Productivity Analysis of Horizontal Directional Drilling

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ABSTRACT

Horizontal Directional Drilling Productivity Analysis

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The National Research Council of Canada reported that rehabilitation of municipal water systems between 1997 and 2012 would cost $28 billion (NRC, 2004). With the rapid increase of new installations, the need for replacement and repair of pipe utilities and also the demand for trenchless excavation methods, increase. This must be done with minimum disruption to public. One alternative to reduce disruption is to use horizontal directional drilling (HDD) for new pipe installation scenarios. Consequently, contractors, engineers, and decision makers are facing continuous challenges regarding to estimation of execution time and cost of new pipe installations, while using HDD. This is because productivity prediction and consequently the cost estimation of HDD involves a large number of objective and subjective factors that need to be considered. It is well known that prediction of both productivity and cost is an important process in establishing and employing management strategies for a construction operation. This calls for the need of developing a dedicated HDD productivity model that meets present day requirements of this area of construction industry.

There are two main objectives of the current research. The first objective is to identify the factors that affect productivity of HDD operations. The second objective is to develop a productivity prediction model for different soil conditions. To achieve these two objectives a thorough literature review was carried out. Thereafter, data on potential factors on productivity were collected from HDD experts across North America and abroad. Following data collection, the current research identified managerial, mechanical, environmental and pipe physical conditions parameters operating in three types of soils: clay, rock and sandy soils. Prior to model development, Analytical Hierarchy Process (AHP) technique was used to classify and rank these factors according to their relative importance.

A neurofuzzy (NF) approach is employed to develop HDD productivity prediction model for pipe installation. The merits of this approach are that it decreases uncertainties in results, addresses non-linear relationships and deals well with imprecise and linguistic data. The following eight factors were finally selected as inputs of the model to be developed: operator/ crew skills, soil type, drilling rig capabilities, machine conditions, unseen buried obstacles, pipe diameter, pipe length and site weather and safety conditions. The model is validated using actual project data. The developed NF model showed average validation percent of 94.7%, 82.3% and 86.7%, for clay, rock and sand, respectively. The model is also used to produce productivity curves (production rate vs. influencing factors) for each soil type.

Finally, an automated user-friendly productivity prediction tool (HDD-PP) based on present NF model is developed to predict HDD productivity. This tool is coded in MatLab® language using the graphical user interface tool (GUI). The tool was used to test a case study. It was proved to be helpful for contractors, consultants and HDD professionals in predicting execution time and to estimate cost of HDD projects during the preconstruction phase in the environment of imprecise and noisy inputs.

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NOMENCLATURE & ABBREVIATIONS

NRC	National Research Council
TT	Trenchless Technology
HDD	Horizontal Directional Drilling
NF	Neurofuzzy
ANN	Artificial Neural Network
FL	Fuzzy Logic
PP	Productivity Predictor
AB	Auger Boring
PB	Pipe Bursting
MT	Micro-Tunneling
PJ	Pipe Jacking
LP	Lining of Pipe
RSR	Robotic Spot Repair
PS&E	Pipe Scanning and Evaluation
TCM	Trenchless Construction Methods
TRM	Trenchless Rehabilitation Methods
HEB	Horizontal Earth Boring
HAB	Horizontal Auger Boring
PR	Pipe Ramming
UT	Utility Tunneling
LOR'S	Localized Repair
CIP	Cured In Place

SL	Slip Lining
TP	Thermoformed Pipe
CFP	Close Fit pipe
PV	Pipe Removal
HDPE	High Density Poly Ethylene
PI	Productivity Index
PVC	Polyvinyl Chloride
ANFIS	Adaptive Neurofuzzy Inference Systems
FES	Fuzzy Expert Systems
HDD-PP	Horizontal Directional Drilling Productivity Predictor
GUI	Graphical User Interface
AVP	Average Validity Percent
AIP	Average Invalidity Percent
TAVP	Total Average Validity Percent
TAIP	Total Average Invalidity Percent

CHAPTER I

INTRODUCTION

Since the beginning of century, both Canada and USA, witness enormous challenge in continuous need for maintaining and repairing existing utilities in addition to increasing demand for constructing new utilities installations (power, telecommunications, water mains, and sewer). These operations are proven expensive, especially in crowded urban areas. In addition to cost involved for execution there are cost of ground surface repair (i.e., sidewalks, pavement, brick paving) and social costs due to traffic disruptions and unfavorable impact on nearby activities (Ariaratnam *et al.* 1999).

To face urgent demand of replacement or renovation of these aged utility networks, in addition to environmental constrains that are pressing to replace aged utilities, municipalities, utility companies and contractors started to seek alternatives to open cut methodology in order to install or repair their underground assets. Trenchless Technology (TT) proved to be a viable option due to its possible various alternatives of methods, materials and equipment (Allouche *et al.* 2000).

Trenchless technology has gained wide popularity among municipal engineers throughout Canada. Canadian municipalities spent $29.68/capita on new municipal construction service lines and $18.21/capita on rehabilitation of existing lines. Over period of 1994 to 1999, percentage of municipal projects, that utilized trenchless technology methods, had increased by 180% and 270% for new installations and rehabilitation, respectively (Ariaratnam *et al.* 1999). The present research focuses on horizontal directional drilling (HDD), since it is the most rapidly growing method in pipe installation techniques among trenchless family. The major advantage of HDD is that it can efficiently be performed in high dense urban areas with the least potential for settlement and minimal social, structural, road and environmental damages.

I.1. PROBLEM STATEMENT

At present, Canada and USA are facing a growing problem in rehabilitating their decaying underground utility systems. Because of rapid increase in need for utility service line replacement, with constraints that new installations or repairs should have minimum disruption to surface, demand for trenchless excavation methods such as horizontal directional drilling (HDD) has increased. These resulted in technology advancement towards achievement of efficient and cost effective utility installation, repair and renewal. The Canadian National Research Council emphasized that the rehabilitation of municipal water systems would cost about $28 billion from year 1997 to 2012 (NRC, 2004).

As common practice, productivity of trenchless technology methods is usually predicted using heuristic techniques to process expert opinions without considering effect of subjective factors. Contractors usually consider the average production rate of previous projects. This is mainly due to lack of models that predict productivity of trenchless techniques (Ali *et al.*, 2007).

Contractors, engineers, and decision makers are always facing a challenge to estimate the duration and cost of new pipe installations using HDD, due to the presence of subjective factors. The HDD process involves a large number of factors that must be considered for productivity prediction. Therefore, there is an emergent need for developing a dedicated productivity model designed to meet special industrial needs that are coherent with increased complexity and size of projects.

I.2. RESEARCH OBJECTIVES

The main goal of current research is to identify key factors that affect productivity of horizontal directional drilling (HDD) operations, and to predict productivity of HDD operations under different soil conditions. The research has the following sub-objectives:

- identify and study factors that significantly impact productivity of HDD operations,
- develop and validate a productivity prediction model for HDD operations, and
- develop an automated tool (Productivity Predictor) to assist professionals in predicting HDD productivity.

I.3. RESEARCH METHODOLOGY

The research methodology consists of the following seven steps:

1. Review of literature and problem formulation are carried out for identifying all input factors as well as HDD productivity prediction tools that are to be used in proposed system development. The review includes the following topics:

problem definition, factors affecting HDD applications, cycle time and exploring available techniques to deal with the current research problem.

2. Data collection is utilized to encompass: project information, cycle time and surrounding factors affecting HDD operations. Questionnaire is mainly used to collect both HDD operations information and activities duration. The collected data is used to develop neurofuzzy model.
3. Ranking/sorting productivity factors: Analytical Hierarchy Process (a quantitative comparison method) is applied to identify factors affecting HDD productivity and rank them according to their relative importance.
4. Neurofuzzy model development: the model is implemented to adapt the chosen neurofuzzy system for representing relationships between productivity and the identified input factors.
5. Neurofuzzy system verification and validation: involves neurofuzzy model testing for proper functionality in productivity prediction.
6. Sensitivity analysis is performed to observe inconsistent effect of main input factors on the model performance. Sensitivity analysis holds the studied HDD factor at actual values while other factors are kept at their constant average values.
7. Development of automated HDD productivity prediction tool: the tool is addressed in a user-friendly graphical interface for professional use.

I.4. THESIS ORGANIZATION

Chapter II presents a literature review, beginning with overall trenchless technology methods and ending with major disciplines needed for productivity prediction for the horizontal directional drilling pipe installation technique. It embraces HDD method, machine and equipment, factors that contribute to productivity prediction of water and sewer pipe installation and previous work done in productivity prediction. In addition, an overview of artificial neural network (ANN), fuzzy logic (FL), Neurofuzzy (NF), Analytic Hierarchy process (AHP) approaches and their application was performed. Consequently, abundance of analysis focuses on these approaches.

Chapter III provides illustrations of the proposed methodology and laying out the NF productivity prediction model. Moreover, it presents the automated; user-friendly graphical interface; and Horizontal Directional Drilling Productivity Prediction decision support tool (HDD-PP).

Chapter IV describes the established data collection procedure in this study. This chapter classifies data according to target soil type. In addition, it organizes collected data for further analysis and modeling.

Chapter V provides an overview of the AHP implementation framework, which describes and sorts main contributing factors to HDD productivity. It also illustrates NF framework that identifies input and output factors, explains model development and presents training and testing results. Moreover, it demonstrates model validation process. Finally, it presents discussion and analysis of results and pipe installation productivity curves for different soil types.

Chapter VI describes automated, graphical, user-friendly, productivity prediction decision support tool (HDD-PP). An application is designed to describe methodology and implementation and to demonstrate the potential of this productivity prediction tool. Finally, it presents discussion of results and limitations of the HDD-PP user interface.

Chapter VII presents conclusions, limitations and main research contributions. In addition, the chapter highlights future research recommendations.

CHAPTER II

LITERARURE REVIEW

Many of failing water and sewer pipelines are located in established urban areas, where applying excavation and open trench methods are difficult or almost impossible. With emerging need for installing new underground/underwater pipes or cables, trenchless technology was addressed as the best solution and the most effective option for new pipe installation. The most versatile method of the various trenchless procedures available is horizontal directional drilling (HDD). It is a proven and widely used technology for installing underground water and sewer pipes with minimal disturbance to surrounding area and the earth surface (Lawson, 2003).

