.700	1.609	5.700
	1.437	5.700	1.403	3.000	1.390	2.200	1.606	5.000
	1.447	5.000	1.412	2.900	1.408	2.600	1.607	3.600

Volume of Drilling Fluid (liters)

Drilling:	943
Reaming:	12929

Field Survey Data: Installation 2

Reamer	Fluted							
Depth	900 mm		1,200 mm		1,200 mm		900 mm	
BRR	2 minutes/rod							
Mud	50 liters/rod				100 liters/rod			
	Point 1		**Point 2**		**Point 3**		**Point 4 - Drill**	
Day 1	(m)	(mm)	(m)	(mm)	(m)	(mm)	(m)	(mm)
Initial	1.542		1.400		1.370		1.605	
	1.535		1.401		1.365		1.601	
	1.528		1.405		1.368		1.592	
	1.526		1.412		1.375		1.595	
	1.524		1.403		1.390		1.590	
Day 2		Movement		Movement		Movement		Movement
Drill	1.537	0.500	1.399	0.100	1.370	0.000	1.604	0.100
	1.532	0.300	1.399	0.200	1.365	0.000	1.600	0.100
	1.526	0.200	1.403	0.200	1.367	0.100	1.589	0.300
	1.524	0.200	1.410	0.200	1.373	0.200	1.593	0.200
	1.523	0.100	1.402	0.100	1.389	0.100	1.589	0.100
Day 2								
Initial	1.568		1.429		1.408		1.634	
	1.565		1.428		1.393		1.628	
	1.556		1.433		1.397		1.619	
	1.554		1.440		1.403		1.622	
	1.555		1.432		1.420		1.618	
Day 2								
Ream	1.548	2.000	1.391	3.800	1.382	2.600	1.595	3.900
	1.525	4.000	1.390	3.800	1.363	3.000	1.588	4.000
	1.515	4.100	1.395	3.800	1.366	3.100	1.583	3.600
	1.514	4.000	1.406	3.400	1.378	2.500	1.592	3.000
	1.521	3.400	1.407	2.500	1.400	2.000	1.598	2.000

Volume of Drilling Fluid (liters)

Drilling:	423
Reaming:	3409

Field Survey Data: Installation 3

Reamer	Spiral Compactor							
Depth	900 mm		1,200 mm		1,200 mm		900 mm	
BRR	2 minutes/rod							
Mud	50 liters/rod				100 liters/rod			
	Point 1		**Point 2**		**Point 3**		**Point 4 - Drill**	
	(m)	(mm)	(m)	(mm)	(m)	(mm)	(m)	(mm)
Initial	1.526		1.394		1.362		1.583	
	1.530		1.401		1.367		1.592	
	1.527		1.401		1.375		1.599	
	1.528		1.412		1.366		1.586	
	1.524		1.415		1.362		1.578	
		Movement		Movement		Movement		Movement
Drill	1.525	0.100	1.393	0.100	1.361	0.100	1.582	0.100
	1.528	0.200	1.399	0.200	1.365	0.200	1.590	0.200
	1.525	0.200	1.398	0.300	1.373	0.200	1.594	0.500
	1.526	0.200	1.409	0.300	1.366	0.000	1.585	0.100
	1.523	0.100	1.413	0.200	1.361	0.100	1.577	0.100
Ream	1.478	4.700	1.341	5.200	1.323	3.800	1.540	4.200
	1.473	5.500	1.346	5.300	1.325	4.000	1.538	5.200
	1.470	5.500	1.346	5.200	1.332	4.100	1.545	4.900
	1.479	4.700	1.365	4.400	1.328	3.800	1.546	3.900
	1.486	3.700	1.382	3.100	1.332	2.900	1.548	2.900

Volume of Drilling Fluid (liters)

Drilling:	472
Reaming:	3525

Field Survey Data: Installation 4

Reamer	Spiral Compactor							
Depth	900 mm		1,200 mm		1,200 mm		900 mm	
BRR	6 minutes/rod							
Mud	50 liters/rod				100 liters/rod			
	Point 1		**Point 2**		**Point 3**		**Point 4 - Drill**	
	(m)	(mm)	(m)	(mm)	(m)	(mm)	(m)	(mm)
Initial	1.595		1.503		1.453		1.648	
	1.602		1.505		1.455		1.650	
	1.592		1.485		1.435		1.641	
	1.600		1.494		1.428		1.637	
	1.584		1.496		1.430		1.642	
		Movement		Movement		Movement		Movement
Drill	1.595	0.000	1.502	0.100	1.452	0.100	1.648	0.000
	1.602	0.000	1.505	0.000	1.454	0.100	1.649	0.100
	1.590	0.200	1.484	0.100	1.434	0.100	1.639	0.200
	1.598	0.200	1.494	0.000	1.427	0.100	1.637	0.000
	1.582	0.200	1.495	0.100	1.430	0.000	1.642	0.000
Ream	1.543	5.200	1.453	4.900	1.416	3.600	1.592	5.600
	1.542	6.000	1.447	5.800	1.413	4.100	1.589	6.000
	1.532	5.800	1.423	6.100	1.390	4.400	1.581	5.800
	1.545	5.300	1.435	5.900	1.389	3.800	1.585	5.200
	1.540	4.200	1.445	5.000	1.398	3.200	1.613	2.900

Volume of Drilling Fluid (liters)

Drilling:	425
Reaming:	13492

APPENDIX D

Preprocessed Vectors for Neural Network Development

File: 20all.nna

Installation	Reamer	Depth	BRR	Flow	Heave
1-1 A	0.6	0.45	0.6	0.25	0.565
1-1 B	0.6	0.45	0.6	0.25	0.585
1-4 A	0.6	0.45	0.6	0.5	0.51
1-4 B	0.6	0.45	0.6	0.5	0.535
2-1 A	0.6	0.45	0.2	0.25	0.405
2-1 B	0.6	0.45	0.2	0.25	0.405
2-4 A	0.6	0.45	0.2	0.5	0.38
2-4 B	0.6	0.45	0.2	0.5	0.33
3-1 A	0.15	0.45	0.2	0.25	0.55
3-1 B	0.15	0.45	0.2	0.25	0.51
3-4 A	0.15	0.45	0.2	0.5	0.505
3-4 B	0.15	0.45	0.2	0.5	0.44
4-1 A	0.15	0.45	0.6	0.25	0.59
4-1 B	0.15	0.45	0.6	0.25	0.555
4-4 A	0.15	0.45	0.6	0.5	0.59
4-4 B	0.15	0.45	0.6	0.5	0.55
1-2 A	0.6	0.6	0.6	0.25	0.3
1-2 B	0.6	0.6	0.6	0.25	0.31
1-3 A	0.6	0.6	0.6	0.5	0.27
1-3 B	0.6	0.6	0.6	0.5	0.245
2-2 A	0.6	0.6	0.2	0.25	0.38
2-2 B	0.6	0.6	0.2	0.25	0.36
2-3 A	0.6	0.6	0.2	0.5	0.305
2-3 B	0.6	0.6	0.2	0.5	0.28
3-2 A	0.15	0.6	0.2	0.25	0.525
3-2 B	0.15	0.6	0.2	0.25	0.48
3-3 A	0.15	0.6	0.2	0.5	0.405
3-3 B	0.15	0.6	0.2	0.5	0.395
4-2 A	0.15	0.6	0.6	0.25	0.595
4-2 B	0.15	0.6	0.6	0.25	0.6
4-3 A	0.15	0.6	0.6	0.5	0.425
4-3 B	0.15	0.6	0.6	0.5	0.41
Average	**0.375**	**0.525**	**0.4**	**0.375**	**0.447**

Note: Average values used to construct statistically comparable training and test sets.

Configuration 1 – Training and Test Data Set

File: 20lrn1.nna
Training Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.25	0.565
0.6	0.45	0.6	0.25	0.585
0.6	0.45	0.6	0.5	0.51
0.6	0.45	0.6	0.5	0.535
0.6	0.45	0.2	0.25	0.405
0.6	0.45	0.2	0.5	0.38
0.15	0.45	0.2	0.25	0.55
0.15	0.45	0.2	0.25	0.51
0.15	0.45	0.2	0.5	0.44
0.15	0.45	0.6	0.25	0.59
0.15	0.45	0.6	0.25	0.555
0.15	0.45	0.6	0.5	0.59
0.15	0.45	0.6	0.5	0.55
0.6	0.6	0.6	0.25	0.3
0.6	0.6	0.6	0.25	0.31
0.6	0.6	0.6	0.5	0.27
0.6	0.6	0.2	0.25	0.38
0.6	0.6	0.2	0.25	0.36
0.6	0.6	0.2	0.5	0.305
0.6	0.6	0.2	0.5	0.28
0.15	0.6	0.2	0.25	0.525
0.15	0.6	0.2	0.25	0.48
0.15	0.6	0.2	0.5	0.395
0.15	0.6	0.6	0.25	0.6
0.15	0.6	0.6	0.5	0.425
0.15	0.6	0.6	0.5	0.41

File: 20tst1.nna
Test Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.2	0.5	0.33
0.15	0.45	0.2	0.5	0.505
0.6	0.6	0.6	0.5	0.245
0.15	0.6	0.6	0.25	0.595
0.6	0.45	0.2	0.25	0.405
0.15	0.6	0.2	0.5	0.405

Averages:					
Training	0.375	0.525	0.415	0.365	0.454
Test	0.375	0.525	0.333	0.417	0.414
Population	**0.375**	**0.525**	**0.4**	**0.375**	**0.447**

Configuration 2 – Training and Test Data Set

File: 20lrn2.nna
Training Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.25	0.565
0.6	0.45	0.6	0.5	0.51
0.6	0.45	0.6	0.5	0.535
0.6	0.45	0.2	0.25	0.405
0.6	0.45	0.2	0.25	0.405
0.6	0.45	0.2	0.5	0.38
0.6	0.45	0.2	0.5	0.33
0.15	0.45	0.2	0.25	0.55
0.15	0.45	0.2	0.25	0.51
0.15	0.45	0.2	0.5	0.505
0.15	0.45	0.6	0.25	0.59
0.15	0.45	0.6	0.25	0.555
0.15	0.45	0.6	0.5	0.59
0.15	0.45	0.6	0.5	0.55
0.6	0.6	0.6	0.25	0.3
0.6	0.6	0.6	0.5	0.27
0.6	0.6	0.6	0.5	0.245
0.6	0.6	0.2	0.25	0.36
0.6	0.6	0.2	0.5	0.305
0.6	0.6	0.2	0.5	0.28
0.15	0.6	0.2	0.25	0.525
0.15	0.6	0.2	0.25	0.48
0.15	0.6	0.2	0.5	0.395
0.15	0.6	0.6	0.25	0.6
0.15	0.6	0.6	0.5	0.425
0.15	0.6	0.6	0.5	0.41

File: 20tst2.nna
Test Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.25	0.585
0.15	0.45	0.2	0.5	0.44
0.6	0.6	0.6	0.25	0.31
0.15	0.6	0.2	0.5	0.405
0.6	0.6	0.2	0.25	0.38
0.15	0.6	0.6	0.25	0.595

Averages:					
Training	0.375	0.519	0.4	0.385	0.445
Test	0.375	0.550	0.4	0.333	0.453
Population	**0.375**	**0.525**	**0.4**	**0.375**	**0.447**

Configuration 3 – Training and Test Data Set

File: 20lrn3.nna
Training Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.25	0.585
0.6	0.45	0.6	0.5	0.51
0.6	0.45	0.6	0.5	0.535
0.6	0.45	0.2	0.25	0.405
0.6	0.45	0.2	0.5	0.38
0.6	0.45	0.2	0.5	0.33
0.15	0.45	0.2	0.25	0.55
0.15	0.45	0.2	0.5	0.505
0.15	0.45	0.2	0.5	0.44
0.15	0.45	0.6	0.25	0.59
0.15	0.45	0.6	0.25	0.555
0.15	0.45	0.6	0.5	0.59
0.15	0.45	0.6	0.5	0.55
0.6	0.6	0.6	0.25	0.3
0.6	0.6	0.6	0.25	0.31
0.6	0.6	0.6	0.5	0.245
0.6	0.6	0.2	0.25	0.38
0.6	0.6	0.2	0.25	0.36
0.6	0.6	0.2	0.5	0.305
0.6	0.6	0.2	0.5	0.28
0.15	0.6	0.2	0.25	0.525
0.15	0.6	0.2	0.25	0.48
0.15	0.6	0.2	0.5	0.405
0.15	0.6	0.2	0.5	0.395
0.15	0.6	0.6	0.25	0.6
0.15	0.6	0.6	0.5	0.425

File: 20tst3.nna
Test Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.25	0.565
0.6	0.45	0.2	0.25	0.405
0.6	0.6	0.6	0.5	0.27
0.15	0.6	0.6	0.25	0.595
0.15	0.6	0.6	0.5	0.41
0.15	0.45	0.2	0.25	0.51

Averages:

Training	0.375	0.525	0.385	0.385	0.444
Test	0.375	0.525	0.467	0.333	0.459
Population	**0.375**	**0.525**	**0.4**	**0.375**	**0.447**

Configuration 4 – Training and Test Data Set

File: 20lrn4.nna
Training Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.25	0.565
0.15	0.45	0.2	0.5	0.44
0.6	0.6	0.2	0.25	0.36
0.15	0.6	0.6	0.25	0.6
0.15	0.45	0.2	0.25	0.51
0.15	0.6	0.6	0.5	0.425
0.6	0.45	0.2	0.25	0.405
0.6	0.6	0.2	0.5	0.28
0.15	0.6	0.2	0.25	0.525
0.6	0.45	0.2	0.5	0.38
0.6	0.45	0.2	0.5	0.33
0.15	0.6	0.2	0.5	0.405
0.15	0.6	0.2	0.5	0.395
0.15	0.45	0.6	0.5	0.55
0.6	0.6	0.6	0.25	0.3
0.15	0.6	0.6	0.5	0.41
0.6	0.6	0.6	0.5	0.245
0.6	0.6	0.2	0.25	0.38
0.6	0.6	0.6	0.25	0.31
0.15	0.45	0.2	0.5	0.505
0.6	0.45	0.6	0.25	0.585
0.6	0.45	0.6	0.5	0.51
0.6	0.45	0.2	0.25	0.405
0.15	0.45	0.6	0.25	0.59
0.15	0.45	0.6	0.25	0.555
0.15	0.45	0.6	0.5	0.59

File: 20tst4.nna
Test Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.5	0.535
0.15	0.45	0.2	0.25	0.55
0.6	0.6	0.6	0.5	0.27
0.15	0.6	0.6	0.25	0.595
0.6	0.6	0.2	0.5	0.305
0.15	0.6	0.2	0.25	0.48

Averages:

Training	0.375	0.519	0.4	0.375	0.444
Test	0.375	0.550	0.4	0.375	0.456
Population	**0.375**	**0.525**	**0.4**	**0.375**	**0.447**