II.1. TRENCHLESS TECHNOLOGY

The North American Society of Trenchless Technology (NASTT) defined trenchless construction as ''a family of methods, materials, and equipment capable of being used for the installation of new or replacement or rehabilitation of existing underground infrastructure with minimal disruption to surface traffic, business, and other activities''. Trenchless Technology (TT) has created new materials, methods and equipment for underground infrastructure rehabilitation and new installation methods as shown in Appendix (A). TT is a qualified alternative to replace the open trench method for underground constructions. It is applied to minimize environmental and social negative impact in addition to reducing the cost of underground works. It also provides cost effective infrastructure asset management. Contrary to open trench methodology, which causes major disturbances to surface activities, TT has minimal or no effect on earth surface. The TT family is divided into two main categories; construction and non-construction methods as shown in Figure (II.1).

Wilkinson (1999) stated the following negative social impacts of the open-trench pipe construction:

- Vehicular/pedestrian traffic: Often, roadways and sidewalks will be removed from daily use in order to place pipes beneath them.
- Worker safety: Trench safety is a major concern for contractors when performing open-trench construction.
- Interruption of local businesses: Local businesses are likely to lose customers due to resulting traffic disruptions associated with open-trench pipe construction. Residential: Major inconvenience, congestion, and delays are often imposed on neighborhoods and their residents due to open-trench pipe construction nearby.
- The increased number of pavement joints at patched surfaces increases maintenance resulting in additional traffic impacts and higher life-cycle costs.
- Existing utilities: During open-trench construction, existing utilities near the trench are often damaged during the trench excavation and from subsequent soil settlement.
- Soil disposal: Contaminated soil is sometimes encountered during pipe construction.
- Air pollution: Fine soil particles may become airborne, which can blow these fine soil particles from soil stockpiles created during the open-trench excavation.
- Water pollution: Water (rain or subsurface pumping discharge) can cause soil erosion and solids may runoff into streams, rivers, and storm sewers.

- Roadways: Open-trench construction often requires sawing, demolition, or removal of pavements followed by subsequent restoration. This significantly reduces pavement life by up to 40% (Stahli and Hermanson, 1996).
- Noise: Open-trench excavation requires the use of heavy equipment that produces levels of noise that cause disturbances to hospital, schools, business, and residences.
- Land defacement: Open-trench pipe construction frequently causes damage and can have adverse short-term effects on grass, trees, and other landscaping features.
- The no dig emerging TT eliminates the need of digging up roads or pathways for sewer, water, telecommunication and gas pipe installation, replacement or rehabilitation. Accordingly, trenchless technology allows for the reparation of pipes without having to excavate along the road section, thereby minimizing or eliminating traffic problems and save on road repair costs.

Eighty-seven municipalities in Canada have participated in a survey to provide an indication of current and future trends in the application of trenchless construction technologies in the municipal field (Ariaratnam *et al*, 1999). The survey concerned the percentage of projects that employed trenchless technology, frequency and type of technologies employed and contractor selection methods. The municipalities were asked to rank the technologies that had the highest possibility for future development. The results showed that for new construction techniques, the greatest potential growth was in horizontal directional drilling (HDD) followed by pipe bursting, auger boring, micro-tunneling, and pipe jacking. Table II.1, shows the summary of main advantages and disadvantages of the most commonly used TT techniques.

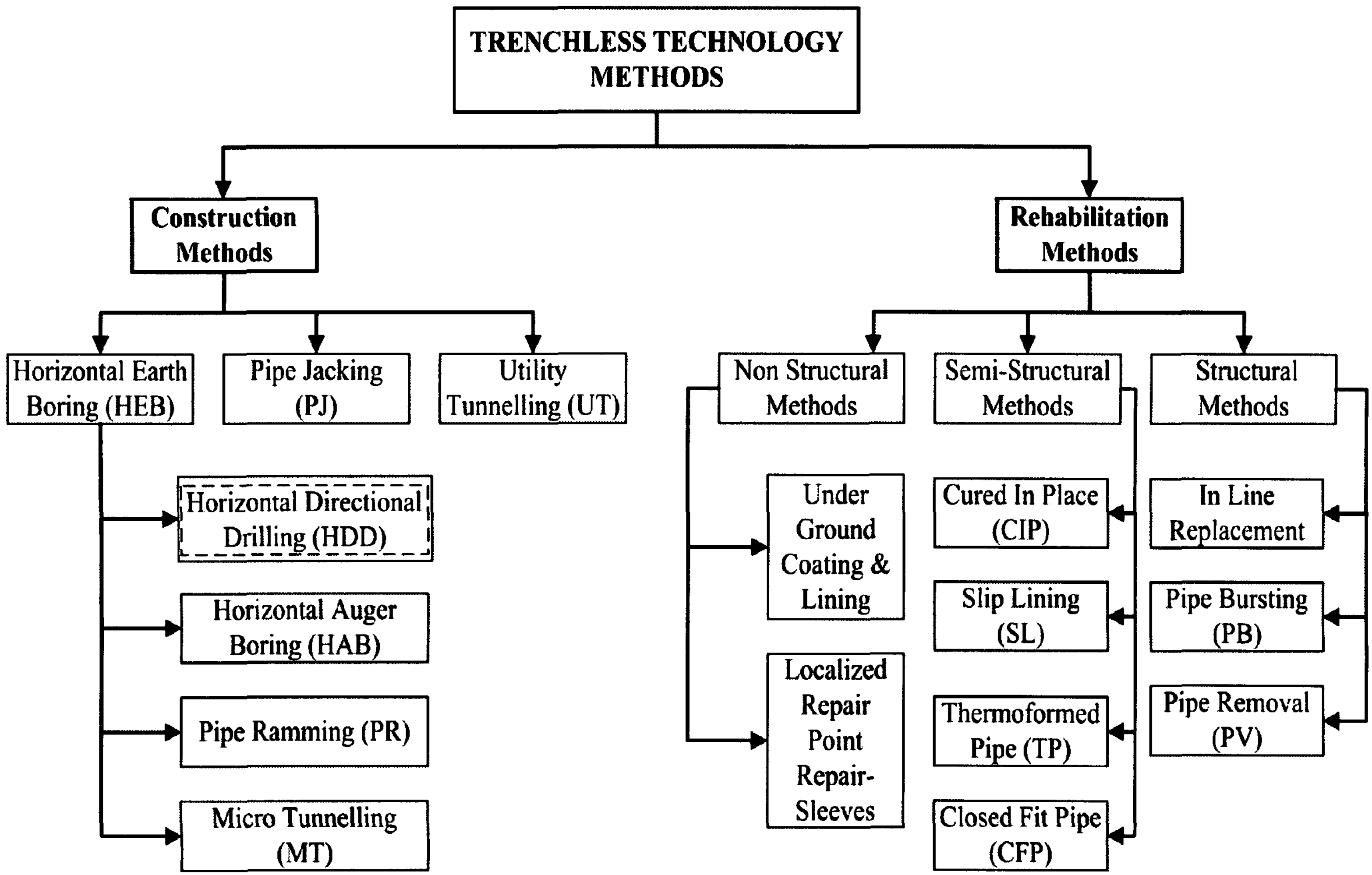


Figure II.1 Trenchless Technology (TT) Methods (Najafi, 2005)

Table II.1 Advantages and Limitations of Trenchless Technology (TT) Methods (Najafi, 2005)

TT Method	Advantages	Limitations
Horizontal Auger Boring	▪ Casing is installed as the borehole excavation takes place, and can be used in wide variety of soil types.	▪ Not successful in sands and unstable soils; requires dewatering under water table and needs initial setup.
Horizontal Directional Drilling	▪ Pipeline installation without serious incidents of hydro-fracture and the alignment can be maintained within acceptable limits. ▪ Large drilling equipment could be precisely located in underground operations with sophisticated tracking systems like GPS and GPR.	▪ Specific geotechnical investigation ▪ Accurate Planning and selection of suitable equipment and preparation of a proper work area is required ▪ Experience and qualifications of the contractor ▪ Three stages and equipment encumbrance difficult to launch in some downtown area.
Pipe Ramming	▪ Applicable to a wide variety of pipe lengths and sizes; can be used for driving vertical piles.	▪ No control over line and grade during ramming and it is a very noisy application.
Pipe Jacking	▪ Used in all types of soils ▪ High degree of accuracy obtained, and correction action is taken immediately ▪ Rapidly manually and electronically inspected ▪ Unforeseen obstacles identified and removed.	▪ Requires a lot of planning and coordination ▪ Pipes and liners should be strong enough to resist jacking forces
Pipe Bursting	▪ Applied to non-ductile types of pipes ▪ Ability to upsize the existing diameter by about 30% ▪ One pass for application, thus reduce cost of labor and time needed for replacement. ▪ Cleaning of host pipes not required	▪ Pipes used to replace the old pipes are HDPE ▪ All lateral services and fire hydrants connected to the host pipe main must be excavated and uncovered. ▪ Pulling force must be less than the new pipe tensile strength and that the outer diameter of the new pipe will not be damaged by the fragments of the host pipe. ▪ Any underground utility close to the host main must be excavated and exposed to avoid any damage to the bursting force.
Underground Coatings and Linings	▪ Minimal excavation space ▪ Can accommodate a variety of diameters ▪ Improves hydraulic characteristics, ▪ Services connections do not have to be excavated	▪ Pipe must be structurally sound, cleaned and dried, ▪ Services must be cleaned ▪ Minor reduction in internal diameter. ▪ Limit on bends less than 45 degrees

Table II.1 Advantages and Limitations of Trenchless Technology (TT) Methods (Najafi, 2005) (Continued)

TT Method	Advantages	Limitations
Cured-In-Place Pipelining	▪ Both structural and non-structural purpose, and without excavation or a little excavation ▪ Fast and simple way to install large pipe diameters ▪ Accommodating bends and deformation of pipes (ex: gaps, holes and cracks) ▪ Grouting required only at manhole and lateral openings if required with high corrosion resistant ▪ Minimal impact on neighborhood	▪ Cannot increase the diameter of the host pipe, and the old pipe alignment may result in structural problems. ▪ The curing process may create styrene, therefore the curing water must be removed from the job site. ▪ Safety measures related to hot water and steam must be considered. ▪ Every project needs different tubes or hoses which may not be available ▪ Bypassing of the existing flow is mandatory during the installation process. ▪ Cost-effective depending on situation.
Slip-Lining	▪ Does not require investment in costly specialized equipment; Simple technique ▪ Jacking pipes and fittings can also be used for SL ▪ Can be used for structural and non-structural purposes	▪ Reduction of pipe diameter ▪ Pit excavation is required for access during installation process ▪ For lateral connections, open-cut excavation is required. ▪ Grouting is generally required.
Thermoformed Pipe	▪ Installation process is faster since the pipe is manufactured at factory (efficient QA) ▪ No impact on the environment, since no use of chemicals. ▪ Reduction of the cross section of existing pipe is minimal. ▪ Can solve the corrosion problem of pipeline.	▪ Large working space is needed for Fused and expanded type. ▪ Diameter range availability is limited. ▪ Large working space is needed for Fused and expanded type. ▪ During the installation Bypassing of flow is required ▪ The location of valves and connections needed to be excavated.
Close Fit Pipe	▪ Efficient QA since the pipe is manufactured in factory ▪ Reduction in existing pipe diameter is minimal ▪ Solution for corrosion and water quality problems ▪ Can be installed up to 1000' and can accommodate 45 degree bends ▪ Possibility for internal lateral connections.	▪ Diameter range availability and installation length is limited. ▪ Large working space is needed for fused and expanded types. ▪ Bypassing of flow is required ▪ Services needed to be excavated. ▪ An insertion pit is required.