Configuration 5 – Training and Test Data Set

File: **20lrn5.nna**
Training Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.25	0.565
0.6	0.45	0.6	0.5	0.51
0.6	0.45	0.6	0.5	0.535
0.6	0.45	0.2	0.25	0.405
0.6	0.45	0.2	0.25	0.405
0.6	0.45	0.2	0.5	0.38
0.6	0.45	0.2	0.5	0.33
0.15	0.45	0.2	0.25	0.55
0.15	0.45	0.2	0.5	0.505
0.15	0.45	0.2	0.5	0.44
0.15	0.45	0.6	0.25	0.555
0.15	0.45	0.6	0.5	0.59
0.15	0.45	0.6	0.5	0.55
0.6	0.6	0.6	0.25	0.3
0.6	0.6	0.6	0.25	0.31
0.6	0.6	0.6	0.5	0.245
0.6	0.6	0.2	0.25	0.38
0.6	0.6	0.2	0.25	0.36
0.6	0.6	0.2	0.5	0.28
0.15	0.6	0.2	0.25	0.525
0.15	0.6	0.2	0.25	0.48
0.15	0.6	0.2	0.5	0.395
0.15	0.6	0.6	0.25	0.595
0.15	0.6	0.6	0.25	0.6
0.15	0.6	0.6	0.5	0.425
0.15	0.6	0.6	0.5	0.41

File: **20tst5.nna**
Test Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.25	0.585
0.15	0.6	0.2	0.5	0.405
0.6	0.6	0.2	0.5	0.305
0.15	0.45	0.6	0.25	0.59
0.6	0.6	0.6	0.5	0.27
0.15	0.45	0.2	0.25	0.51

Averages:

Training	0.375	0.525	0.4	0.375	0.447
Test	0.375	0.525	0.4	0.375	0.444
Population	**0.375**	**0.525**	**0.4**	**0.375**	**0.447**

Configuration 6 – Training and Test Data Set

File: 20lrn6.nna
Training Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.25	0.565
0.6	0.45	0.6	0.25	0.585
0.6	0.45	0.6	0.5	0.535
0.6	0.45	0.2	0.25	0.405
0.6	0.45	0.2	0.25	0.405
0.6	0.45	0.2	0.5	0.38
0.6	0.45	0.2	0.5	0.33
0.15	0.45	0.2	0.25	0.55
0.15	0.45	0.2	0.25	0.51
0.15	0.45	0.2	0.5	0.505
0.15	0.45	0.2	0.5	0.44
0.15	0.45	0.6	0.25	0.59
0.15	0.45	0.6	0.5	0.59
0.6	0.6	0.6	0.25	0.3
0.6	0.6	0.6	0.25	0.31
0.6	0.6	0.6	0.5	0.27
0.6	0.6	0.6	0.5	0.245
0.6	0.6	0.2	0.25	0.36
0.6	0.6	0.2	0.5	0.305
0.15	0.6	0.2	0.25	0.48
0.15	0.6	0.2	0.5	0.405
0.15	0.6	0.2	0.5	0.395
0.15	0.6	0.6	0.25	0.595
0.15	0.6	0.6	0.25	0.6
0.15	0.6	0.6	0.5	0.425
0.15	0.6	0.6	0.5	0.41

File: 20tst6.nna
Test Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.5	0.51
0.15	0.6	0.2	0.25	0.525
0.6	0.6	0.2	0.25	0.38
0.15	0.45	0.6	0.5	0.55
0.6	0.6	0.2	0.5	0.28
0.15	0.45	0.6	0.25	0.555

Averages:

Training	0.375	0.525	0.4	0.375	0.442
Test	0.375	0.525	0.4	0.375	0.467
Population	**0.375**	**0.525**	**0.4**	**0.375**	**0.447**

Configuration 7 – Training and Test Data Set

File: 20lrn7.nna
Training Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.25	0.565
0.6	0.45	0.6	0.25	0.585
0.6	0.45	0.6	0.5	0.51
0.6	0.45	0.6	0.5	0.535
0.6	0.45	0.2	0.25	0.405
0.6	0.45	0.2	0.5	0.38
0.15	0.45	0.2	0.25	0.55
0.15	0.45	0.2	0.25	0.51
0.15	0.45	0.2	0.5	0.44
0.15	0.45	0.2	0.5	0.505
0.15	0.45	0.6	0.25	0.555
0.15	0.45	0.6	0.5	0.59
0.15	0.45	0.6	0.5	0.55
0.6	0.6	0.6	0.25	0.3
0.6	0.6	0.6	0.25	0.31
0.6	0.6	0.6	0.5	0.27
0.6	0.6	0.2	0.25	0.38
0.6	0.6	0.2	0.25	0.36
0.6	0.6	0.2	0.5	0.305
0.6	0.6	0.2	0.5	0.28
0.15	0.6	0.2	0.25	0.525
0.15	0.6	0.2	0.25	0.48
0.15	0.6	0.2	0.5	0.395
0.15	0.6	0.6	0.25	0.6
0.15	0.6	0.6	0.5	0.425
0.15	0.6	0.6	0.5	0.41

File: 20tst7.nna
Test Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.2	0.5	0.33
0.15	0.45	0.6	0.25	0.59
0.6	0.6	0.6	0.5	0.245
0.15	0.6	0.6	0.25	0.595
0.6	0.45	0.2	0.25	0.405
0.15	0.6	0.2	0.5	0.405

Averages:					
Training	0.375	0.525	0.4	0.375	0.451
Test	0.375	0.525	0.4	0.375	0.428
Population	**0.375**	**0.525**	**0.4**	**0.375**	**0.447**

Configuration 8 – Training and Test Data Set

File: 20lrn8.nna
Training Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.25	0.565
0.6	0.45	0.6	0.25	0.585
0.6	0.45	0.6	0.5	0.51
0.6	0.45	0.2	0.5	0.33
0.6	0.45	0.2	0.25	0.405
0.6	0.45	0.2	0.5	0.38
0.15	0.45	0.2	0.25	0.55
0.15	0.45	0.6	0.25	0.59
0.15	0.45	0.2	0.5	0.44
0.15	0.45	0.2	0.5	0.505
0.15	0.45	0.6	0.25	0.555
0.15	0.45	0.6	0.5	0.59
0.15	0.45	0.6	0.5	0.55
0.6	0.6	0.6	0.25	0.3
0.6	0.6	0.6	0.25	0.31
0.6	0.6	0.6	0.5	0.245
0.6	0.6	0.2	0.25	0.38
0.6	0.6	0.2	0.25	0.36
0.6	0.6	0.2	0.5	0.305
0.6	0.6	0.2	0.5	0.28
0.15	0.6	0.2	0.25	0.525
0.15	0.6	0.2	0.25	0.48
0.15	0.6	0.2	0.5	0.395
0.15	0.6	0.6	0.25	0.595
0.15	0.6	0.6	0.5	0.425
0.15	0.6	0.6	0.5	0.41

File: 20tst8.nna
Test Set

Reamer	Depth	BRR	Flow	Heave
0.6	0.45	0.6	0.5	0.535
0.15	0.45	0.2	0.25	0.51
0.6	0.6	0.6	0.5	0.27
0.15	0.6	0.6	0.25	0.6
0.15	0.6	0.2	0.5	0.405
0.6	0.45	0.2	0.25	0.405

Averages:

Training	0.375	0.525	0.4	0.375	0.445
Test	0.375	0.525	0.4	0.375	0.454
Population	**0.375**	**0.525**	**0.4**	**0.375**	**0.447**

APPENDIX E

Summary of Neural Network Training and Development

Varying number of hidden nodes – with file configuration 1

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
1	1	0.3	0.15	0.4	0.618	0.569	15.274	20tst1.nna
2	2	0.3	0.15	0.4	0.461	0.436	12.464	20tst1.nna
3	3	0.3	0.15	0.4	0.279	0.235	5.632	20tst1.nna
4	4	0.3	0.15	0.4	0.281	0.251	6.049	20tst1.nna
5	5	0.3	0.15	0.4	0.351	0.295	6.979	20tst1.nna
6	6	0.3	0.15	0.4	0.398	0.329	7.756	20tst1.nna
7	7	0.3	0.15	0.4	0.350	0.292	6.777	20tst1.nna
8	8	0.3	0.15	0.4	0.343	0.255	6.421	20tst1.nna
9	9	0.3	0.15	0.4	0.343	0.264	5.822	20tst1.nna
10	10	0.3	0.15	0.4	0.305	0.252	6.184	20tst1.nna
11	11	0.3	0.15	0.4	0.335	0.237	6.102	20tst1.nna

Varying number of hidden nodes – with file configuration 2

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
12	1	0.3	0.15	0.4	0.671	0.596	13.463	20tst2.nna
13	2	0.3	0.15	0.4	0.589	0.520	12.055	20tst2.nna
14	3	0.3	0.15	0.4	0.424	0.329	7.273	20tst2.nna
15	4	0.3	0.15	0.4	0.426	0.337	7.732	20tst2.nna
16	5	0.3	0.15	0.4	0.363	0.309	6.947	20tst2.nna
17	6	0.3	0.15	0.4	0.515	0.442	10.306	20tst2.nna
18	7	0.3	0.15	0.4	0.322	0.270	6.003	20tst2.nna
19	8	0.3	0.15	0.4	0.363	0.312	7.050	20tst2.nna
20	9	0.3	0.15	0.4	0.317	0.262	5.672	20tst2.nna

Varying number of hidden nodes – with file configuration 3

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
21	1	0.3	0.15	0.4	0.578	0.528	12.655	20tst3.nna
22	2	0.3	0.15	0.4	0.420	0.360	8.219	20tst3.nna
23	3	0.3	0.15	0.4	0.336	0.264	5.875	20tst3.nna
24	4	0.3	0.15	0.4	0.374	0.313	6.452	20tst3.nna
25	5	0.3	0.15	0.4	0.292	0.252	6.150	20tst3.nna
26	6	0.3	0.15	0.4	0.256	0.241	5.876	20tst3.nna
27	7	0.3	0.15	0.4	0.256	0.240	5.975	20tst3.nna
28	8	0.3	0.15	0.4	0.291	0.256	6.301	20tst3.nna
29	9	0.3	0.15	0.4	0.256	0.210	5.348	20tst3.nna

Varying number of hidden nodes – with file configuration 4

I Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
30	1	0.3	0.15	0.4	0.631	0.495	11.901	20tst4.nna
31	2	0.3	0.15	0.4	0.403	0.364	8.770	20tst4.nna
32	3	0.3	0.15	0.4	0.356	0.303	7.195	20tst4.nna
33	4	0.3	0.15	0.4	0.359	0.346	8.032	20tst4.nna
34	5	0.3	0.15	0.4	0.342	0.322	8.030	20tst4.nna
35	6	0.3	0.15	0.4	0.351	0.345	8.110	20tst4.nna
36	7	0.3	0.15	0.4	0.344	0.331	8.037	20tst4.nna
37	8	0.3	0.15	0.4	0.352	0.351	8.542	20tst4.nna
38	9	0.3	0.15	0.4	0.341	0.335	8.209	20tst4.nna

Varying number of hidden nodes – with file configuration 5

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
39	1	0.3	0.15	0.4	0.452	0.412	10.290	20tst5.nna
40	2	0.3	0.15	0.4	0.503	0.405	9.730	20tst5.nna
41	3	0.3	0.15	0.4	0.367	0.309	7.944	20tst5.nna
42	4	0.3	0.15	0.4	0.500	0.396	9.396	20tst5.nna
43	5	0.3	0.15	0.4	0.315	0.261	6.884	20tst5.nna
44	6	0.3	0.15	0.4	0.295	0.259	6.894	20tst5.nna
45	7	0.3	0.15	0.4	0.264	0.226	6.239	20tst5.nna
46	8	0.3	0.15	0.4	0.311	0.261	6.985	20tst5.nna
47	9	0.3	0.15	0.4	0.310	0.268	7.117	20tst5.nna

Varying number of hidden nodes – with file configuration 6

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
48	1	0.3	0.15	0.4	0.589	0.512	11.613	20tst6.nna
49	2	0.3	0.15	0.4	0.623	0.485	9.562	20tst6.nna
50	3	0.3	0.15	0.4	0.504	0.419	8.847	20tst6.nna
51	4	0.3	0.15	0.4	0.471	0.395	8.165	20tst6.nna
52	5	0.3	0.15	0.4	0.412	0.332	6.542	20tst6.nna
53	6	0.3	0.15	0.4	0.549	0.488	10.116	20tst6.nna
54	7	0.3	0.15	0.4	0.458	0.375	7.581	20tst6.nna
55	8	0.3	0.15	0.4	0.396	0.336	6.937	20tst6.nna
56	9	0.3	0.15	0.4	0.371	0.306	6.021	20tst6.nna

Varying number of hidden nodes – with file configuration 7

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
57	1	0.3	0.15	0.4	0.613	0.573	15.106	20tst7.nna
58	2	0.3	0.15	0.4	0.434	0.391	11.350	20tst7.nna
59	3	0.3	0.15	0.4	0.244	0.179	4.415	20tst7.nna
60	4	0.3	0.15	0.4	0.333	0.249	5.986	20tst7.nna
61	5	0.3	0.15	0.4	0.298	0.229	5.515	20tst7.nna
62	6	0.3	0.15	0.4	0.363	0.272	6.554	20tst7.nna
63	7	0.3	0.15	0.4	0.290	0.237	5.762	20tst7.nna
64	8	0.3	0.15	0.4	0.263	0.193	5.212	20tst7.nna
65	9	0.3	0.15	0.4	0.246	0.176	4.269	20tst7.nna

Using file configuration 7 and 3 hidden nodes – vary momentum

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
66	3	0.3	0.15	0.1	0.256	0.201	5.094	20tst7.nna
67	3	0.3	0.15	0.2	0.251	0.192	4.832	20tst7.nna
68	3	0.3	0.15	0.3	0.247	0.185	4.610	20tst7.nna
69	3	0.3	0.15	0.4	0.244	0.179	4.415	20tst7.nna
70	3	0.3	0.15	0.5	0.241	0.171	4.229	20tst7.nna
71	3	0.3	0.15	0.6	0.238	0.161	4.031	20tst7.nna
72	3	0.3	0.15	0.7	0.237	0.156	3.992	20tst7.nna
73	3	0.3	0.15	0.8	0.241	0.169	4.468	20tst7.nna
74	3	0.3	0.15	0.9	0.257	0.189	5.164	20tst7.nna

Using file configuration 5 and 3 hidden nodes – vary momentum

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
75	3	0.3	0.15	0.1	0.456	0.367	9.094	20tst5.nna
76	3	0.3	0.15	0.2	0.437	0.356	8.903	20tst5.nna
77	3	0.3	0.15	0.3	0.415	0.343	8.672	20tst5.nna
78	3	0.3	0.15	0.4	0.367	0.309	7.944	20tst5.nna
79	3	0.3	0.15	0.5	0.306	0.265	6.903	20tst5.nna
80	3	0.3	0.15	0.6	0.273	0.249	6.448	20tst5.nna
81	3	0.3	0.15	0.7	0.262	0.242	6.251	20tst5.nna
82	3	0.3	0.15	0.8	0.259	0.234	6.044	20tst5.nna
83	3	0.3	0.15	0.9	0.252	0.221	5.702	20tst5.nna

Using file configuration 7, 3 hidden nodes, momentum of 0.7 – vary hidden layer learning coefficient

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
84	3	0.1	0.15	0.7	0.255	0.182	4.543	20tst7.nna
85	3	0.2	0.15	0.7	0.240	0.165	4.043	20tst7.nna
86	3	0.3	0.15	0.7	0.237	0.156	3.992	20tst7.nna
87	3	0.4	0.15	0.7	0.239	0.163	4.317	20tst7.nna
88	3	0.5	0.15	0.7	0.243	0.175	4.712	20tst7.nna
89	3	0.6	0.15	0.7	0.246	0.179	4.901	20tst7.nna
90	3	0.7	0.15	0.7	0.248	0.181	4.985	20tst7.nna
91	3	0.8	0.15	0.7	0.250	0.181	5.014	20tst7.nna
92	3	0.9	0.15	0.7	0.250	0.180	5.011	20tst7.nna