II.2. HORIZONTAL DIRECTIONAL DRILLING (HDD)

The HDD technology is one of the horizontal earth boring methods that belong to the trenchless technology construction methods. It is employed in the installation of several kinds of underground facilities. Industrial applications vary across civil engineering fields from the installation of natural gas and utility conduit pipelines, through municipal applications, water mains, gravity sewers, to environmental and geo-construction applications such as geotechnical investigations and remediation of contaminated sites (Allouche et al., 2000).

Horizontal Directional Drilling (HDD) is a trenchless technique, which proposes several advantages over traditional open-cut methods. The HDD was originally developed by the oil industry in the United States in which this technique is now widely used for installing all pressure pipes under obstacles such as motorways, large rivers and airport runways. A steerable drill bit of 90mm diameter starts digging from the earth surface and generates a pilot hole. Upon completion, the pilot string is removed and a rotating reamer is attached to travel back along the pilot hole. Subsequent reaming continues until the required diameter is achieved. (Allouche *et al.*, 2000; Ariaratnam and Allouche, 2000; Ariaratnam, 2005).

According to Allouche *et al.* (2000), it was found that the majority of pipes installed using the HDD technique are for 100 mm or smaller diameters, which was about 72% of the total pipe products installed. Products in this diameter range are mostly used in telecommunications (e.g. fiber-optic), natural gas distribution systems, electrical conduits and environmental applications. Pipes in the range of 150 mm to 300 mm are found to have 16 percent of the total product line installed. This diameter range is typically utilized in crude oil and natural gas delivery systems, municipal applications (i.e. water and sewer pipelines) and industrial applications. Only 12% of all product installations account for pipes over 300 mm in diameter, where these pipes are mainly used for utilizing water trunk lines, sewers and transmission lines. HDD equipment consist of five group components as explained in Appendix (B): 1) Drill rigs, 2) Bore drilling, 3) Drilling fluid system, 4) Tracking system, and 5) Accessories.

Allouche *el al.* (2000) reported that traditional open cut excavation has been gradually replaced by HDD in various cases because of the high costs associated with utility conduit installation in crowded urban areas (i.e. traffic control, the need to dig around existing utilities and restoration costs), consideration of social costs (i.e. traffic delays, distraction of business activities) and environmental regulations (i.e. placement of pipelines across rivers, and other environmentally sensitive areas). Allouche *et al.*, (2003) stated the advantages of the HDD technique over other trenchless technologies as: 1) no need for vertical shafts as drilling starts from the surface, 2) short installation and setup time, 3) flexibility of borehole elevation alignment and maneuverability around the existing underground services, and 4) one single drive installation length is longer than any other non-man entry trenchless method.

II.3. PRODUCTIVITY OF TRENCHLESS TECHNOLOGY METHODS

According to Ali *et al.* (2007) most of the factors that affect productivity of the TT techniques are subjective factors, which are usually predicted using heuristic techniques and expert opinions. These factors complicate the productivity assessment process. In addition, there is a shortage of models that predict productivity of trenchless techniques. There are two main steps for TT productivity estimation: 1) assessment of the effect of subjective factors on productivity and how it can be quantified and 2) quantitative factor assessment (i.e. duration of activities, labor, equipment rates, etc.). Ali *et al.* (2007) have developed a methodology for calculating the productivity Index (PI) in order to represent the subjective effect in refining productivity assessment. The proposed PI model was developed using AHP and Fuzzy Logic (FL) based on 12 sub-factors categorized under three main categories as shown in Figure II.2:

1. Management Conditions
   - Managerial skills, safety regulations, mechanical conditions and operator skill
2. Environmental Conditions
   - Unseen soil obstacles, water table level, soil conditions and site conditions
3. Physical Conditions
   - Pipe type, pipe usage, pipe length and pipe depth

The designed tool demonstrates its robustness in assessing the PI with 89% validity. Due to the limitation of collected data, the developed models are limited to new HDD and Micro-tunneling operations, in only clay and sand soils (Ali et al., 2007).

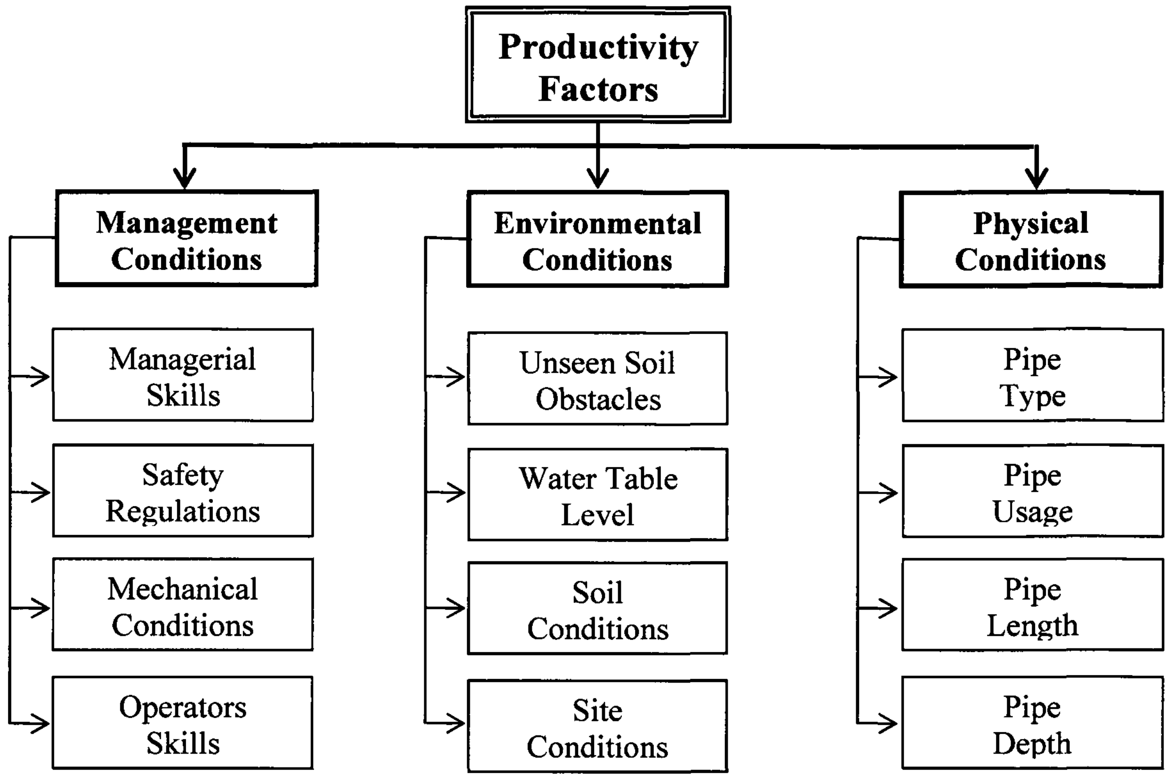


Figure II.2 TT Productivity Qualitative Factors (Adopted form Ali *et al.*, 2007)

II.3.1. Previous Work in Micro-Tunneling Productivity

Nido *et al.*, (1999) identified the factors that influence micro-tunneling productivity based on expert opinion:

- Cutting Head
- Soil Conditions
- Separation equipment
- Geotechnical investigation
- Use of intermediate jacking station
- Water jets at the excavation face
- Use of appropriate machine type
- Obstruction or unusual soil conditions
- Groundwater conditions
- Slurry flow rate
- Straight Vs curved alignment
- Use of lubricant
- Crew/operator experience
- Drive length
- Pipe section length
- Pipe material
- Shaft design
- Technical support
- Restrictions to working hours
- Rotating cutter torque

The limitation of Nido *et al.*, (1999) work was that the significance/effect of the above factors on productivity of micro-tunneling operations was not presented. However, understanding the relative importance of these factors is very essential. Actual data was collected by Nido *et al.*, (1999) to predict the productivity of the micro-tunneling machine with a diameter of 305mm using simulation techniques. Penetration rate, cycle time, and daily production were recorded. On the other hand same factors were predicted for a number of percentage combinations of sand and clay. The research concluded that soil condition has the most significant influence on productivity, followed by the jacking system, which affects the operation performance (Nido *et al.*, 1999).

Based on a pilot survey conducted to validate and rank twenty factors that affect micro-tunneling productivity, Hegab (2003) developed a statistical productivity model for micro-tunneling operations. Preparation, delay and penetration times were modeled. A deterministic technique was used to predict the penetration time in different soil types, while a probabilistic technique was used to predict preparation and delay times. The factors are classified into four categories to facilitate the analysis of the results. The most important category was found to be the underground conditions followed by the operator's experience. This was followed by the system mechanism and finally "others". Productivity factors were ranked as follows:

1. Soil Conditions
2. Geotechnical investigation
3. Crew/operator experience
4. Obstruction or unusual soil conditions
5. Use of lubricant during tunneling
6. Rotating cutter torque
7. Jacking thrust and its maximum limit
8. Separation equipment
9. Curved alignment
10. Machine type
11. Shape of cutting tool
12. Drive length
13. Technical support
14. Working hours
15. Slurry flow rate
16. Water jetting
17. Shaft design
18. Ground water condition
19. Pipe section length
20. Pipe material

In order to calculate the overall productivity of the micro-tunneling machine for different soil types, Hegab (2005) used 17,000 data points collected from thirty-five micro-tunneling projects to develop a probabilistic model using statistical regression techniques. The developed model is considered as a tool to help the contractor estimate costs in bidding phase before any operational data has been obtained. It should be noted that quantitative factors were only considered in this research. Nevertheless, most of the factors affecting the productivity analysis are qualitative where the soil type has the largest influence in productivity prediction (Hegab, 2003). However, it was hard to incorporate this factor in a statistical model due to the lack of sufficient data. Therefore, the proposed factors that are affecting the project time prediction model were driven length (L), machine diameter (D) and number of driven pipes (n). The overall time was given as follows:

$$\textit{Overall Time} = \text{Penetration Time} + \text{Preparation Time} + \text{Delay Time}$$

Equation II.1

According to Hegab (2005), soil was classified according to its shear strength, into three categories:

1. Soil with high shear strength (hard clay and dense sand (H/D Soil)).
2. Soil with medium shear strength (medium clay and medium sand)
3. Soil with low shear strength (soft clay and loose sand (S/L Soil)).

The model developed by Hegab (2005) was limited to the applications with drives of length less than 400 m., diameters between 400 and 1760 mm., a jacking force of 700 tones, and shearing forces less than 300 tones.

II.3.2. Previous Work in Auger Boring Productivity

According to Iseley and Gokhale (1997), which defined the factors affecting the selection of trenchless technology methods; and Nido *et al.* (1999), which identified the factors affecting the micro-tunneling methods; Salem *et al.* (2003) found that upon conversations with auger boring contractors, it was found that micro-tunneling and auger boring productivity factors are common. The main factors affecting auger boring are as follows:

1. Cutter head
2. Boring machine and equipment
3. Drive length, Length of pipe section
4. Accuracy of geotechnical investigation
5. Soil condition
6. Crew and operation experience
7. Diameter of borehole and casing needed for installation
8. Installation depth
9. Obstruction or unusual soil conditions
10. Ground water conditions
11. Restriction to working hours
12. Appropriateness to auger boring method
13. Accuracy of line and grade
14. Existing under/above ground utilities and structures
15. Pipe alignment and laying path.

Research was conducted by Salem *et al.* (2003) in order to study the effect of bore length on productivity and cost of auger boring operations. Two simulation models were developed using Micro-CYCLONE and Arena to simulate the auger boring process and predict its productivity. Both simulations illustrate that as the bore length increases the productivity increases. This is due to the fact that when repetition of drilling and auger removal cycles at one location are increased, the number of shafts, necessary blocks and installation time are reduced. This model was limited only to the effect of bore length on auger boring productivity and cost. However further studies are essential to understand the influence of other factors like casing diameter on productivity and cost, and to obtain a more accurate tool to help contractors in planning, productivity prediction and cost estimation.

II.3.3. Previous Work in HDD Productivity

Over the last 15 years, the horizontal directional drilling (HDD) industry in North America has grown from a few contractors concerned about a few directional drilling units operations, to a multi-billion dollar industry (Kirby *et al.*, 1997). During 1998, about 20 million meters of underground pipes were installed across North America through the use of approximately 6,000 directional drilling rigs, where it was owned and operated by hundreds of devoted HDD contractors and general underground construction corporations (Allouche *et al.*, 2000).

At present, Canada and USA is facing a growing problem to rehabilitate its decaying underground utility systems (Ali *et al.*, 2007). Currently, HDD has become the chosen method for new underground conduits and pipeline installations (Lueke and Ariaratnam, 2005). The number of HDD contractors has increased as a result of the growth in size and difficulty of the HDD projects. Therefore, there is a need to develop devoted software to meet the special needs and requirements of the industry (Allouche et al., 2003). Due to the lack of HDD productivity prediction models, the research literature is extended to productivity prediction models of earth boring trenchless technology techniques (i.e. micro-tunneling, auger boring), in addition to the available horizontal directional drilling previous works.

Allouche *et al.* (2000) stated that the subsurface conditions and pipe diameter are the two main factors affecting productivity in the utility projects. In his research, contractors were required to identify the average productivity rate in terms of meters per day (based on an 8-h day). The following conclusions were obtained:

- Productivity decreases when pipe diameter increases.
- Drilling in clay and silty clay resulted in the highest productivity scores.
- Drilling in cobble and gravel resulted in the lowest productivity scores.
- Drilling in sand and sandstone resulted in reasonably satisfactory productivity rates.

A comprehensive geotechnical investigation is essential to determine the suitability of the trenchless installation technique and the potential productivity of construction. Productivity is highly dependent on the geological makeup of the working area, therefore it is always difficult to predict with certainty, since the borehole only gives a snapshot of the ground at one small location (Dubey *et al.* 2006).

i. Deterministic Productivity Model for HDD

Dubey *et al.* (2006) developed a deterministic productivity assessment model for HDD. Data was collected from several contractors in Canada and the USA. The model was validated through two case studies:

- 40 mm PE Pipe inserted beneath a green area for a distance of 880 ft in sandy soil.
- 60 mm HDPE inserted in a roadside area in a sandy soil.

Two regression linear models were designed between bore length and cycle time, to calculate the productivity of HDD operations.

The study considered several factors in order to have a full productivity prediction of the entire HDD installation process as follows:

- soil Type (sand and silty sand),
- rig size and capabilities,
- drilling bit (compaction head or mud motor),
- pipe/cable [material (HDPE, steel), diameter, and type of connection,
- bore characteristics (length and curvature),
- connection type between pipe segments (fusing, joint),
- operator skill,
- weather conditions,
- job and management conditions, and
- steering problems (correction in direction).

Dubey et al., (2006) defined two main steps to set different productivity factors: first major HDD steps (pilot hole drilling, pre-reaming/Hole enlargement and pipe pull back) and second minor HDD steps (rod angle adjustment at the entrance, joining of drill pipe segments, attachment of reamer with shackle for pre-reaming, connection of pipe/cable segments, pipe assembling for the pullback and tracking and monitoring). The skills of contractor and his or her expertise, coupled with the geological conditions of soil, were found to be the most significant considerations for HDD operations productivity.

The study considered the connection type between pipe segments (fusing, joint) as a quantitative factor which will be considered in site preparation time. This is a major limitation. In addition, in some cases, pipe connection time may exceed the site preparation time. Moreover, uncertainties were not considered in this study.

ii. Software for Planning and Cost Control in Directional Drilling Projects

Allouche et al., (2003) developed two computerized applications tailored for the HDD industry. The first is an integrated data management system for trenchless contractors (IMS-TC) that combines asset management, cost control, estimating, and project tracking capabilities, enabling decision makers to intimately monitor field performance in terms of expenses and productivity, see Figure II.3. The second is a simulation model developed to optimize the utilization of drilling rigs and hydro-vacuum trucks on large-scale urban projects.

II.4. NEUROFUZZY APPROACH

The integration of neural networks and fuzzy logic are receiving attention for use in the development of real-world applications (Medsker, 1996). A neurofuzzy approach refers to a hybrid of artificial neural networks and fuzzy logic.

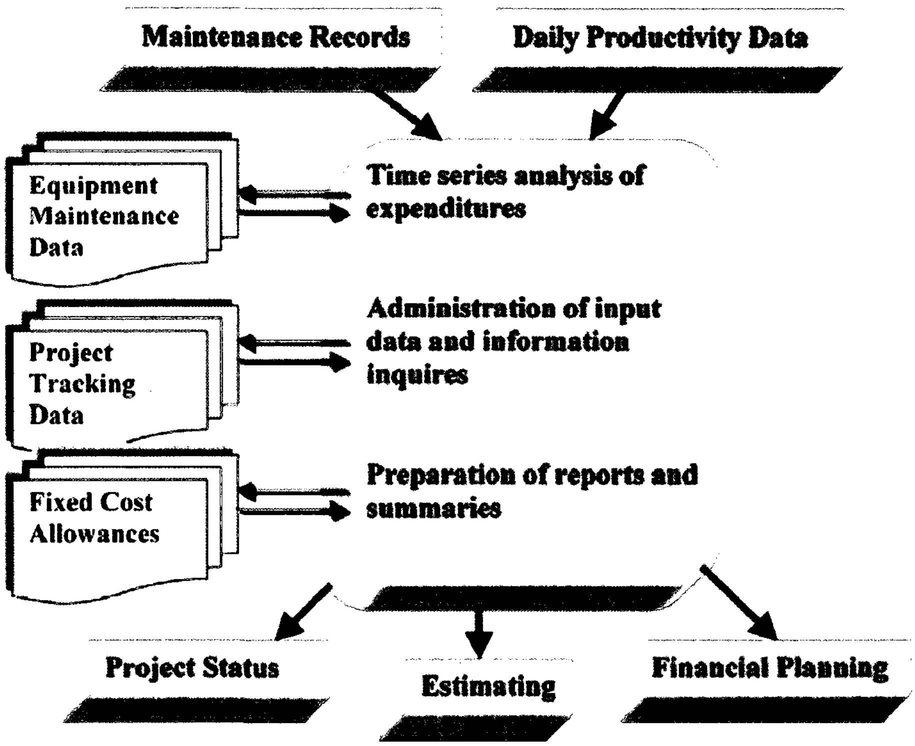


Figure II.3 Conceptual Layout of IMS-TC (Allouche *et al.,* 2003)

II.4.1. Artificial Neural Networks (ANN): Theory and Applications

Neural Network Technology mimics the brain's own problem solving process. Similar to human thinking and decision-making ability, a neural network takes previously solved examples to build a system of neurons that makes new decisions, classifications and forecasts. Neural network learns patterns that are being presented to it during the training or learning phase. During the course of training, it develops by itself, the ability to generalize, thereby becoming able to correctly classify new patterns or to make forecasts and predictions.

Network Structure: The basic building block of neural network technology is the simulated neuron. An independent neuron is interconnected into a network. The neuron processes a number of inputs fed into it, to produce an output in terms of network classification and predications as shown in Figure (II.4). The neurons have weights associated with them that are applied to the values passed from one neuron to the next. A group of neurons is called a slab. Neurons are also grouped into layers by their connection to the outside world. There are three types of layers as shown in Figure (II.5). The first input layer takes the inputs from the user, whereas the last layer (output layer) shows the network output. Neurons in between the input and output layer are in the hidden layer(s). A layer may contain one or more than one slab of neurons.

Network Learning: A typical neural network is a back propagation network that normally has three layers of neurons. Input values in the first layer are weighted and passed to the second hidden layer. Neurons in the hidden layer fire or produce outputs that are based upon the sum of the weighted values passed to them. The hidden layers pass values to the output layer in the same fashion, and the output layer produces the desired results. The network learns by adjusting the interconnection weights between the layers. The answers that the network is predicting are repeatedly compared with the correct answers, and each time the corresponding weights are adjusted slightly in the direction of the correct answer depending upon the settings chosen for learning rate and momentum. Eventually, if the problem can be learned, a stable set of weights adaptively evolves and produces good answers for all of the sample decisions and predictions.