Using file configuration 7, 3 hidden nodes, momentum of 0.7, hidden layer learning coefficient of 0.3 – vary output learning coefficient

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
93	3	0.3	0.1	0.7	0.238	0.159	4.077	20tst7.nna
94	3	0.3	0.2	0.7	0.237	0.159	4.049	20tst7.nna
95	3	0.3	0.3	0.7	0.237	0.161	4.094	20tst7.nna
96	3	0.3	0.4	0.7	0.237	0.163	4.148	20tst7.nna
97	3	0.3	0.5	0.7	0.238	0.166	4.214	20tst7.nna
98	3	0.3	0.6	0.7	0.240	0.169	4.271	20tst7.nna
99	3	0.3	0.7	0.7	0.245	0.176	4.487	20tst7.nna
100	3	0.3	0.8	0.7	0.329	0.283	7.692	20tst7.nna
101	3	0.3	0.9	0.7	0.277	0.250	6.193	20tst7.nna

Using file configuration 7, momentum of 0.7, hidden layer learning coefficient of 0.3, output learning coefficient of 0.15 – confirm number of nodes in hidden layer

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
102	1	0.3	0.15	0.7	0.615	0.547	14.573	20tst7.nna
103	2	0.3	0.15	0.7	0.438	0.384	11.430	20tst7.nna
104	3	0.3	0.15	0.7	0.237	0.156	3.992	20tst7.nna
105	4	0.3	0.15	0.7	0.253	0.218	5.301	20tst7.nna
106	5	0.3	0.15	0.7	0.237	0.187	4.558	20tst7.nna
107	6	0.3	0.15	0.7	0.238	0.164	4.064	20tst7.nna
108	7	0.3	0.15	0.7	0.214	0.152	4.185	20tst7.nna
109	8	0.3	0.15	0.7	0.271	0.209	5.815	20tst7.nna
110	9	0.3	0.15	0.7	0.200	0.153	3.711	20tst7.nna

Looking at Importance with best factor levels - initializing the network prior to each run

Best factor levels:	File configuration 7
	Momentum of 0.7
	Hidden layer learning coefficient of 0.3
	Output learning coefficient of 0.15
	Number of hidden nodes set at 3

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
104	3	0.3	0.15	0.7	0.237	0.156	3.992	20tst7.nna
111	3	0.3	0.15	0.7	0.211	0.155	4.053	20tst7.nna
112	3	0.3	0.15	0.7	0.217	0.173	4.146	20tst7.nna
113	3	0.3	0.15	0.7	0.201	0.155	4.164	20tst7.nna
114	3	0.3	0.15	0.7	0.211	0.158	4.328	20tst7.nna
115	3	0.3	0.15	0.7	0.244	0.159	4.052	20tst7.nna
116	3	0.3	0.15	0.7	0.234	0.180	4.317	20tst7.nna
117	3	0.3	0.15	0.7	0.219	0.162	4.293	20tst7.nna
118	3	0.3	0.15	0.7	0.259	0.165	4.272	20tst7.nna
119	3	0.3	0.15	0.7	0.199	0.153	3.887	20tst7.nna

Using file configuration 7, hidden layer learning coefficient of 0.3, output learning coefficient of 0.15, hidden layers of 3 – confirm momentum

Model Run	Number of Hidden Nodes	Learning Coefficient Hidden Layer	Learning Coefficient Output Layer	Momentum	RMS	MAE	ASE (%)	File
120	3	0.3	0.15	0.1	0.256	0.201	5.094	20tst7.nna
121	3	0.3	0.15	0.2	0.251	0.192	4.832	20tst7.nna
122	3	0.3	0.15	0.3	0.247	0.185	4.610	20tst7.nna
123	3	0.3	0.15	0.4	0.244	0.179	4.415	20tst7.nna
124	3	0.3	0.15	0.5	0.241	0.171	4.229	20tst7.nna
125	3	0.3	0.15	0.6	0.238	0.161	4.031	20tst7.nna
126	3	0.3	0.15	0.7	0.237	0.156	3.992	20tst7.nna
127	3	0.3	0.15	0.8	0.241	0.169	4.468	20tst7.nna
128	3	0.3	0.15	0.9	0.257	0.189	5.164	20tst7.nna

APPENDIX F

Summary of Regression Analysis performed with LINEST Function

In the development of the regression equation parameters input vectors from file 20lrn7.nna were used. The equation was tested on file 20tst7.nna.

Output from LINEST function using Training Vectors:

Flow m4	BRR m3	Depth m2	Reamer m1	Constant b
-0.24898	0.141834	-0.79058	-0.23084	0.989024
0.094447	0.059084	0.157412	0.052519	0.097436
0.731133	0.059685	#N/A	#N/A	#N/A
14.27635	**21**	#N/A	#N/A	#N/A
0.203426	0.074808	#N/A	#N/A	#N/A

r^2 Statistic:	**0.731133**
F_{obs}:	**14.27635**
Degrees of Freedom:	**21**

F Statistic:

v_1:	4
v_2:	21
F_{crit} (0.05):	2.84

Since the F observed value of 14.28 (degrees of freedom $v_1 = 4$ and $v_2 = 21$), is greater than the F critical (0.05) value of 2.84, there is a 95% chance that there is a definite relationship between the installation practice and the development of surface heave.

T Statistics:

	Flow	BRR	Depth	Reamer
t:	2.636229	2.400539	5.022393	4.395276
t_{crit} (0.05):	1.721	1.721	1.721	1.721

Since the observed value of T is greater than the critical value for all four factors, it indicates that all the prescribed factors were useful in the prediction of surface heave, for the specified field conditions measured in this study.

APPENDIX G

Sensitivity Analysis of Neural Network Model

The optimum neural network model obtained in this work has four input nodes, three hidden processing elements, and one output node. A sensitivity analysis as proposed by Garson (1991) was performed on the trained weightings between the processing elements from ten training runs. The general procedure for the sensitivity analysis is as follows:

Model Run 104 (Appendix E)

Trained weightings from links between processing elements, and input and output layers:

	Input Variables				Output
Nodes	RE	DoC	BRR	FR	Heave
Hidden 1	-0.9056	-2.0337	-1.3819	-0.9798	1.7237
Hidden 2	-1.1647	-0.4183	-0.7449	0.4591	-1.525
Hidden 3	2.7613	1.0714	-1.9397	0.1168	-1.6699

1. For each hidden node i, obtain the products P_{ij} by multiplying the absolute value of the hidden-output layer connection weight by the absolute value of the hidden-input layer connection weight of each input variable j. ($P_{11} = 0.9056 \times 1.7237 = 1.5510$)

	RE	DoC	BRR	FR	Sum
Hidden 1	1.5610	3.5055	2.3820	1.6889	9.1373
Hidden 2	1.7762	0.6379	1.1360	0.7001	4.2502
Hidden 3	4.6111	1.7891	3.2391	0.1950	9.8344

2. For each hidden node, divide P_{ij} by the sum of all input variables to obtain Q_{ij}. ($Q_{11} = 1.5610 / (1.5610 + 3.5055 + 2.3820 + 1.6889) = 0.1708$) For each input node, sum Q_{ij} to obtain S_j. ($S_1 = 0.1708 + 0.4179 + 0.4689 = 1.0576$)

	RE	DoC	BRR	FR
Hidden 1	0.1708	0.3836	0.2607	0.1848
Hidden 2	0.4179	0.1501	0.2673	0.1647
Hidden 3	0.4689	0.1819	0.3294	0.0198
Sum:	1.0576	0.7157	0.8573	0.3694

3. Divide S_j by the sum of all input variables to get the relative importance of all output weights attributed to the given input variable. RE would be equal to (1.0576 x 100) / (1.0576 + 0.7157 + 0.8573 + 0.3694) = 35.3%.

	RE	DoC	BRR	FR
Relative Importance (%)	35.3%	23.9%	28.6%	12.3%

RE = Reamer Efficeincy
DoC = Depth of Cover
BRR = Backream Rate
FR = Mud Flow Rate

Garson, G.D. (1991). "Interpreting neural network connections weights." AI Expert, (6)7, 47-51.

Model Run 111 (Appendix E)

Trained weightings from links between processing elements, and input and output layers:

Nodes	Input Variables RE	 DoC	 BRR	 FR	Output Heave
Hidden 1	-1.1058	-1.8399	2.3109	-0.4697	1.5678
Hidden 2	1.1617	2.5511	0.5179	1.0826	-1.6307
Hidden 3	0.4163	-1.8116	0.8746	0.0506	-1.2145

Step 1:

	RE	DoC	BRR	FR	Sum
Hidden 1	1.7337	2.8846	3.6230	0.7364	8.9777
Hidden 2	1.8944	4.1601	0.8445	1.7654	8.6644
Hidden 3	0.5056	2.2002	1.0622	0.0615	3.8294

Step 2:

	RE	DoC	BRR	FR
Hidden 1	0.1931	0.3213	0.4036	0.0820
Hidden 2	0.2186	0.4801	0.0975	0.2038
Hidden 3	0.1320	0.5745	0.2774	0.0160
Sum:	0.5438	1.3760	0.7784	0.3018

Step 3:

	RE	DoC	BRR	FR
Relative Importance (%)	18.1%	45.9%	25.9%	10.1%

Model Run 112 (Appendix E)

Trained weightings from links between processing elements, and input and output layers:

	Input Variables				Output
Nodes	RE	DoC	BRR	FR	Heave
Hidden 1	-1.2305	-2.6808	-1.1794	-0.5089	2.3058
Hidden 2	1.4541	1.1505	-1.9505	0.3132	-1.6462
Hidden 3	-0.8503	-1.8202	-0.0407	0.654	-1.1730

Step 1:

	RE	DoC	BRR	FR	Sum
Hidden 1	2.8373	6.1814	2.7195	1.1734	12.9116
Hidden 2	2.3937	1.8940	3.2109	0.5156	8.0142
Hidden 3	0.9974	2.1351	0.0477	0.7671	3.9474

Step 2:

	RE	DoC	BRR	FR
Hidden 1	0.2197	0.4787	0.2106	0.0909
Hidden 2	0.2987	0.2363	0.4007	0.0643
Hidden 3	0.2527	0.5409	0.0121	0.1943
Sum:	0.7711	1.2560	0.6234	0.3496

Step 3:

	RE	DoC	BRR	FR
Relative Importance (%)	25.7%	41.9%	20.8%	11.7%

Model Run 113 (Appendix E)

Trained weightings from links between processing elements, and input and output layers:

Nodes	Input Variables RE	DoC	BRR	FR	Output Heave
Hidden 1	-1.1844	-2.6489	-0.5114	-1.1475	1.6594
Hidden 2	-0.3814	1.9436	-0.8341	0.0791	1.2990
Hidden 3	1.0687	1.9047	-2.2441	0.5143	-1.6168

Step 1:

	RE	DoC	BRR	FR	Sum
Hidden 1	1.9654	4.3956	0.8486	1.9042	9.1138
Hidden 2	0.4954	2.5247	1.0835	0.1028	4.2064
Hidden 3	1.7279	3.0795	3.6283	0.8315	9.2672

Step 2:

	RE	DoC	BRR	FR
Hidden 1	0.2157	0.4823	0.0931	0.2089
Hidden 2	0.1178	0.6002	0.2576	0.0244
Hidden 3	0.1865	0.3323	0.3915	0.0897
Sum:	0.5199	1.4148	0.7422	0.3231

Step 3:

	RE	DoC	BRR	FR
Relative Importance (%)	17.3%	47.2%	24.7%	10.8%

Model Run 114 (Appendix E)

Trained weightings from links between processing elements, and input and output layers:

Nodes	Input Variables RE	DoC	BRR	FR	Output Heave
Hidden 1	1.1151	1.8739	-2.2286	0.5097	-1.6700
Hidden 2	-1.2391	-2.7291	-0.5612	-1.1157	1.7322
Hidden 3	-0.2009	1.9792	-0.8835	0.0893	1.3115

Step 1:

	RE	DoC	BRR	FR	Sum
Hidden 1	1.8622	3.1294	3.7218	0.8512	9.5646
Hidden 2	2.1464	4.7273	0.9721	1.9326	9.7784
Hidden 3	0.2635	2.5957	1.1587	0.1171	4.1350

Step 2:

	RE	DoC	BRR	FR
Hidden 1	0.1947	0.3272	0.3891	0.0890
Hidden 2	0.2195	0.4834	0.0994	0.1976
Hidden 3	0.0637	0.6277	0.2802	0.0283
Sum:	0.4779	1.4384	0.7688	0.3150

Step 3:

	RE	DoC	BRR	FR
Relative Importance (%)	15.9%	47.9%	25.6%	10.5%

Model Run 115 (Appendix E)

Trained weightings from links between processing elements, and input and output layers:

	Input Variables				Output
Nodes	RE	DoC	BRR	FR	Heave
Hidden 1	0.9843	2.1459	1.4375	0.6340	-1.9572
Hidden 2	-1.1188	-1.1424	2.4210	-0.1249	1.4835
Hidden 3	0.8300	-0.7932	0.2687	0.9199	-1.0469

Step 1:

	RE	DoC	BRR	FR	Sum
Hidden 1	1.9265	4.2000	2.8135	1.2409	10.1808
Hidden 2	1.6597	1.6948	3.5916	0.1853	7.1313
Hidden 3	0.8689	0.8304	0.2813	0.9630	2.9437

Step 2:

	RE	DoC	BRR	FR
Hidden 1	0.1892	0.4125	0.2764	0.1219
Hidden 2	0.2327	0.2376	0.5036	0.0260
Hidden 3	0.2952	0.2821	0.0956	0.3272
Sum:	0.7172	0.9323	0.8755	0.4750

Step 3:

	RE	DoC	BRR	FR
Relative Importance (%)	23.9%	31.1%	29.2%	15.8%

Model Run 116 (Appendix E)

Trained weightings from links between processing elements, and input and output layers:

	Input Variables				Output
Nodes	RE	DoC	BRR	FR	Heave
Hidden 1	1.7680	0.9006	-1.9827	0.2927	-1.6987
Hidden 2	-0.9820	-1.4757	-0.0943	0.4700	-1.0227
Hidden 3	-1.0968	-2.5969	-1.2310	-0.6672	2.1829

Step 1:

	RE	DoC	BRR	FR	Sum
Hidden 1	3.0033	1.5298	3.3680	0.4972	8.3984
Hidden 2	1.0043	1.5092	0.0964	0.4807	3.0906
Hidden 3	2.3942	5.6688	2.6871	1.4564	12.2066

Step 2:

	RE	DoC	BRR	FR
Hidden 1	0.3576	0.1822	0.4010	0.0592
Hidden 2	0.3250	0.4883	0.0312	0.1555
Hidden 3	0.1961	0.4644	0.2201	0.1193
Sum:	0.8787	1.1349	0.6524	0.3340

Step 3:

	RE	DoC	BRR	FR
Relative Importance (%)	29.3%	37.8%	21.7%	11.1%

Model Run 117 (Appendix E)

Trained weightings from links between processing elements, and input and output layers:

Nodes	Input Variables RE	DoC	BRR	FR	Output Heave
Hidden 1	1.0405	2.2382	1.3530	0.7056	-2.0577
Hidden 2	-1.4732	-0.8767	-0.0707	0.7274	-1.0908
Hidden 3	-2.4813	-0.6193	2.3737	-0.0999	1.9468

Step 1:

	RE	DoC	BRR	FR	Sum
Hidden 1	2.1410	4.6055	2.7841	1.4519	10.9826
Hidden 2	1.6070	0.9563	0.0771	0.7934	3.4338
Hidden 3	4.8306	1.2057	4.6211	0.1945	10.8519

Step 2:

	RE	DoC	BRR	FR
Hidden 1	0.1949	0.4194	0.2535	0.1322
Hidden 2	0.4680	0.2785	0.0225	0.2311
Hidden 3	0.4451	0.1111	0.4258	0.0179
Sum:	1.1081	0.8089	0.7018	0.3812

Step 3:

	RE	DoC	BRR	FR
Relative Importance (%)	36.9%	27.0%	23.4%	12.7%

Model Run 118 (Appendix E)

Trained weightings from links between processing elements, and input and output layers:

	Input Variables				Output
Nodes	RE	DoC	BRR	FR	Heave
Hidden 1	-1.0562	0.8326	-0.5220	-0.7852	1.0797
Hidden 2	0.7885	1.8722	0.9569	0.7148	-1.5295
Hidden 3	-1.1787	-1.7424	2.6158	-0.2197	1.4190

Step 1:

	RE	DoC	BRR	FR	Sum
Hidden 1	1.1404	0.8990	0.5636	0.8478	3.4507
Hidden 2	1.2060	2.8635	1.4636	1.0933	6.6264
Hidden 3	1.6726	2.4725	3.7118	0.3118	8.1686

Step 2:

	RE	DoC	BRR	FR
Hidden 1	0.3305	0.2605	0.1633	0.2457
Hidden 2	0.1820	0.4321	0.2209	0.1650
Hidden 3	0.2048	0.3027	0.4544	0.0382
Sum:	0.7172	0.9953	0.8386	0.4488

Step 3:

	RE	DoC	BRR	FR
Relative Importance (%)	23.9%	33.2%	28.0%	15.0%

Model Run 119 (Appendix E)

Trained weightings from links between processing elements, and input and output layers:

	Input Variables				Output
Nodes	RE	DoC	BRR	FR	Heave
Hidden 1	0.6471	-1.7313	1.1435	0.1815	-1.2677
Hidden 2	-1.1825	-2.5797	-0.4013	-1.1274	1.5849
Hidden 3	-0.9521	-1.8960	2.5845	-0.3756	1.5386

Step 1:

	RE	DoC	BRR	FR	Sum
Hidden 1	0.8203	2.1948	1.4496	0.2301	4.6948
Hidden 2	1.8741	4.0886	0.6360	1.7868	8.3855
Hidden 3	1.4649	2.9172	3.9765	0.5779	8.9365

Step 2:

	RE	DoC	BRR	FR
Hidden 1	0.1747	0.4675	0.3088	0.0490
Hidden 2	0.2235	0.4876	0.0758	0.2131
Hidden 3	0.1639	0.3264	0.4450	0.0647
Sum:	0.5622	1.2815	0.8296	0.3268

Step 3:

	RE	DoC	BRR	FR
Relative Importance (%)	18.7%	42.7%	27.7%	10.9%

Summary of Relative Importance:

Model Run	Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow Rate
104	0.3525	0.2386	0.2858	0.1231
111	0.1813	0.4587	0.2595	0.1006
112	0.2570	0.4187	0.2078	0.1165
113	0.1733	0.4716	0.2474	0.1077
114	0.1593	0.4795	0.2563	0.1050
115	0.2391	0.3108	0.2918	0.1583
116	0.2929	0.3783	0.2175	0.1113
117	0.3694	0.2696	0.2339	0.1271
118	0.2391	0.3318	0.2795	0.1496
119	0.1874	0.4272	0.2765	0.1089
Average	0.2451	0.3785	0.2556	0.1208

Ranking of Importance by Iteration:

Model Run		Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow Rate
104		1	3	2	4
111		3	1	2	4
112		2	1	3	4
113		3	1	2	4
114		3	1	2	4
115		3	1	2	4
116		2	1	3	4
117		1	2	3	4
118		3	1	2	4
119		3	1	2	4
Average		2.4	1.3	2.3	4.0
Number of Ordinal Placements	1st	2	8	0	0
	2nd	2	1	7	0
	3rd	6	1	3	0
	4th	0	0	0	10

APPENDIX H

Sensitivity Analysis – Table 1

Primary Factor: Depth of Cover
Secondary Factor: Reamer Efficiency
Held Field Installation Factor: Backream Rate (6 min/rod)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.2	0.1	0.6	0.375	0.748	0.804	0.710	0.754	-0.691
0.2	0.2	0.6	0.375	0.716	0.753	0.687	0.718	
0.2	0.3	0.6	0.375	0.674	0.691	0.655	0.673	
0.2	0.4	0.6	0.375	0.622	0.621	0.613	0.619	
0.2	0.5	0.6	0.375	0.559	0.547	0.556	0.554	
0.2	0.6	0.6	0.375	0.484	0.467	0.479	0.477	
0.2	0.7	0.6	0.375	0.394	0.381	0.381	0.385	
0.2	0.8	0.6	0.375	0.300	0.294	0.281	0.292	
0.2	0.9	0.6	0.375	0.221	0.222	0.209	0.217	
0.4	0.1	0.6	0.375	0.756	0.828	0.715	0.767	-0.808
0.4	0.2	0.6	0.375	0.725	0.780	0.690	0.732	
0.4	0.3	0.6	0.375	0.679	0.712	0.654	0.682	
0.4	0.4	0.6	0.375	0.617	0.623	0.600	0.613	
0.4	0.5	0.6	0.375	0.531	0.516	0.520	0.523	
0.4	0.6	0.6	0.375	0.424	0.401	0.413	0.413	
0.4	0.7	0.6	0.375	0.313	0.295	0.303	0.304	
0.4	0.8	0.6	0.375	0.227	0.217	0.223	0.222	
0.4	0.9	0.6	0.375	0.176	0.171	0.179	0.175	
0.6	0.1	0.6	0.375	0.759	0.837	0.717	0.771	-0.870
0.6	0.2	0.6	0.375	0.723	0.788	0.687	0.733	
0.6	0.3	0.6	0.375	0.666	0.711	0.638	0.672	
0.6	0.4	0.6	0.375	0.579	0.596	0.561	0.578	
0.6	0.5	0.6	0.375	0.460	0.453	0.449	0.454	
0.6	0.6	0.6	0.375	0.336	0.319	0.329	0.328	
0.6	0.7	0.6	0.375	0.242	0.226	0.241	0.236	
0.6	0.8	0.6	0.375	0.187	0.175	0.192	0.184	
0.6	0.9	0.6	0.375	0.157	0.148	0.167	0.157	
0.8	0.1	0.6	0.375	0.750	0.826	0.712	0.763	-0.858
0.8	0.2	0.6	0.375	0.699	0.765	0.670	0.711	
0.8	0.3	0.6	0.375	0.614	0.664	0.596	0.625	
0.8	0.4	0.6	0.375	0.494	0.522	0.485	0.500	
0.8	0.5	0.6	0.375	0.364	0.372	0.359	0.365	
0.8	0.6	0.6	0.375	0.266	0.260	0.263	0.263	
0.8	0.7	0.6	0.375	0.206	0.195	0.208	0.203	
0.8	0.8	0.6	0.375	0.172	0.160	0.179	0.170	
0.8	0.9	0.6	0.375	0.152	0.141	0.163	0.152	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

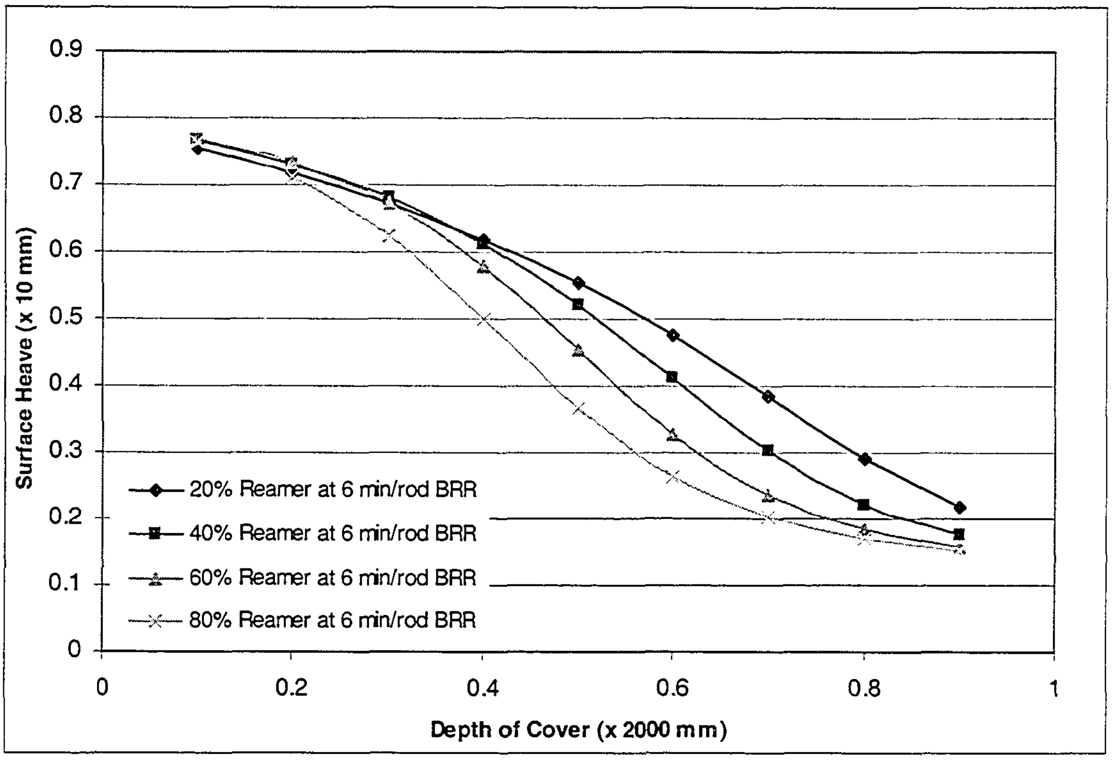

Figure 1: Surface Heave Trend by Neural Network – Effect of Depth of Cover and Reamer Efficiency at 6 min/rod Backream Rate

Sensitivity Analysis – Table 2

Primary Factor: Depth of Cover
Secondary Factor: Reamer Efficiency
Held Field Installation Factor: Backream Rate (2 min/rod)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.2	0.1	0.2	0.375	0.671	0.663	0.644	0.660	-0.532
0.2	0.2	0.2	0.375	0.628	0.613	0.608	0.616	
0.2	0.3	0.2	0.375	0.582	0.567	0.568	0.572	
0.2	0.4	0.2	0.375	0.535	0.524	0.527	0.528	
0.2	0.5	0.2	0.375	0.486	0.480	0.482	0.482	
0.2	0.6	0.2	0.375	0.431	0.433	0.428	0.431	
0.2	0.7	0.2	0.375	0.367	0.378	0.359	0.368	
0.2	0.8	0.2	0.375	0.293	0.316	0.279	0.296	
0.2	0.9	0.2	0.375	0.224	0.251	0.211	0.229	
0.4	0.1	0.2	0.375	0.687	0.694	0.652	0.678	-0.652
0.4	0.2	0.2	0.375	0.642	0.631	0.615	0.629	
0.4	0.3	0.2	0.375	0.590	0.569	0.571	0.577	
0.4	0.4	0.2	0.375	0.531	0.508	0.521	0.520	
0.4	0.5	0.2	0.375	0.463	0.445	0.459	0.456	
0.4	0.6	0.2	0.375	0.383	0.377	0.380	0.380	
0.4	0.7	0.2	0.375	0.296	0.305	0.291	0.297	
0.4	0.8	0.2	0.375	0.221	0.236	0.218	0.225	
0.4	0.9	0.2	0.375	0.171	0.185	0.174	0.177	
0.6	0.1	0.2	0.375	0.698	0.724	0.658	0.693	-0.740
0.6	0.2	0.2	0.375	0.649	0.650	0.617	0.639	
0.6	0.3	0.2	0.375	0.586	0.567	0.564	0.572	
0.6	0.4	0.2	0.375	0.505	0.479	0.496	0.493	
0.6	0.5	0.2	0.375	0.407	0.388	0.407	0.401	
0.6	0.6	0.2	0.375	0.305	0.300	0.308	0.304	
0.6	0.7	0.2	0.375	0.224	0.226	0.228	0.226	
0.6	0.8	0.2	0.375	0.173	0.176	0.180	0.177	
0.6	0.9	0.2	0.375	0.147	0.148	0.157	0.151	
0.8	0.1	0.2	0.375	0.701	0.743	0.658	0.701	-0.769
0.8	0.2	0.2	0.375	0.640	0.658	0.608	0.635	
0.8	0.3	0.2	0.375	0.552	0.549	0.536	0.546	
0.8	0.4	0.2	0.375	0.439	0.426	0.439	0.434	
0.8	0.5	0.2	0.375	0.322	0.311	0.329	0.321	
0.8	0.6	0.2	0.375	0.233	0.225	0.241	0.233	
0.8	0.7	0.2	0.375	0.181	0.174	0.189	0.181	
0.8	0.8	0.2	0.375	0.153	0.147	0.164	0.154	
0.8	0.9	0.2	0.375	0.138	0.132	0.151	0.140	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

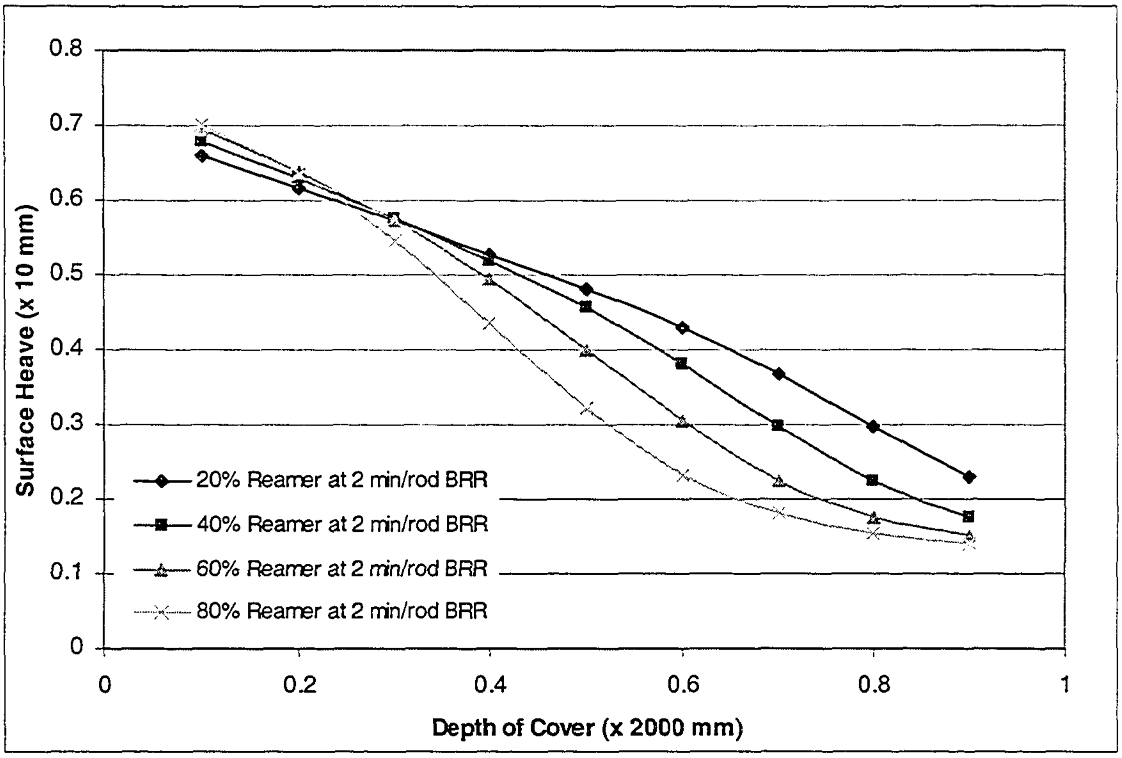

Figure 2: Surface Heave Trend by Neural Network – Effect of Depth of Cover and Reamer Efficiency at 2 min/rod Backream Rate