Neural Network Modeling Applications: Since the proposal of the back-propagation algorithm, a number of successful neural network models have been developed (Fletcher and Goss 1993; Karunanithi *et al.*, 1994; Refenes *et al.* 1994; Faghri and Hua 1995; Goh 1995; and Chua *et al.*, 1997). The application of neural networks in civil engineering can be traced to the late 1980s (Zafar, 2005).

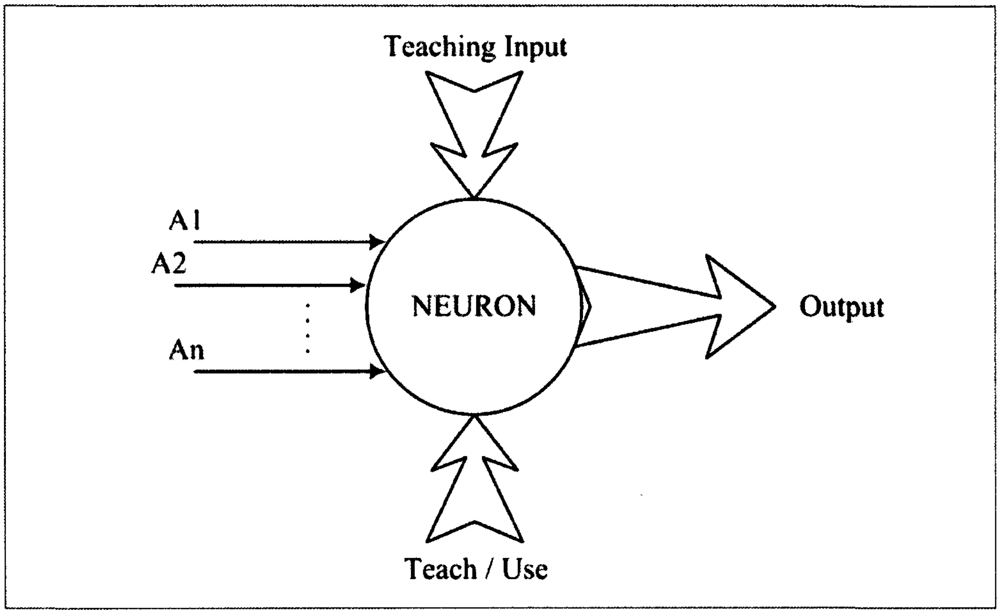


Figure II.4 Neuron –The Information Processing Unit

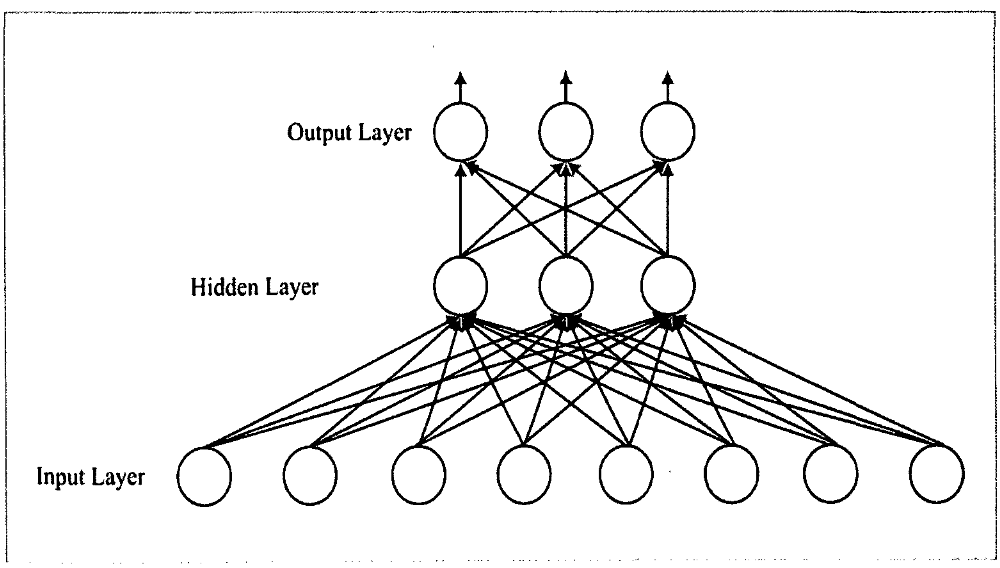


Figure II.5 Typical Back Propagation Neural Network Architecture

Karshenas and Feng (1992), and Chao and Skiniewski (1994) developed neural network models to analyze the productivity of earth-moving equipment and predict excavator productivity, respectively. Their studies examined the effect of the operational elements on the productivity. Portas and AbouRizk (1997) developed a neural network model to predict the productivity of concrete formwork tasks in construction operations. Abu Rizk and Hermann (2000) estimated the industrial labor productivity by developing a probability inference neural network model. Another neural network methodology is presented by Abu Rizk (2001) in developing a model for the estimation of industrial labor production rates.

Moselhi (2005) introduced a neural network model capable of quantifying the impacts of change orders on construction labor productivity. Samer and Sharara (2006) developed three productivity estimation models to calculate the concreting time using the artificial neural network (ANN). Productivity estimation models have been developed to estimate the productivity of formwork assembly, concrete pouring and steel fixing activities. The artificial neural network (ANN) approach was used in developing these models in order to overcome the variability and impact of subjective factors on the cost of concrete-related activities in developing countries. The study considered fourteen qualitative and quantitative factors. The developed framework results indicate a relatively strong generalization capability. In addition, the sensitivity analysis of the input factors that are influencing the productivity of the developed three models, demonstrated a good potential in identifying trends of these factors. Elwakil *et al.* (2009) developed a NN model to predict the performance of a construction organization based on estimated values of its success factors.

II.4.2. Fuzzy Logic: Theory and Applications

The potential of fuzzy expert systems lies in their ability to handle imprecise, uncertain and vague information used by human experts. Fuzzy knowledge based expert systems are of two types; subjective and objective. The objective models are constructed from input and output data of the system by using a systematic process with a specific objective function. In either case, a set of Fuzzy IF–THEN rules forms the fuzzy knowledge based body of the system. This fuzzy knowledge based system identification and modeling process is composed of two parts; variable identification and factor identification.

In variable identification, the significant variables of the system are identified among the set of possible variables, as shown Figure (II.6). In factor identification, the factors of the knowledge based systems that describe the relationship between input and output variables are identified. These are the factors of the membership functions (i.e. the factors describing the rules). For variable identification and modeling a problem, fuzzy clustering is utilized. Fuzzy clustering is a process to obtain a partition Z of a set A of N objects x_i = (1, 2, 3,.....N) using a resemblance or dissemblance measure such as distance measure 'd' between x_i and x_j, where i, j =1, 2, 3...N. A partition Z is normally a set of disjoint or partially overlapping subsets of A, and the elements ZC of Z are regarded as clusters centers. The intended purpose of clustering is to segregate the data into its natural grouping sets to produce a concise representation of a system's behavior.

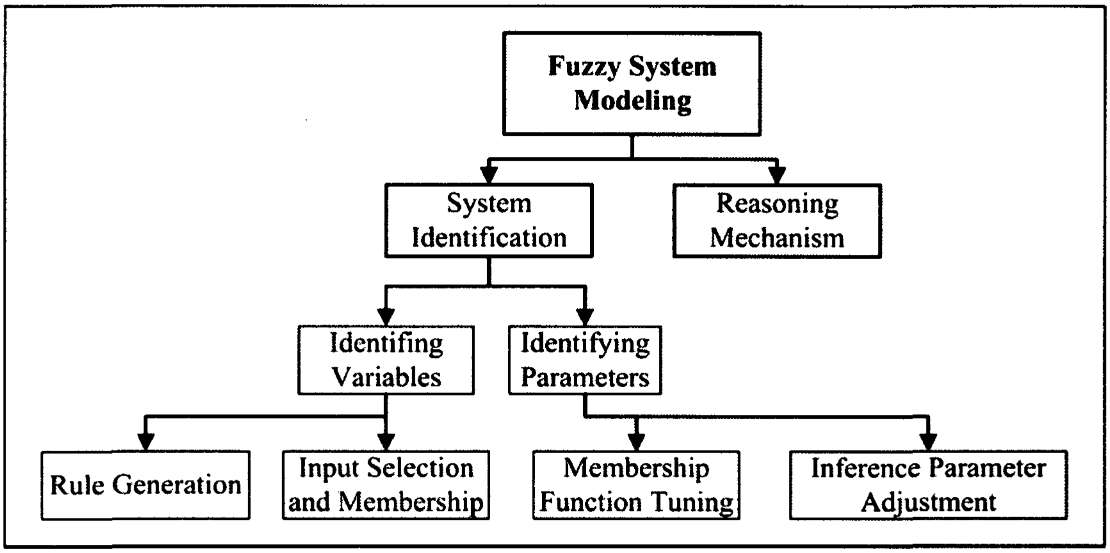


Figure II.6 Schematic of Fuzzy System Modeling

Fuzzy Logic Modeling Applications: During the last decade, "Fuzzy Techniques" have been increasingly applied to the construction management research discipline (Albert *et al.*, 2009). Fuzzy logic applications can be seen in the disciplines of project scheduling (Ayub and Hadlar, 1984), resource strategies (Padilla, 1991), resource constrained scheduling (Loterapong, 1984), and project network analysis, (Loterapong and Moselhi, 1996).

Zayed and Halpin (2004) developed a productivity index model using analytic hierarchy process (AHP) and Fuzzy Logic to assess the effect of subjective factors on the productivity of bored pile construction. Fayek and Oduba (2005) developed a model to predict labor productivity of two common industrial construction activities; rigging pipe and welding pipe. The fuzzy expert systems were used in developing these models in order to overcome the impact of variability and subjective factors on real world activities. The application of fuzzy expert systems (FES) framework based on fuzzy IF-THEN rules, relates the linguistic input and output factor(s) together. The IF-THEN rules are composed of fuzzy premises and fuzzy conclusions, which are represented by the membership functions of the input and output factors, respectively.

II.4.3. Neurofuzzy Systems: Theory and Applications

The application of the neurofuzzy technique is based on the integration of the explicit knowledge representation of the fuzzy logic with the learning power of the neural networks (Simon and Biro, 2005). A common characteristic of neural and fuzzy systems are model-free function estimators that can be adjusted or trained for improved performance, where they are by nature readily implemented with parallel processing techniques. Neural networks consist of a connection among a distribution of nodes. In addition, fuzzy systems process rules that associate, in parallel, fuzzy inputs with fuzzy output sets (Medsker, 1996). Neurofuzzy logic can be implemented throughout different types including, Neurofuzzy Systems for Function Approximation, NEFPROX (Nauck and Kruse, 1999), Adaptive Neurofuzzy Inference Systems, ANFIS (Jang *et al.*, 1997), and Adaptive Spline Modeling of Data, ASMOD (Bossley, 1997). The ASMOD split the model into smaller sub-models using the involved global partitioning. One option of integrating neural networks incorporating fuzzy techniques and produce an improved performance neural network, is to allow the neurofuzzy network to receive and process fuzzy input.

Another approach is adding layers on the front end of the network to "fuzzify" the crisp input data to the fuzzy neural processing. The fundamental concept used in many approaches to integrate fuzzy and neural network is the fuzzy neuron. Nodes in every layer in networks that maps fuzzy input to crisp output can have modified neurons. The mechanism of a neurofuzzy system can simply be explained as having the input vector consist of a set of fuzzy values, as well as having the connection weights of the nodes to the nodes in the previous layer in fuzzy values, as shown in Figure (II.7). In addition, the weights and input values are each represented by a membership function. A further summation process is implemented to find the product of the membership function of the fuzzy inputs and weights and then add the resulting membership function to get another single that represents the integration of weighted fuzzy inputs to the node. Lastly, a final operation takes place on the resultant finding out a crisp value for the node output (Medsker, 1996).

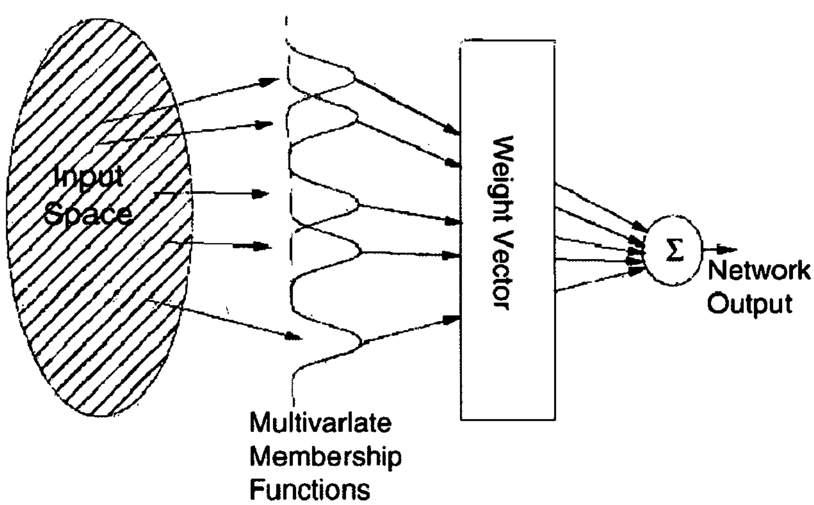


Figure II.7 Basic Structure of A Neurofuzzy System (Adapted from Bossley, 1997)

Neurofuzzy methods provide supervised learning methods. The heuristic methods combine the two learning steps of competitive learning with the idea of error back propagation. After a system output is computed by a forward propagation, an output error is identified by comparing the given sample output data with the system output. The neural networks can be used as the design and tuning tool for the fuzzy system where, fuzzy principles can be used in the neural network design embedding fuzziness in the internal workings of the basic neural system (Medsker, 1996).

A Major limitation of the fuzzy systems is that as the number of system inputs and outputs increases, the designing of the fuzzy rule base becomes complicated. Neurofuzzy networks can have three main functions, as shown in Figure (II.8). The starting layers process crisp input data by assigning groups of nodes to the linguistic variable labels and implementing membership functions in nodes (Medsker, 1996).

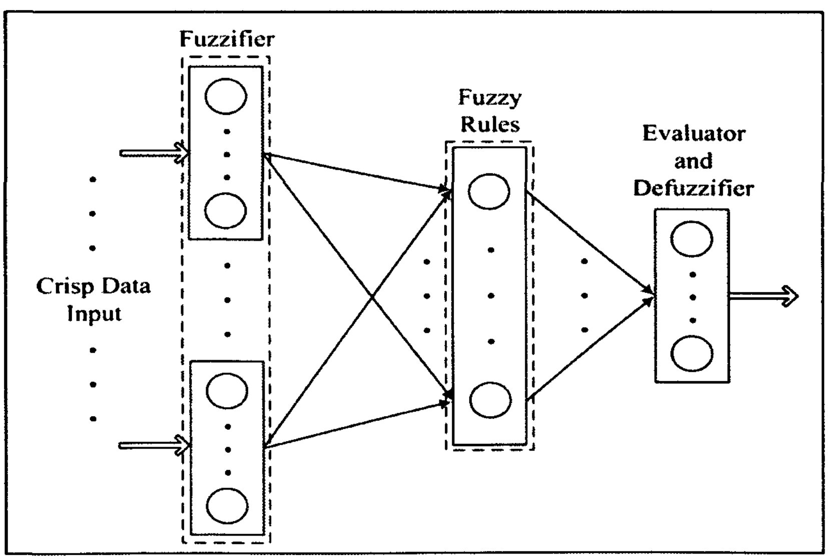


Figure II.8 High-Level View of a Neuro-fuzzy Network

Therefore, crisp input data can be transformed into membership function values that represent the output of the first layers of nodes. These values move to the layers that function as fuzzy rules operating on the fuzzified input. Finally, the last layers collect the results of applying the rules and defuzzify the results to get crisp values that can receive further processing as part of a decision or control system, or become outputs of the network. The neurofuzzy network can be implemented as several layers of nodes, where these first layer nodes can correspond to the different crisp values in the input vector. Furthermore, they can distribute those values to sets of nodes in the second layer which represent the different linguistic variables (Medsker, 1996), as shown in Figure (II.9).

Research and development addressing the neurofuzzy approach is proceeding at a rapid rate as of the distributed nature of neural and fuzzy systems, which provides such rich opportunities for creative combinations of the two for powerful, useful implementations. The goal of fuzzy systems is to mimic the aspect of human cognition that can be called approximate reasoning, in which it is more like our every day experiences as human decision makers. Fuzzy systems allow users to give inputs in imprecise real-world situations and reason terms like tall, large or rarely and use them to give either fuzzy or precise advice (Medsker, 1996).

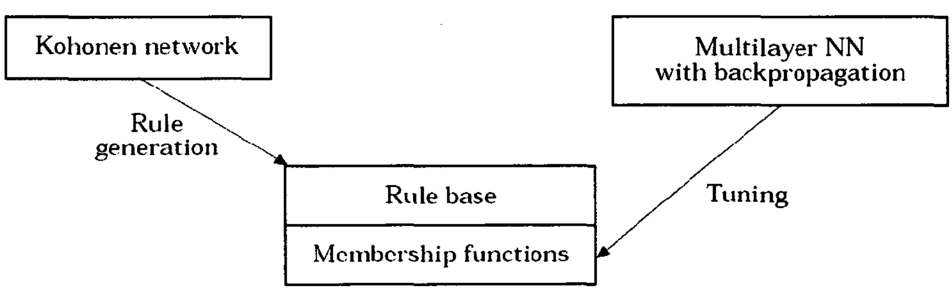


Figure II.9 Overall Architecture for Neurofuzzy Learning Control System (Medsker, 1996)

Neurofuzzy Modeling Applications: Symeon (2004) utilized the neurofuzzy systems and multidimensional risk analysis algorithm to present a methodology for reaching the optimum bid markups in static competitive bidding environments. In order to assess the engineering performance in industrial construction projects, engineering performance predicting models were developed by Georgy (2000); Georgy *et al.*, (2005) and Georgy and Chang (2005) to predict such performance by utilizing the neurofuzzy intelligent systems. The data set used for the study consisted of 50 industrial construction projects, in which the model was developed based on 25 input parameters.

A performance prediction model is developed to estimate the engineering performance in industrial construction projects. A neurofuzzy approach is used in developing this model because of their fault tolerance, ability to model nonlinearity and their systematic procedure for modeling linguistic variables. The application of NF network framework passes through two phases; training and validation. In the training phase, the qualitative variables are translated into numeric format (i.e. project size, contract type). The training phase consists of five steps that are: 1) data input, 2) data fuzzification, 3) intermediate layer, 4) data defuzzification and 5) data output. In the validation phase, the data subset is fed into the trained NF network to generate the outputs that will be later compared to confirm the neurofuzzy model validity. Based on different factors such as; project size, contract type, relative size of project, relative level of complexity and site conditions, an engineering prediction model is developed.

Twenty-five input variables (three numeric and 22 linguistic) are identified and selected based on data availability. The system architecture is composed of ten NFs. Each network deals with one of the identified performance measures, in which 10 performance measures are addressed. Chae and Abraham (2001) developed this model by obtaining data from the Sewer Scanning and Evaluation Technology (SSET) for the City of San Jose, California. The development of the automated interpretation system using ANN's is divided into four steps – image acquisition, preprocessing, defect recognition using multiple neural networks, and estimation of overall condition using fuzzy system, as shown in Figure (II.10). A fuzzy implication technique identifies, classifies and rates pipe defects while minimizing the errors from the neural network system. The major advantage of using a fuzzy system is that instead of sharp switching between modes based on break points, the outputs can glide smoothly from regions where the system's behavior is dominated by either one rule or another. The distance between joint and crack is taken between 0 to 10, where 10 signifies a large distance, and number of cracks detected is taken 0 to 20, where 20 is the maximum number of cracks in a pipe section.