Sensitivity Analysis – Table 3

Primary Factor: Depth of Cover
Secondary Factor: Backream Rate
Held Field Installation Factor: Reamer Efficiency (60% Spoil Removal)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.6	0.1	0.2	0.375	0.698	0.724	0.658	0.693	-0.740
0.6	0.2	0.2	0.375	0.649	0.650	0.617	0.639	
0.6	0.3	0.2	0.375	0.586	0.567	0.564	0.572	
0.6	0.4	0.2	0.375	0.505	0.479	0.496	0.493	
0.6	0.5	0.2	0.375	0.407	0.388	0.407	0.401	
0.6	0.6	0.2	0.375	0.305	0.300	0.308	0.304	
0.6	0.7	0.2	0.375	0.224	0.226	0.228	0.226	
0.6	0.8	0.2	0.375	0.173	0.176	0.180	0.177	
0.6	0.9	0.2	0.375	0.147	0.148	0.157	0.151	
0.6	0.1	0.4	0.375	0.734	0.793	0.692	0.740	-0.818
0.6	0.2	0.4	0.375	0.691	0.728	0.656	0.692	
0.6	0.3	0.4	0.375	0.629	0.641	0.604	0.624	
0.6	0.4	0.4	0.375	0.542	0.532	0.529	0.534	
0.6	0.5	0.4	0.375	0.431	0.412	0.426	0.423	
0.6	0.6	0.4	0.375	0.317	0.302	0.316	0.312	
0.6	0.7	0.4	0.375	0.230	0.221	0.231	0.227	
0.6	0.8	0.4	0.375	0.178	0.172	0.184	0.178	
0.6	0.9	0.4	0.375	0.151	0.146	0.160	0.152	
0.6	0.1	0.6	0.375	0.759	0.837	0.717	0.771	-0.870
0.6	0.2	0.6	0.375	0.723	0.788	0.687	0.733	
0.6	0.3	0.6	0.375	0.666	0.711	0.638	0.672	
0.6	0.4	0.6	0.375	0.579	0.596	0.561	0.578	
0.6	0.5	0.6	0.375	0.460	0.453	0.449	0.454	
0.6	0.6	0.6	0.375	0.336	0.319	0.329	0.328	
0.6	0.7	0.6	0.375	0.242	0.226	0.241	0.236	
0.6	0.8	0.6	0.375	0.187	0.175	0.192	0.184	
0.6	0.9	0.6	0.375	0.157	0.148	0.167	0.157	
0.6	0.1	0.8	0.375	0.776	0.860	0.734	0.790	-0.889
0.6	0.2	0.8	0.375	0.746	0.822	0.708	0.759	
0.6	0.3	0.8	0.375	0.694	0.756	0.663	0.704	
0.6	0.4	0.8	0.375	0.609	0.649	0.585	0.614	
0.6	0.5	0.8	0.375	0.488	0.501	0.470	0.486	
0.6	0.6	0.8	0.375	0.359	0.354	0.346	0.353	
0.6	0.7	0.8	0.375	0.260	0.249	0.256	0.255	
0.6	0.8	0.8	0.375	0.201	0.189	0.204	0.198	
0.6	0.9	0.8	0.375	0.167	0.157	0.177	0.167	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

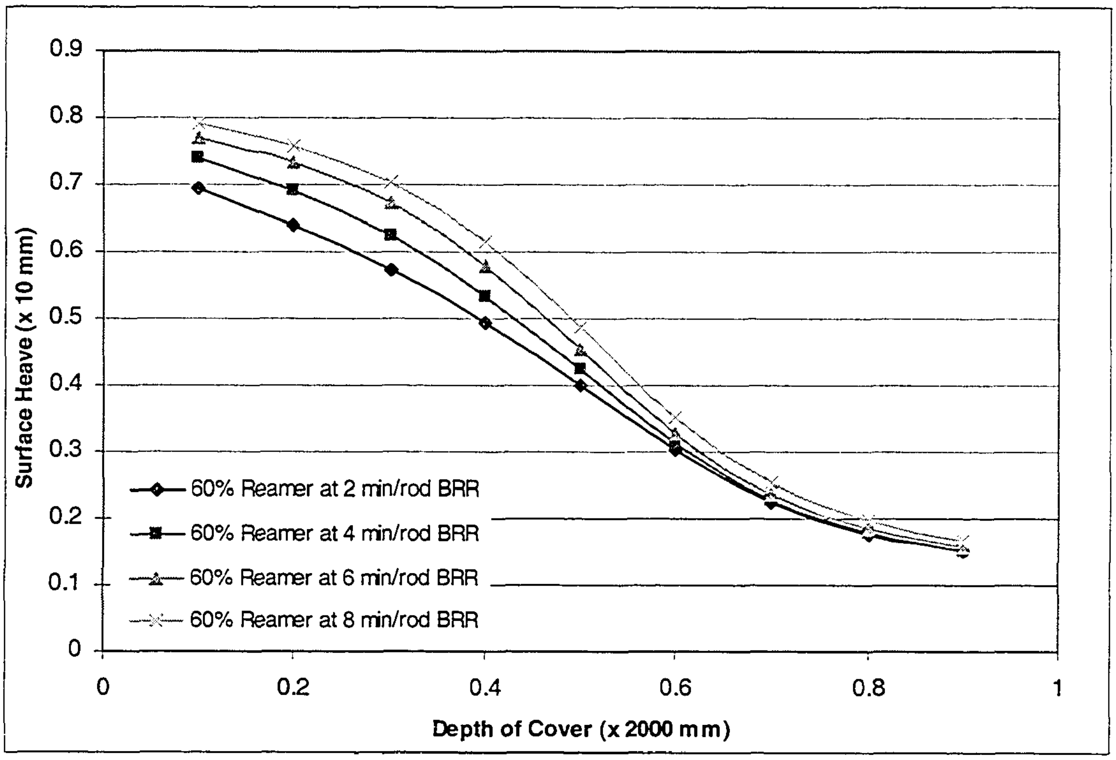

Figure 3: Surface Heave Trend by Neural Network – Effect of Depth of Cover and Backream Rate at 60% Reamer Efficiency

Sensitivity Analysis – Table 4

Primary Factor: Depth of Cover
Secondary Factor: Backream Rate
Held Field Installation Factor: Reamer Efficiency (15% Spoil Removal)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.15	0.1	0.2	0.375	0.667	0.656	0.642	0.655	-0.501
0.15	0.2	0.2	0.375	0.624	0.609	0.606	0.613	
0.15	0.3	0.2	0.375	0.579	0.567	0.567	0.571	
0.15	0.4	0.2	0.375	0.534	0.527	0.526	0.529	
0.15	0.5	0.2	0.375	0.488	0.487	0.484	0.486	
0.15	0.6	0.2	0.375	0.438	0.443	0.435	0.439	
0.15	0.7	0.2	0.375	0.380	0.393	0.373	0.382	
0.15	0.8	0.2	0.375	0.311	0.335	0.296	0.314	
0.15	0.9	0.2	0.375	0.241	0.271	0.224	0.245	
0.15	0.1	0.4	0.375	0.710	0.727	0.680	0.706	-0.582
0.15	0.2	0.4	0.375	0.670	0.670	0.650	0.663	
0.15	0.3	0.4	0.375	0.624	0.616	0.613	0.618	
0.15	0.4	0.4	0.375	0.574	0.564	0.570	0.569	
0.15	0.5	0.4	0.375	0.521	0.512	0.520	0.518	
0.15	0.6	0.4	0.375	0.462	0.458	0.459	0.460	
0.15	0.7	0.4	0.375	0.393	0.396	0.383	0.390	
0.15	0.8	0.4	0.375	0.314	0.325	0.295	0.312	
0.15	0.9	0.4	0.375	0.238	0.255	0.221	0.238	
0.15	0.1	0.6	0.375	0.745	0.797	0.709	0.750	-0.657
0.15	0.2	0.6	0.375	0.713	0.745	0.685	0.714	
0.15	0.3	0.6	0.375	0.671	0.684	0.654	0.670	
0.15	0.4	0.6	0.375	0.621	0.618	0.614	0.618	
0.15	0.5	0.6	0.375	0.562	0.551	0.561	0.558	
0.15	0.6	0.6	0.375	0.492	0.479	0.490	0.487	
0.15	0.7	0.6	0.375	0.410	0.400	0.399	0.403	
0.15	0.8	0.6	0.375	0.320	0.316	0.299	0.312	
0.15	0.9	0.6	0.375	0.238	0.241	0.221	0.233	
0.15	0.1	0.8	0.375	0.771	0.848	0.729	0.783	-0.710
0.15	0.2	0.8	0.375	0.747	0.811	0.712	0.756	
0.15	0.3	0.8	0.375	0.713	0.758	0.687	0.719	
0.15	0.4	0.8	0.375	0.667	0.690	0.652	0.670	
0.15	0.5	0.8	0.375	0.607	0.608	0.600	0.605	
0.15	0.6	0.8	0.375	0.530	0.515	0.524	0.523	
0.15	0.7	0.8	0.375	0.434	0.412	0.420	0.422	
0.15	0.8	0.8	0.375	0.330	0.311	0.309	0.317	
0.15	0.9	0.8	0.375	0.241	0.231	0.226	0.232	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

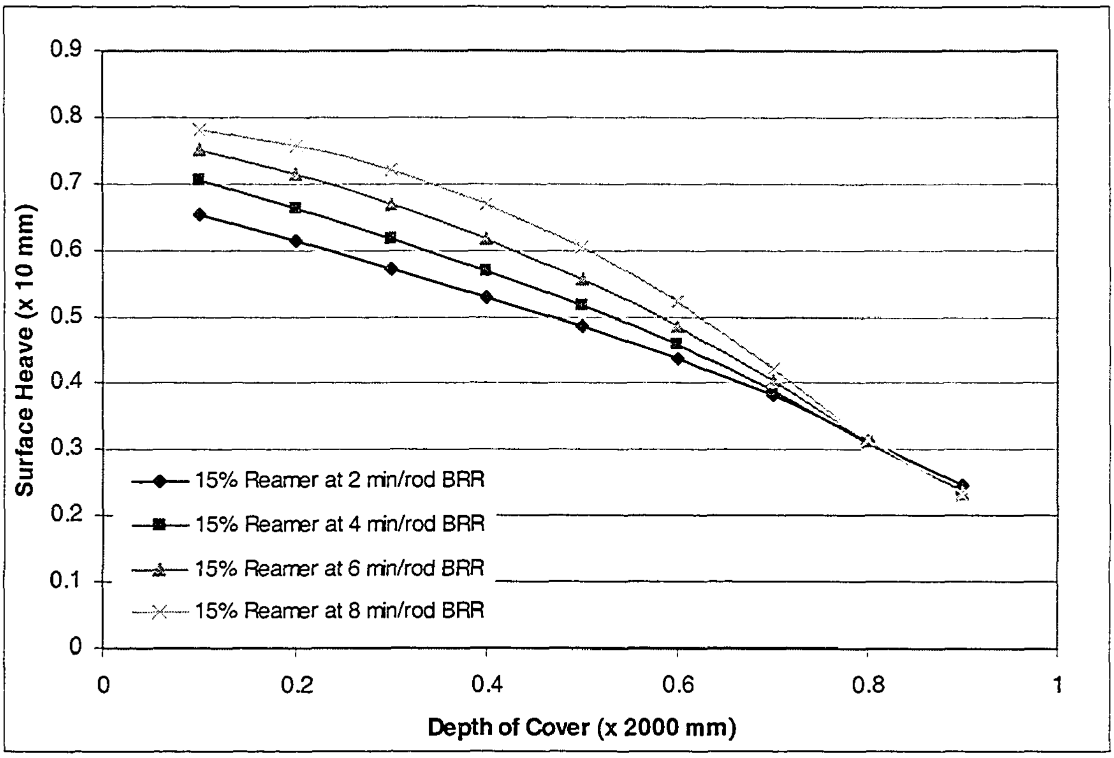

Figure 4: Surface Heave Trend by Neural Network – Effect of Depth of Cover and Backream Rate at 15% Reamer Efficiency

Sensitivity Analysis – Table 5

Primary Factor: Reamer Efficiency
Secondary Factor: Depth of Cover
Held Field Installation Factor: Backream Rate (2 min/rod)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.1	0.2	0.2	0.375	0.620	0.606	0.604	0.610	0.025
0.2	0.2	0.2	0.375	0.628	0.613	0.608	0.616	
0.3	0.2	0.2	0.375	0.635	0.622	0.612	0.623	
0.4	0.2	0.2	0.375	0.642	0.631	0.615	0.629	
0.5	0.2	0.2	0.375	0.647	0.641	0.616	0.635	
0.6	0.2	0.2	0.375	0.649	0.650	0.617	0.639	
0.7	0.2	0.2	0.375	0.648	0.656	0.614	0.639	
0.8	0.2	0.2	0.375	0.640	0.658	0.608	0.635	
0.9	0.2	0.2	0.375	0.623	0.651	0.596	0.623	
0.1	0.4	0.2	0.375	0.532	0.530	0.526	0.529	-0.161
0.2	0.4	0.2	0.375	0.535	0.524	0.527	0.528	
0.3	0.4	0.2	0.375	0.535	0.517	0.525	0.526	
0.4	0.4	0.2	0.375	0.531	0.508	0.521	0.520	
0.5	0.4	0.2	0.375	0.522	0.496	0.511	0.510	
0.6	0.4	0.2	0.375	0.505	0.479	0.496	0.493	
0.7	0.4	0.2	0.375	0.477	0.456	0.472	0.468	
0.8	0.4	0.2	0.375	0.439	0.426	0.439	0.434	
0.9	0.4	0.2	0.375	0.393	0.389	0.399	0.394	
0.1	0.6	0.2	0.375	0.443	0.452	0.441	0.446	-0.317
0.2	0.6	0.2	0.375	0.431	0.433	0.428	0.431	
0.3	0.6	0.2	0.375	0.412	0.408	0.408	0.409	
0.4	0.6	0.2	0.375	0.383	0.377	0.380	0.380	
0.5	0.6	0.2	0.375	0.346	0.340	0.345	0.344	
0.6	0.6	0.2	0.375	0.305	0.300	0.308	0.304	
0.7	0.6	0.2	0.375	0.265	0.260	0.272	0.265	
0.8	0.6	0.2	0.375	0.233	0.225	0.241	0.233	
0.9	0.6	0.2	0.375	0.210	0.200	0.218	0.209	
0.1	0.8	0.2	0.375	0.328	0.352	0.313	0.331	-0.232
0.2	0.8	0.2	0.375	0.293	0.316	0.279	0.296	
0.3	0.8	0.2	0.375	0.256	0.276	0.246	0.259	
0.4	0.8	0.2	0.375	0.221	0.236	0.218	0.225	
0.5	0.8	0.2	0.375	0.193	0.202	0.196	0.197	
0.6	0.8	0.2	0.375	0.173	0.176	0.180	0.177	
0.7	0.8	0.2	0.375	0.161	0.158	0.170	0.163	
0.8	0.8	0.2	0.375	0.153	0.147	0.164	0.154	
0.9	0.8	0.2	0.375	0.149	0.139	0.160	0.149	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

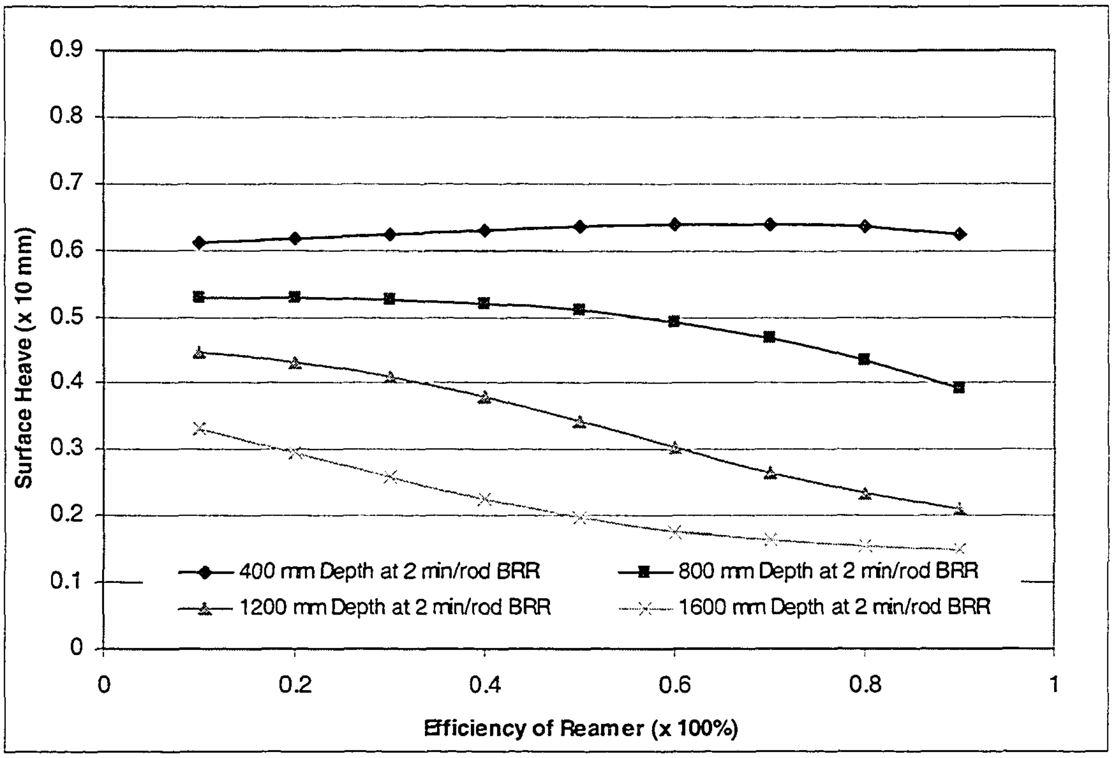

Figure 5: Surface Heave Trend by Neural Network – Effect of Reamer Efficiency and Depth of Cover at 2 min/rod Backream Rate

Sensitivity Analysis – Table 6

Primary Factor: Reamer Efficiency
Secondary Factor: Depth of Cover
Held Field Installation Factor: Backream Rate (6 min/rod)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.1	0.2	0.6	0.375	0.709	0.736	0.684	0.710	-0.019
0.2	0.2	0.6	0.375	0.716	0.753	0.687	0.718	
0.3	0.2	0.6	0.375	0.721	0.768	0.689	0.726	
0.4	0.2	0.6	0.375	0.725	0.780	0.690	0.732	
0.5	0.2	0.6	0.375	0.726	0.787	0.690	0.734	
0.6	0.2	0.6	0.375	0.723	0.788	0.687	0.733	
0.7	0.2	0.6	0.375	0.715	0.782	0.681	0.726	
0.8	0.2	0.6	0.375	0.699	0.765	0.670	0.711	
0.9	0.2	0.6	0.375	0.672	0.736	0.651	0.687	
0.1	0.4	0.6	0.375	0.619	0.616	0.614	0.616	-0.200
0.2	0.4	0.6	0.375	0.622	0.621	0.613	0.619	
0.3	0.4	0.6	0.375	0.622	0.624	0.608	0.618	
0.4	0.4	0.6	0.375	0.617	0.623	0.600	0.613	
0.5	0.4	0.6	0.375	0.603	0.615	0.584	0.601	
0.6	0.4	0.6	0.375	0.579	0.596	0.561	0.578	
0.7	0.4	0.6	0.375	0.542	0.564	0.527	0.544	
0.8	0.4	0.6	0.375	0.494	0.522	0.485	0.500	
0.9	0.4	0.6	0.375	0.441	0.473	0.436	0.450	
0.1	0.6	0.6	0.375	0.499	0.490	0.499	0.496	-0.341
0.2	0.6	0.6	0.375	0.484	0.467	0.479	0.477	
0.3	0.6	0.6	0.375	0.459	0.438	0.450	0.449	
0.4	0.6	0.6	0.375	0.424	0.401	0.413	0.413	
0.5	0.6	0.6	0.375	0.381	0.360	0.371	0.371	
0.6	0.6	0.6	0.375	0.336	0.319	0.329	0.328	
0.7	0.6	0.6	0.375	0.296	0.285	0.292	0.291	
0.8	0.6	0.6	0.375	0.266	0.260	0.263	0.263	
0.9	0.6	0.6	0.375	0.246	0.245	0.242	0.245	
0.1	0.8	0.6	0.375	0.339	0.339	0.318	0.332	-0.202
0.2	0.8	0.6	0.375	0.300	0.294	0.281	0.292	
0.3	0.8	0.6	0.375	0.260	0.252	0.248	0.254	
0.4	0.8	0.6	0.375	0.227	0.217	0.223	0.222	
0.5	0.8	0.6	0.375	0.203	0.192	0.204	0.199	
0.6	0.8	0.6	0.375	0.187	0.175	0.192	0.184	
0.7	0.8	0.6	0.375	0.177	0.165	0.184	0.175	
0.8	0.8	0.6	0.375	0.172	0.160	0.179	0.170	
0.9	0.8	0.6	0.375	0.170	0.159	0.177	0.168	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

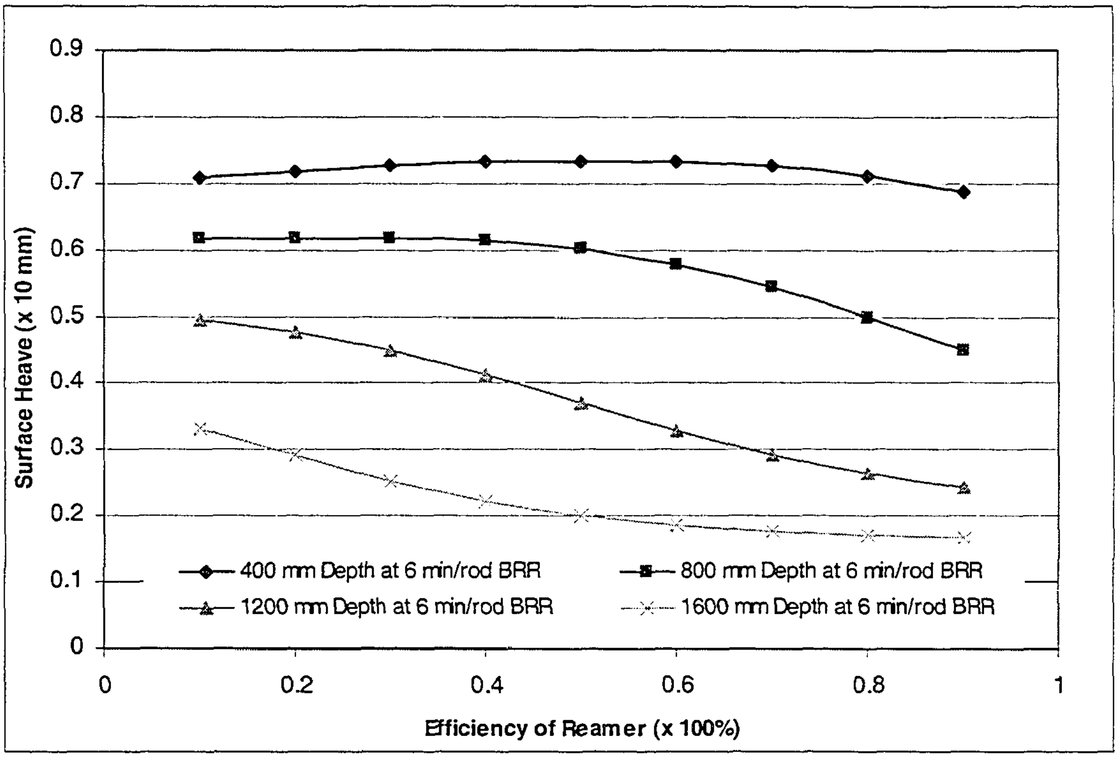

Figure 6: Surface Heave Trend by Neural Network – Effect of Reamer Efficiency and Depth of Cover at 6 min/rod Backream Rate

Sensitivity Analysis – Table 7

Primary Factor: Reamer Efficiency
Secondary Factor: Backream Rate
Held Field Installation Factor: Depth of Cover (900 mm)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.1	0.45	0.2	0.375	0.511	0.512	0.506	0.509	-0.217
0.2	0.45	0.2	0.375	0.510	0.502	0.505	0.506	
0.3	0.45	0.2	0.375	0.507	0.491	0.500	0.499	
0.4	0.45	0.2	0.375	0.499	0.477	0.491	0.489	
0.5	0.45	0.2	0.375	0.483	0.458	0.476	0.473	
0.6	0.45	0.2	0.375	0.458	0.434	0.454	0.448	
0.7	0.45	0.2	0.375	0.422	0.403	0.422	0.416	
0.8	0.45	0.2	0.375	0.378	0.366	0.384	0.376	
0.9	0.45	0.2	0.375	0.333	0.327	0.342	0.334	
0.1	0.45	0.4	0.375	0.548	0.541	0.546	0.545	-0.234
0.2	0.45	0.4	0.375	0.548	0.535	0.544	0.542	
0.3	0.45	0.4	0.375	0.545	0.527	0.538	0.537	
0.4	0.45	0.4	0.375	0.536	0.515	0.527	0.526	
0.5	0.45	0.4	0.375	0.518	0.497	0.508	0.508	
0.6	0.45	0.4	0.375	0.489	0.472	0.481	0.481	
0.7	0.45	0.4	0.375	0.449	0.439	0.444	0.444	
0.8	0.45	0.4	0.375	0.402	0.400	0.401	0.401	
0.9	0.45	0.4	0.375	0.355	0.361	0.357	0.358	
0.1	0.45	0.6	0.375	0.592	0.585	0.590	0.589	-0.258
0.2	0.45	0.6	0.375	0.592	0.585	0.586	0.588	
0.3	0.45	0.6	0.375	0.588	0.581	0.578	0.582	
0.4	0.45	0.6	0.375	0.577	0.572	0.564	0.571	
0.5	0.45	0.6	0.375	0.556	0.554	0.541	0.550	
0.6	0.45	0.6	0.375	0.522	0.526	0.509	0.519	
0.7	0.45	0.6	0.375	0.478	0.488	0.467	0.478	
0.8	0.45	0.6	0.375	0.427	0.444	0.421	0.431	
0.9	0.45	0.6	0.375	0.379	0.402	0.374	0.385	
0.1	0.45	0.8	0.375	0.638	0.649	0.631	0.639	-0.299
0.2	0.45	0.8	0.375	0.638	0.652	0.625	0.638	
0.3	0.45	0.8	0.375	0.632	0.650	0.614	0.632	
0.4	0.45	0.8	0.375	0.617	0.639	0.596	0.617	
0.5	0.45	0.8	0.375	0.591	0.615	0.569	0.592	
0.6	0.45	0.8	0.375	0.552	0.578	0.532	0.554	
0.7	0.45	0.8	0.375	0.502	0.531	0.486	0.506	
0.8	0.45	0.8	0.375	0.448	0.480	0.436	0.455	
0.9	0.45	0.8	0.375	0.399	0.433	0.389	0.407	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

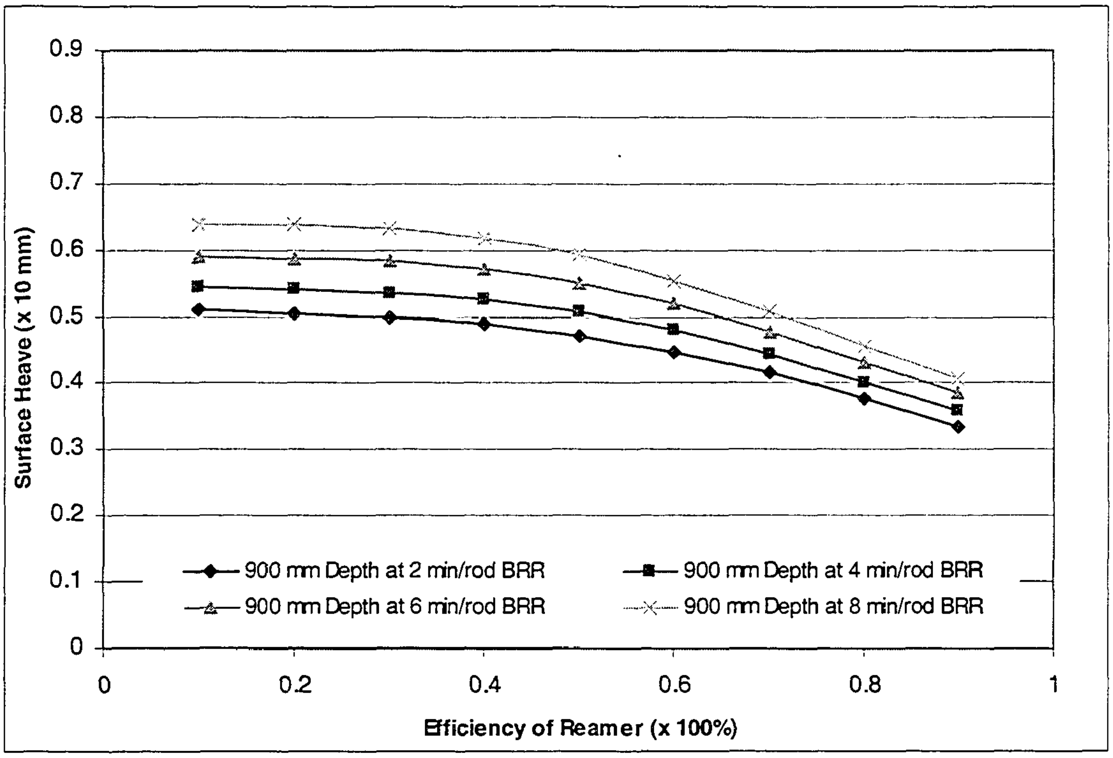

Figure 7: Surface Heave Trend by Neural Network – Effect of Reamer Efficiency and Backream Rate at 900 mm Depth of Cover