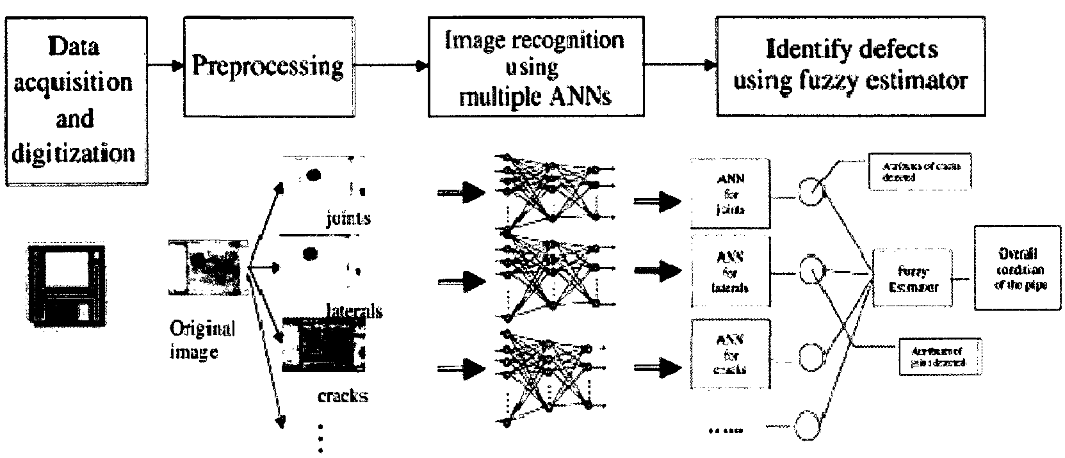


Figure II.10 Model Methodology Using NeuroFuzzy System

(Adopted from Chae and Abraham, 2001)

II.5. NEUROFUZZY SYSTEM VS NEURAL NETWORKS

Shahin *et al.* (2003) developed a model to predict the settlement of shallow foundation on granular soils. The model is also used to provide a better understanding regarding the relationships between settlement and the factors affecting settlement. The model is developed by using neurofuzzy techniques to overcome the multi-layer perceptions (MLPs) shortcoming, which occurs in the knowledge that is acquired during training, is distributed across their connection weights in a complex manner that is often difficult to interpret. Therefore, in MLPs it is difficult to quantify the rules governing the relationships between the network input/output variables.

The results indicate that neurofuzzy networks are able to make good predictions for the settlement of shallow foundations on granular soils and are able to provide a clear understanding of the relationships between settlement and the affecting factors. Also, the results indicate that modifying neurofuzzy networks by fitting it in existing engineering knowledge can enhance model performance and improve the constructed model interpretation.

Neural networks play a significant role in detecting complex non-linear relationships between a set of inputs and outputs. In addition, they aid in the estimation of the magnitude of the relationships without requiring a mathematical description regarding how the output functionally depends on the input (Taylor, 1996). However, the neural network interpretation cannot be expressed in a simple form (Colobourn, 2003). Nevertheless, the use of sensitivity analysis makes it possible to interpret simple models

(Olden and Jackson, 2002). Therefore, hybrid systems are needed, as it is difficult to handle complex models with large numbers of inputs. Neurofuzzy is one approach to increase insight (Shao *et al*, 2006) where it integrates the generality of representation of fuzzy logic with the adaptive learning capabilities from neural networks (Zadeh, 1965). Neurofuzzy not only can produce predictive models as a neural network, but it also generates understandable rules in an "IF-THEN" format explicitly representing the cause-effect relationships (Shao *et al.*, 2006).

Shao *et al.*, (2006) compared the performance of neurofuzzy logic and neural networks as applied to an immediate release tablet formulation database. Both approaches are successful in developing quality models that gave good predictions. Neural network models showed a better capability of predicting unseen data than neurofuzzy logic models (as judged by validation R2). Nevertheless, neural networks are not able to show or give information about how output is reached. In addition, while training new data, the existing knowledge held by the trained network can be lost. Conversely, the neurofuzzy technique has the advantage of generating understandable and reusable knowledge. The generated neurofuzzy rule sets revealed the hidden knowledge from within the interrogated data set.

II.6. ANALYTIC HIERARCHY PROCESS (AHP): Theory and Applications

Saaty, (1982) stated that construction hierarchies, establishing priorities and logical consistency form the basis for analytical problem resolution. Ersoz, (1995) defined AHP as a theory of measurement that deals with qualitative and/or intangible criteria that affect a decision. Saaty, (1982; 1991) addressed several steps to model a problem using AHP, which are summarized as follows:

1. Setting up hierarchy

Problem definition and development of a hierarchy, which defined problem by breaking it down into its components, are carried out.

2. Pair-wise comparison matrix

Through the use of a pair-wise comparison matrix that compares the identified factors with themselves, the AHP structure relation is established. The main matrix diagonal has a value of one, where the elements below the main diagonal are the reciprocal of the elements above.

3. Assigning Priorities

The matrix is then filled by numerical values representing the relative importance of one factor over the others based on the common attribute they share to achieve the main goal. A priority ratio could be established based on a qualitative scale of 1 to 5 or 1 to 9. This method could be applied on both qualitative and quantitative data. The higher the factor value the greater the relative importance will be.

4. Establishing priority vector

Saaty (1982) developed the eigenvalue method and used it to calculate the weighting vector for each pair-wise matrix. The overall priority weights for each factor are achieved by using the matrix eigenvalues according to Saaty's (1982) method. The results provide the relative weights for each factor on a scale out of 1.0. The weight of each factor represents its relative importance among all factors.

5. Logical consistency

Calculating the consistency ratio helps decision makers check on the previous step by verifying that the achieved results are acceptable and the consistency ratio is equal to or less that 10%. If inconsistent results of more than 10% were achieved, then decision makers have to repeat the weighting process until a consistent result of 10% or less is achieved.

6. Combining priority weights

Lastly, decision makers linearly combine the various priority matrices to achieve the final rank for each factor.

AHP Application in Engineering Research: Semaan (2006) developed a condition assessment model for subway stations. His model identified and evaluated the various functional/operational criteria for subway stations; architectural, structural, mechanical, electrical, security and communications criteria. He utilized AHP in order to determine the criteria weights. Hassan (2006) and Hassan and Zayed (2006) used the AHP technique to develop a condition rating model for the evaluation of water mains. They utilized the AHP to set the hierarchy for the factors that contribute to water main deterioration. Consequently, using the pair-wise comparison matrix of the main factors and sub-factors, the relative importance weight of these factors are obtained, in which each factor weight represents its relative importance among the other factors. Zayed and Halpin (2004) used AHP and Fuzzy Logic to assess and identify the effect of subjective factors of bored pile construction productivity. Fuzzy logic and AHP approaches were used in developing this model by translating the subjective modeling factors into quantitative measured values in order to overcome the impact and variability of subjective factors on the bored piling activities.

II.7. SUMMARY OF CHAPTER II

HDD is a complex construction operation. Its productivity depends on various uncertain factors, which affect construction time. HDD is a relatively new technique to be used in wide infrastructure market. As a result, literature in predicting its productivity, estimating execution time, cost and number of man to accomplish the job is not available. Due to the lack of HDD productivity prediction models, the literature was extended to the previous work done on productivity prediction of other HEB techniques (micro-tunneling and augur boring) and the factors affecting their productivity. However, Dubey *et al.*, (2006) developed a simplified deterministic productivity assessment model for HDD. Their application is based on few incomplete projects and they validated their results by two projects only, in which two linear regression models were designed between bore length and cycle time. The model is limited to operations in sandy and silty sand soil and medium drilling rigs. In addition, installed pipe connection time is not considered for this study, while soil type, pipe material and diameter, drilling bit capabilities are considered to affect the drilling, pre-reaming and pull back time. Other factors such as weather condition, contractor experience and job & management conditions are entered as efficiency factors. Moreover, Allouche *et al.*, (2003) developed two customized computer applications for the HDD industry. The first software is designed to intimately monitor field performance in terms of expenses and productivity, while the second is developed to optimize the utilization of hydro-vacuum trucks and drilling rigs. Accordingly, current research proposes productivity prediction models for HDD operations in clay, rock and sand soils, using AHP and NF approaches. The proposed decision support tool can be used as a pre-investigation tool during the bidding phase to help allocate crew, budget and time.

CHAPTER III

RESEARCH METHODOLOGY

Research on factors affecting TT industry and its construction progress rate has gained more attentions in recent years. This research intends to analyze and identify the factors that affect the HDD construction method and to develop a model to predict HDD productivity in the pre-construction phase taking into account both practical and academic concerns. Canadian municipalities as well as contractors, consultants and infrastructure professionals worldwide might find benefit from this study.

The research methodology (see Figure III.1) is proposed in order to conduct the target research work. Data collection and analysis come along with the thorough literature review related to factors affecting productivity of HEB systems with a focus on HDD. Also, literature review is extended to previous models conducted to calculate HDD productivity, neurofuzzy modeling techniques and AHP. A new automated HDD productivity prediction model is developed, followed by conclusion of present work and recommendations of future work. .

III.1. LITERATURE REVIEW

This literature review focused on factors that affect HEB techniques in the construction industry, particularly HDD technique. In addition to HEB and HDD, current productivity prediction practices and the neurofuzzy systems and its productivity modeling applications were also reviewed. Moreover, a literature review was performed through interviewing site engineers, contractors, industry professionals and researchers as well as through intensive readings of the related papers, journals, thesis and related books.