Sensitivity Analysis – Table 8

Primary Factor: Reamer Efficiency
Secondary Factor: Backream Rate
Held Field Installation Factor: Depth of Cover (1200 mm)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.1	0.6	0.2	0.375	0.443	0.452	0.441	0.446	-0.317
0.2	0.6	0.2	0.375	0.431	0.433	0.428	0.431	
0.3	0.6	0.2	0.375	0.412	0.408	0.408	0.409	
0.4	0.6	0.2	0.375	0.383	0.377	0.380	0.380	
0.5	0.6	0.2	0.375	0.346	0.340	0.345	0.344	
0.6	0.6	0.2	0.375	0.305	0.300	0.308	0.304	
0.7	0.6	0.2	0.375	0.265	0.260	0.272	0.265	
0.8	0.6	0.2	0.375	0.233	0.225	0.241	0.233	
0.9	0.6	0.2	0.375	0.210	0.200	0.218	0.209	
0.1	0.6	0.4	0.375	0.467	0.468	0.467	0.467	-0.331
0.2	0.6	0.4	0.375	0.454	0.446	0.450	0.450	
0.3	0.6	0.4	0.375	0.432	0.418	0.426	0.426	
0.4	0.6	0.4	0.375	0.401	0.384	0.394	0.393	
0.5	0.6	0.4	0.375	0.361	0.344	0.356	0.353	
0.6	0.6	0.4	0.375	0.317	0.302	0.316	0.312	
0.7	0.6	0.4	0.375	0.278	0.264	0.279	0.274	
0.8	0.6	0.4	0.375	0.246	0.234	0.249	0.243	
0.9	0.6	0.4	0.375	0.225	0.214	0.227	0.222	
0.1	0.6	0.6	0.375	0.499	0.490	0.499	0.496	-0.341
0.2	0.6	0.6	0.375	0.484	0.467	0.479	0.477	
0.3	0.6	0.6	0.375	0.459	0.438	0.450	0.449	
0.4	0.6	0.6	0.375	0.424	0.401	0.413	0.413	
0.5	0.6	0.6	0.375	0.381	0.360	0.371	0.371	
0.6	0.6	0.6	0.375	0.336	0.319	0.329	0.328	
0.7	0.6	0.6	0.375	0.296	0.285	0.292	0.291	
0.8	0.6	0.6	0.375	0.266	0.260	0.263	0.263	
0.9	0.6	0.6	0.375	0.246	0.245	0.242	0.245	
0.1	0.6	0.8	0.375	0.537	0.525	0.535	0.532	-0.352
0.2	0.6	0.8	0.375	0.520	0.503	0.511	0.511	
0.3	0.6	0.8	0.375	0.492	0.472	0.477	0.480	
0.4	0.6	0.8	0.375	0.452	0.434	0.435	0.441	
0.5	0.6	0.8	0.375	0.406	0.393	0.390	0.396	
0.6	0.6	0.8	0.375	0.359	0.354	0.346	0.353	
0.7	0.6	0.8	0.375	0.319	0.323	0.309	0.317	
0.8	0.6	0.8	0.375	0.290	0.301	0.281	0.290	
0.9	0.6	0.8	0.375	0.271	0.287	0.261	0.273	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

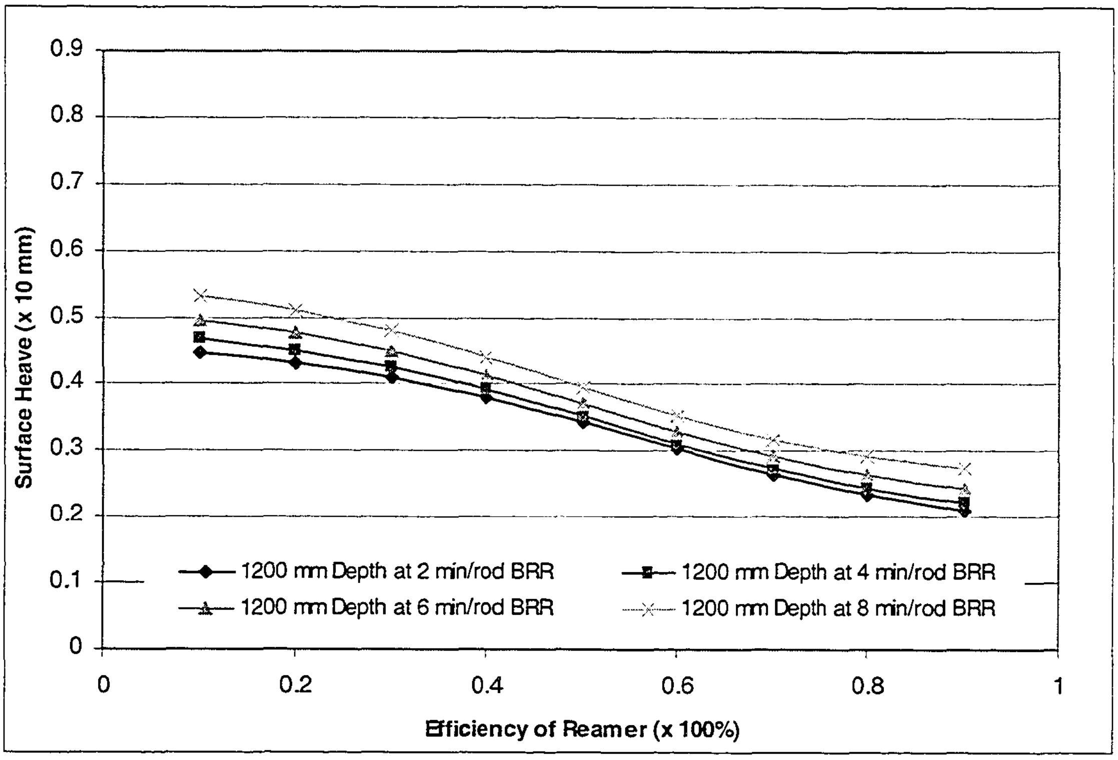

Figure 8: Surface Heave Trend by Neural Network – Effect of Reamer Efficiency and Backream Rate at 1200 mm Depth of Cover

Sensitivity Analysis – Table 9

Primary Factor: Backream Rate
Secondary Factor: Depth of Cover
Held Field Installation Factor: Reamer Efficiency (60% Spoil Removal)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.6	0.2	0.1	0.375	0.626	0.611	0.595	0.611	0.198
0.6	0.2	0.2	0.375	0.649	0.650	0.617	0.639	
0.6	0.2	0.3	0.375	0.671	0.690	0.637	0.666	
0.6	0.2	0.4	0.375	0.691	0.728	0.656	0.692	
0.6	0.2	0.5	0.375	0.708	0.762	0.673	0.714	
0.6	0.2	0.6	0.375	0.723	0.788	0.687	0.733	
0.6	0.2	0.7	0.375	0.736	0.808	0.699	0.748	
0.6	0.2	0.8	0.375	0.746	0.822	0.708	0.759	
0.6	0.2	0.9	0.375	0.753	0.831	0.716	0.767	
0.6	0.4	0.1	0.375	0.488	0.460	0.480	0.476	0.197
0.6	0.4	0.2	0.375	0.505	0.479	0.496	0.493	
0.6	0.4	0.3	0.375	0.523	0.503	0.512	0.513	
0.6	0.4	0.4	0.375	0.542	0.532	0.529	0.534	
0.6	0.4	0.5	0.375	0.561	0.564	0.545	0.556	
0.6	0.4	0.6	0.375	0.579	0.596	0.561	0.578	
0.6	0.4	0.7	0.375	0.595	0.625	0.574	0.598	
0.6	0.4	0.8	0.375	0.609	0.649	0.585	0.614	
0.6	0.4	0.9	0.375	0.620	0.665	0.594	0.627	
0.6	0.6	0.1	0.375	0.301	0.302	0.306	0.303	0.081
0.6	0.6	0.2	0.375	0.305	0.300	0.308	0.304	
0.6	0.6	0.3	0.375	0.310	0.299	0.311	0.307	
0.6	0.6	0.4	0.375	0.317	0.302	0.316	0.312	
0.6	0.6	0.5	0.375	0.326	0.308	0.322	0.319	
0.6	0.6	0.6	0.375	0.336	0.319	0.329	0.328	
0.6	0.6	0.7	0.375	0.347	0.335	0.338	0.340	
0.6	0.6	0.8	0.375	0.359	0.354	0.346	0.353	
0.6	0.6	0.9	0.375	0.371	0.375	0.355	0.367	
0.6	0.8	0.1	0.375	0.172	0.181	0.180	0.178	0.036
0.6	0.8	0.2	0.375	0.173	0.176	0.180	0.177	
0.6	0.8	0.3	0.375	0.175	0.173	0.182	0.177	
0.6	0.8	0.4	0.375	0.178	0.172	0.184	0.178	
0.6	0.8	0.5	0.375	0.182	0.172	0.187	0.180	
0.6	0.8	0.6	0.375	0.187	0.175	0.192	0.184	
0.6	0.8	0.7	0.375	0.193	0.180	0.197	0.190	
0.6	0.8	0.8	0.375	0.201	0.189	0.204	0.198	
0.6	0.8	0.9	0.375	0.210	0.201	0.213	0.208	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

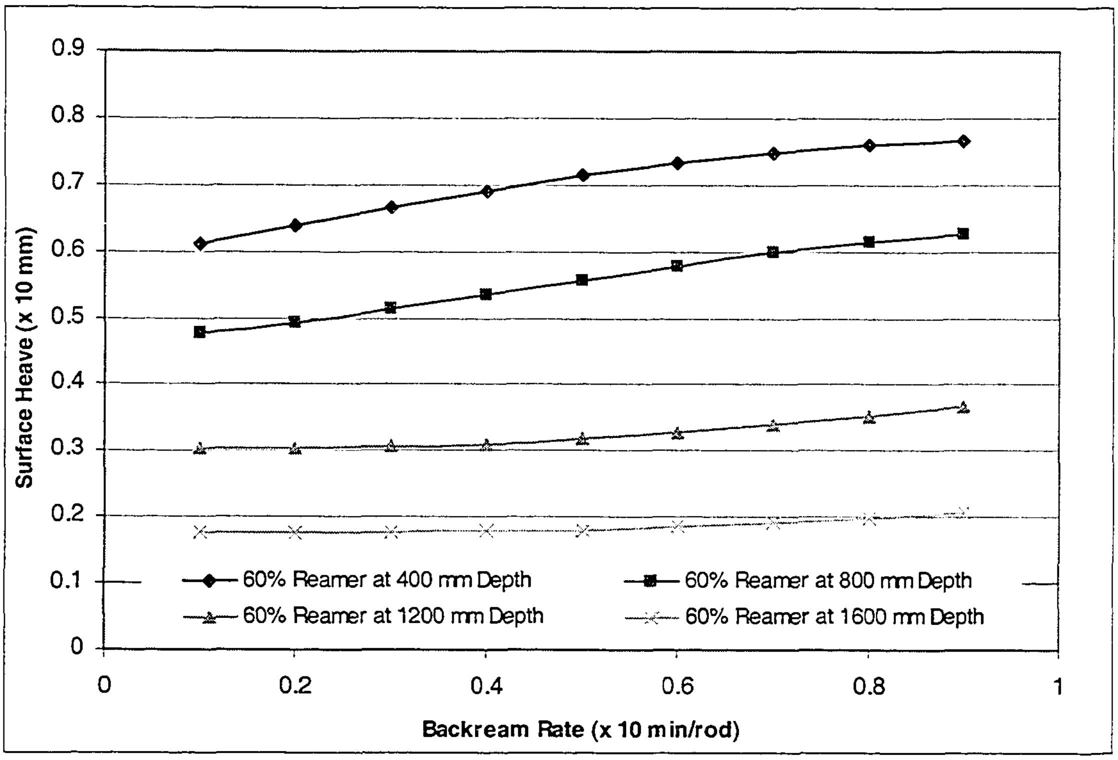

Figure 9: Surface Heave Trend by Neural Network – Effect of Backream Rate and Depth of Cover at 60% Reamer Efficiency

Sensitivity Analysis – Table 10
Primary Factor: Backream Rate
Secondary Factor: Depth of Cover
Held Field Installation Factor: Reamer Efficiency (15% Spoil Removal)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.15	0.2	0.1	0.375	0.601	0.586	0.583	0.590	0.235
0.15	0.2	0.2	0.375	0.624	0.609	0.606	0.613	
0.15	0.2	0.3	0.375	0.647	0.637	0.629	0.638	
0.15	0.2	0.4	0.375	0.670	0.670	0.650	0.663	
0.15	0.2	0.5	0.375	0.692	0.707	0.668	0.689	
0.15	0.2	0.6	0.375	0.713	0.745	0.685	0.714	
0.15	0.2	0.7	0.375	0.731	0.780	0.700	0.737	
0.15	0.2	0.8	0.375	0.747	0.811	0.712	0.756	
0.15	0.2	0.9	0.375	0.760	0.835	0.722	0.772	
0.15	0.4	0.1	0.375	0.516	0.513	0.507	0.512	0.232
0.15	0.4	0.2	0.375	0.534	0.527	0.526	0.529	
0.15	0.4	0.3	0.375	0.553	0.543	0.548	0.548	
0.15	0.4	0.4	0.375	0.574	0.564	0.570	0.569	
0.15	0.4	0.5	0.375	0.597	0.588	0.592	0.593	
0.15	0.4	0.6	0.375	0.621	0.618	0.614	0.618	
0.15	0.4	0.7	0.375	0.644	0.653	0.634	0.644	
0.15	0.4	0.8	0.375	0.667	0.690	0.652	0.670	
0.15	0.4	0.9	0.375	0.688	0.727	0.668	0.694	
0.15	0.6	0.1	0.375	0.428	0.437	0.426	0.430	0.140
0.15	0.6	0.2	0.375	0.438	0.443	0.435	0.439	
0.15	0.6	0.3	0.375	0.449	0.450	0.446	0.448	
0.15	0.6	0.4	0.375	0.462	0.458	0.459	0.460	
0.15	0.6	0.5	0.375	0.476	0.467	0.474	0.472	
0.15	0.6	0.6	0.375	0.492	0.479	0.490	0.487	
0.15	0.6	0.7	0.375	0.510	0.495	0.507	0.504	
0.15	0.6	0.8	0.375	0.530	0.515	0.524	0.523	
0.15	0.6	0.9	0.375	0.550	0.539	0.540	0.543	
0.15	0.8	0.1	0.375	0.311	0.339	0.298	0.316	0.006
0.15	0.8	0.2	0.375	0.311	0.335	0.296	0.314	
0.15	0.8	0.3	0.375	0.312	0.330	0.295	0.313	
0.15	0.8	0.4	0.375	0.314	0.325	0.295	0.312	
0.15	0.8	0.5	0.375	0.316	0.321	0.297	0.311	
0.15	0.8	0.6	0.375	0.320	0.316	0.299	0.312	
0.15	0.8	0.7	0.375	0.324	0.313	0.303	0.314	
0.15	0.8	0.8	0.375	0.330	0.311	0.309	0.317	
0.15	0.8	0.9	0.375	0.338	0.312	0.316	0.322	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

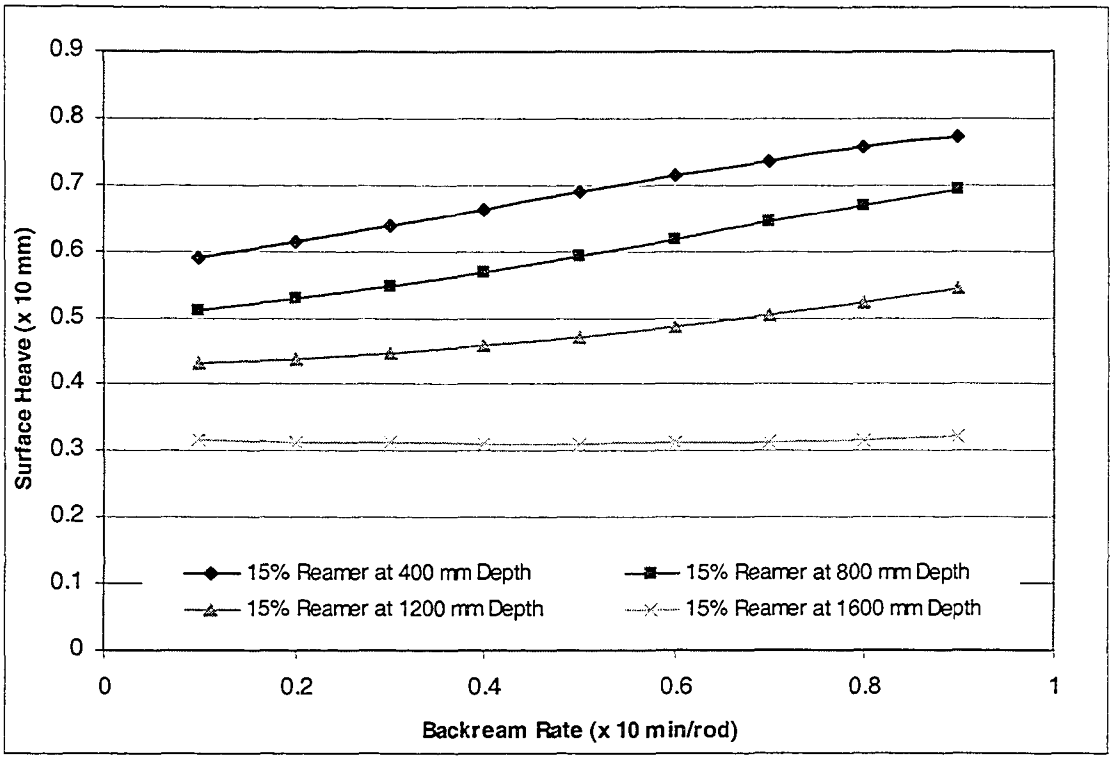

Figure 10: Surface Heave Trend by Neural Network – Effect of Backream Rate and Depth of Cover at 15% Reamer Efficiency

Sensitivity Analysis – Table 11

Primary Factor: Backream Rate
Secondary Factor: Reamer Efficiency
Held Field Installation Factor: Depth of Cover (900 mm)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.2	0.45	0.1	0.375	0.494	0.490	0.488	0.491	0.219
0.2	0.45	0.2	0.375	0.510	0.502	0.505	0.506	
0.2	0.45	0.3	0.375	0.528	0.517	0.524	0.523	
0.2	0.45	0.4	0.375	0.548	0.535	0.544	0.542	
0.2	0.45	0.5	0.375	0.570	0.557	0.565	0.564	
0.2	0.45	0.6	0.375	0.592	0.585	0.586	0.588	
0.2	0.45	0.7	0.375	0.615	0.617	0.607	0.613	
0.2	0.45	0.8	0.375	0.638	0.652	0.625	0.638	
0.2	0.45	0.9	0.375	0.659	0.689	0.642	0.663	
0.4	0.45	0.1	0.375	0.483	0.463	0.476	0.474	0.210
0.4	0.45	0.2	0.375	0.499	0.477	0.491	0.489	
0.4	0.45	0.3	0.375	0.516	0.494	0.508	0.506	
0.4	0.45	0.4	0.375	0.536	0.515	0.527	0.526	
0.4	0.45	0.5	0.375	0.556	0.541	0.545	0.547	
0.4	0.45	0.6	0.375	0.577	0.572	0.564	0.571	
0.4	0.45	0.7	0.375	0.597	0.605	0.581	0.594	
0.4	0.45	0.8	0.375	0.617	0.639	0.596	0.617	
0.4	0.45	0.9	0.375	0.634	0.669	0.609	0.637	
0.6	0.45	0.1	0.375	0.444	0.421	0.442	0.436	0.171
0.6	0.45	0.2	0.375	0.458	0.434	0.454	0.448	
0.6	0.45	0.3	0.375	0.473	0.451	0.467	0.463	
0.6	0.45	0.4	0.375	0.489	0.472	0.481	0.481	
0.6	0.45	0.5	0.375	0.506	0.498	0.495	0.499	
0.6	0.45	0.6	0.375	0.522	0.526	0.509	0.519	
0.6	0.45	0.7	0.375	0.538	0.554	0.521	0.538	
0.6	0.45	0.8	0.375	0.552	0.578	0.532	0.554	
0.6	0.45	0.9	0.375	0.564	0.597	0.540	0.567	
0.8	0.45	0.1	0.375	0.368	0.355	0.376	0.367	0.127
0.8	0.45	0.2	0.375	0.378	0.366	0.384	0.376	
0.8	0.45	0.3	0.375	0.390	0.381	0.392	0.388	
0.8	0.45	0.4	0.375	0.402	0.400	0.401	0.401	
0.8	0.45	0.5	0.375	0.415	0.422	0.411	0.416	
0.8	0.45	0.6	0.375	0.427	0.444	0.421	0.431	
0.8	0.45	0.7	0.375	0.438	0.465	0.429	0.444	
0.8	0.45	0.8	0.375	0.448	0.480	0.436	0.455	
0.8	0.45	0.9	0.375	0.456	0.491	0.441	0.463	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

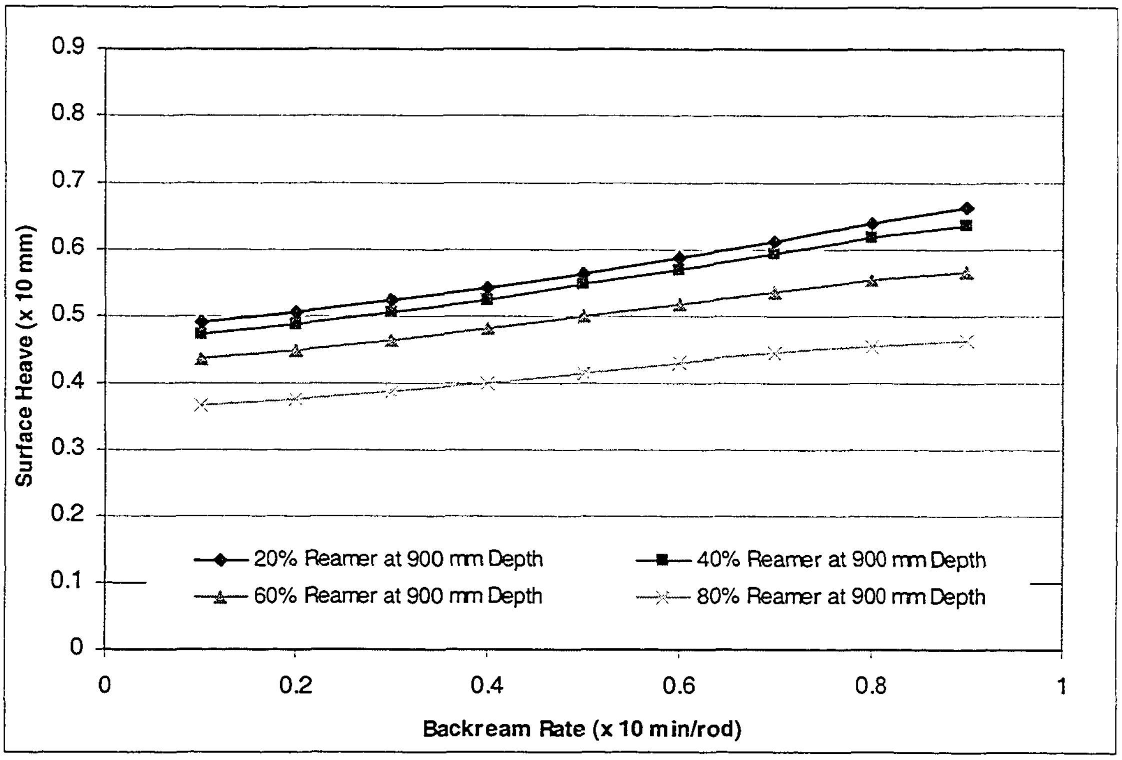

Figure 11: Surface Heave Trend by Neural Network – Effect of Backream Rate and Reamer Efficiency at 900 mm Depth of Cover

Sensitivity Analysis – Table 12

Primary Factor: Backream Rate
Secondary Factor: Reamer Efficiency
Held Field Installation Factor: Depth of Cover (1200 mm)

Reamer Efficiency	Depth of Cover	Backream Rate	Mud Flow	Run 1	Run 2	Run 3	Average NN Surface Heave	Slope
0.2	0.6	0.1	0.375	0.422	0.427	0.419	0.423	0.134
0.2	0.6	0.2	0.375	0.431	0.433	0.428	0.431	
0.2	0.6	0.3	0.375	0.442	0.439	0.438	0.440	
0.2	0.6	0.4	0.375	0.454	0.446	0.450	0.450	
0.2	0.6	0.5	0.375	0.468	0.455	0.464	0.462	
0.2	0.6	0.6	0.375	0.484	0.467	0.479	0.477	
0.2	0.6	0.7	0.375	0.501	0.483	0.495	0.493	
0.2	0.6	0.8	0.375	0.520	0.503	0.511	0.511	
0.2	0.6	0.9	0.375	0.539	0.527	0.526	0.531	
0.4	0.6	0.1	0.375	0.377	0.376	0.375	0.376	0.101
0.4	0.6	0.2	0.375	0.383	0.377	0.380	0.380	
0.4	0.6	0.3	0.375	0.391	0.380	0.386	0.386	
0.4	0.6	0.4	0.375	0.401	0.384	0.394	0.393	
0.4	0.6	0.5	0.375	0.411	0.391	0.403	0.402	
0.4	0.6	0.6	0.375	0.424	0.401	0.413	0.413	
0.4	0.6	0.7	0.375	0.438	0.415	0.424	0.426	
0.4	0.6	0.8	0.375	0.452	0.434	0.435	0.441	
0.4	0.6	0.9	0.375	0.467	0.456	0.446	0.456	
0.6	0.6	0.1	0.375	0.301	0.302	0.306	0.303	0.081
0.6	0.6	0.2	0.375	0.305	0.300	0.308	0.304	
0.6	0.6	0.3	0.375	0.310	0.299	0.311	0.307	
0.6	0.6	0.4	0.375	0.317	0.302	0.316	0.312	
0.6	0.6	0.5	0.375	0.326	0.308	0.322	0.319	
0.6	0.6	0.6	0.375	0.336	0.319	0.329	0.328	
0.6	0.6	0.7	0.375	0.347	0.335	0.338	0.340	
0.6	0.6	0.8	0.375	0.359	0.354	0.346	0.353	
0.6	0.6	0.9	0.375	0.371	0.375	0.355	0.367	
0.8	0.6	0.1	0.375	0.228	0.226	0.239	0.231	0.094
0.8	0.6	0.2	0.375	0.233	0.225	0.241	0.233	
0.8	0.6	0.3	0.375	0.239	0.228	0.244	0.237	
0.8	0.6	0.4	0.375	0.246	0.234	0.249	0.243	
0.8	0.6	0.5	0.375	0.256	0.245	0.256	0.252	
0.8	0.6	0.6	0.375	0.266	0.260	0.263	0.263	
0.8	0.6	0.7	0.375	0.277	0.279	0.272	0.276	
0.8	0.6	0.8	0.375	0.290	0.301	0.281	0.290	
0.8	0.6	0.9	0.375	0.302	0.322	0.290	0.305	

Training Set: 20lrn7.nna
Trend Set: 20trend5.nna (Portion of Results Shown in Table)

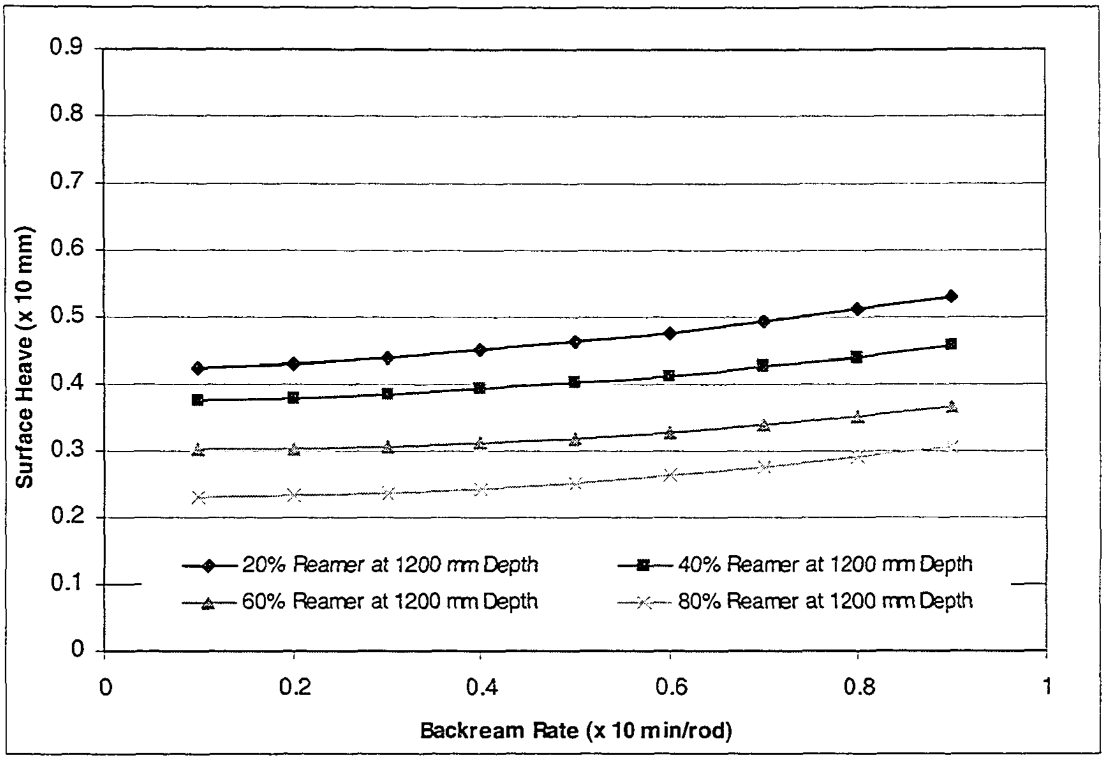

Figure 12: Surface Heave Trend by Neural Network – Effect of Backream Rate and Reamer Efficiency at 1200 mm Depth of Cover