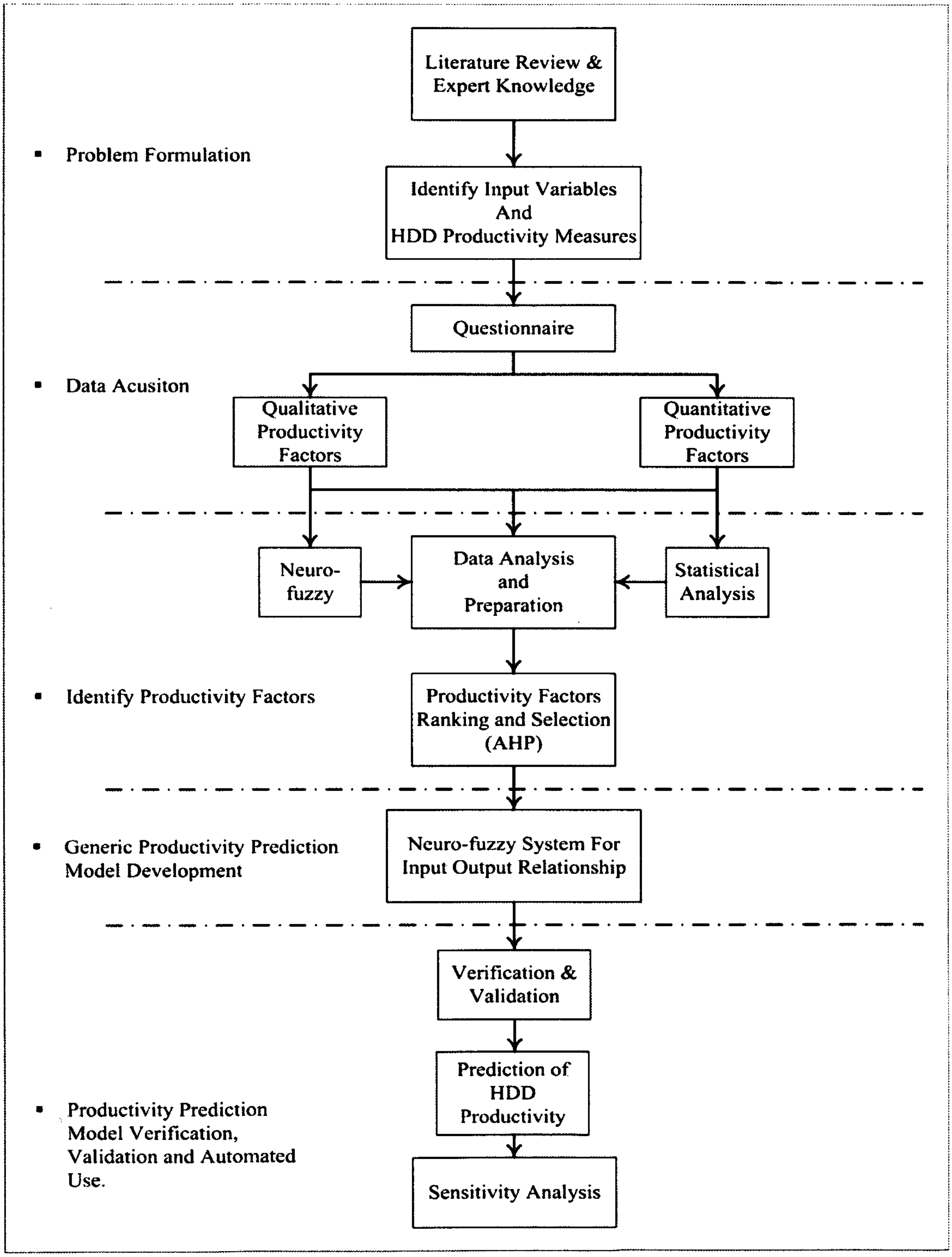


Figure III.1 Schematic Methodology of Studying HDD Productivity Prediction

III.2. FACTORS THAT CONTRIBUTE TO HDD PRODUCTIVITY

The presented study focuses on both quantitative and qualitative factors affecting productivity calculation. Due to lack of HDD productivity studies, the thorough literature review on HEB techniques and available previous studies on HDD productivity, as well as the industry experts, resulted in the identification of thirteen main factors as being the most significant factors affecting the HDD industry. These thirteen factors are categorized under four main categories; management conditions, mechanical conditions, environmental conditions and pipe conditions.

III.2.1. Management Conditions

i. Crew and Operator Skills

The experience of the crew and rig operator might have a direct impact on the preparation time and finishing time of pipe installation (Hegab, 2003). A three-person crew is sufficient for Mini-HDD rigs. Skilled operators finish the job faster, avoid losing the connection with pipes and maintain the right pipe track, (Dubey *et al.*, 2006). Therefore, crew experience, harmony and understanding can directly affect project productivity.

ii. Rig size/Drilling Bit Capabilities

The bore length in HDD operations is determined according to the soil type and the site conditions. The selection of the appropriate machine type may affect the complexity and productivity of the operation. Drilling bit and reamers have teeth or cutting disks that are used for soil excavation. The design, inclination, shape, strength and number of teeth, in addition to the rotational force applied to the drill stem joints affect the performance of drilling the pilot hole. Accordingly, it is important to choose suitable drilling bit and reamer for given soil conditions and bore size.

iii. Legal Issues and Safety Regulations

According to safety manual, which is submitted during the bidding phase, contractors include operating procedures that comply with the applicable regulations, such as excavations and shoring of pits when required. In addition, the installed pipe section must be cleaned prior to the introduction of the product (Ariaratnam and Allouche, 2000). These activities might affect preparation time of installed pipe and may have an indirect effect on productivity.

III.2.2. Mechanical Conditions

i. Machine Conditions

It is recommended to have periodical technical visits by a technician from the machine manufacturer for all projects to ensure fast problem solving (Hegab, 2003). The condition of the machine affects the performance speed, accuracy and quality of the HDD operation.

ii. Slurry Flow Rate

Slurry is used during the HDD borehole drilling and back reaming accompanied with the pipe pull back. The slurry minimizes the friction between the soil and the drilling head/installed pipe. In addition, it carries the muck out of the drilling hole. Moreover, the slurry acts as a lubricant for the pipe that facilitates its insertion and being laid in its place, and support the annular space around the pipe to prevent earth settlements.

Accordingly, HDD equipment performance is affected by the flow rate of slurry, which may affect the production rate indirectly.

iii. Steering Problems (Correction in Direction)

The steering tool is placed within the first drill rod, located directly behind the drill bit. The steering tool is connected to the control unit to be able to direct and locate the drilling bit. Any error occurs from the steering tool may cause work delay in which a direction correction process might take place.

III.2.3. Environmental Conditions

i. Geotechnical investigation and Soil Type

The quality and quantity of the available geological information during the design and bidding phase is very important in estimating the production rates, shaft design and maximum drive length for any construction method (Allouche *et al.*, 2001). Geotechnical investigations are used to define the existing soil types and conditions to enable the contractor to make the best arrangement for the HDD machine and to choose the most suitable equipment for maximum productivity.

ii. Unseen Soil Obstacles/Buried Utilities

Unforeseen ground conditions represent major challenge to the HDD machine. Obstructions, buried utilities, old foundations and unexpected soil conditions might cause a loss of connection with the drilling head and delay the whole pipe installation process. HDD drilling bits are used according to soil type and pipe length. Machine performance might drop dramatically as the number of boulders exceeds the drilling head capability limit. In addition, slurry system may be damaged by rock fragments (Hegab, 2003).

iii. Site and Weather Conditions

Ariaratnam and Allouche (2000) stated that prior to job initiation, work field should be visited for visual inspection to address some important issues that affect quality and speed of work (i.e. sufficient room for entrance and exit pits; HDD equipments; support vehicles; and fusion machines). In addition, it is noted from HDD experts that weather conditions have a major effect on the HDD pipe installation process. Temperature, humidity, rainfall and snowing might cause an obvious delay in work due to their direct effect on the machine, soil and worker productivity.

III.2.4. Pipe Conditions

i. Pipe Material (HDPE, Steel, PVC)

The effect on productivity by pipe material is realized as a result of friction between pipe and soil. However, slurry flow acts as a lubricant to facilitate pipe alignment. Therefore, as long as the pipe material is well fabricated and properly installed, material should have no major effect on productivity (Hegab, 2003). HDD pipe installations require special pipe characteristics. The installed pipelines must show high tensile and buckling strengths. In addition, pipelines must be flexible enough to allow curved alignment that exists in HDD pipeline installations (Allouche, 2003). High-density polyethylene (HDPE) and steel are the two most common pipe materials that have been installed by using HDD (Ariaratnam, 2001).

ii. Pipe Length

The pipe section length affects preparation time and entry shaft size for pipe installation. By increasing pipe section length, both construction cost of entry shaft and construction time increase (Hegab, 2003). Hence, it is concluded that pipe section length through both aligning of drilling segments and preparation time affects HDD process.

iii. Pipe Depth

The increase of pipe installation depth increases installation time of the pipe; however, it decreases the risk of hitting buried utilities. Depth of installation affects the productivity indirectly (Hegab, 2003). To prevent heaving or hydraulic fracturing of the soil, a sufficient cover depth should be applied when installing a utility pipeline using HDD. Recommended minimum cover depths for different pipe diameters are as follows: minimum cover depth of 1.2 m for pipes 50–150 mm in diameter, 1.8 m for pipes 200–350 mm in diameter, 3.0 m for pipes 750–600 mm in diameter and 7.5 m for pipes 625-1,200 mm in diameter.

iv. Pipe Diameter

Based on an actual data survey, Allouche *et al.* (2000) stated that when diameter increases the productivity tends to decrease. As diameter increases, a multi-reaming process may take place to reach the desired borehole diameter gradually to avoid earth heaving. In addition, a longer time is needed for pipe pull back. A rule-of-thumb is to have a borehole 1.5 times the outer diameter of the installed pipe (Popelar et al. 1997). In other words, the bigger the diameter, the wider the borehole, which means that multi back reaming should take place.

III.3. DATA COLLECTION AND ANALYSIS

The main set of collected data includes real HDD project data representing the project input variables, cycle time and productivity measures which were identified in the problem formulation stage. This set of data was mainly used to train the structure connections of the neurofuzzy system to properly relate the defined HDD input variables with the corresponding productivity measures.

A questionnaire was designed based on literature review and interviews of construction industry professionals to investigate the most effective factors on HDD productivity. The questionnaire was sent to professionals, consultants, contractors and equipment operators associated with the HDD technique. The first and second parts were designed to collect the participant and project's information in which some qualitative and quantitative factors were involved (i.e. soil type and pipe diameter). The third part collected the HDD cycle time duration. The last part of the questionnaire collected the effect of the various qualitative factors on productivity using a unified fuzzy performance scale (i.e. crew/operator skills, machine condition...etc.). The participants were given the option of adding more factors and evaluate their impact.

III.4. SCORING AND RANKING FACTORS THAT CONTRIBUTE TO HDD PRODUCTIVITY

Analysis was implemented using analytical hierarchy process in order to rank the thirteen factors (discussed in section III.2) that affect HDD according to their relative importance. The identified factors were compared via a pair-wise matrix, establishing the AHP structure. The eigenvalue method (Saaty, 1982) was used to calculate the weighting vector for each pair-wise matrix. Accordingly, the overall priority weights of factors were achieved. Based on the conducted weights and relative importance ranking, the results were proposed to HDD professionals in which five of these factors were eliminated or merged. Only eight factors were considered in the presented study. Accordingly, this research plans to analyze and assess cycle time and productivity using the eight most comprehensive factors: operation/crew skills, pipe diameter, drilling bit capabilities, machine condition, unseen obstacles, pipe length and site, weather and safety conditions, as well as the identification of their relevant impact.

III.5. MODEL DEVELOPMENT

The hybrid integration of neural networks and fuzzy logic is called a neurofuzzy system. The neurofuzzy systems are capable of addressing nonlinear relations, minimizing level of uncertainties in modeling, addressing imprecision of input-output values and modeling linguistic (non-numerical) data. Accordingly, the current research utilized the neurofuzzy technique in developing the HDDPP model.

The neurofuzzy approach uses the neural network technique to generate fuzzy logic rules and membership functions automatically. The neurofuzzy network model has three main functions as shown in Figure III.2. The input layer processes crisp and fuzzy input data of the eight input factors. Therefore, crisp input data can be transformed into membership function values that are the output of the input layer. These values move to the next layer(s), which function as fuzzy rules operating on the fuzzified input. Finally, the last layer collects the results of applying the rules and defuzzify the results to get the crisp value representing the HDD predicted output (i.e. productivity).

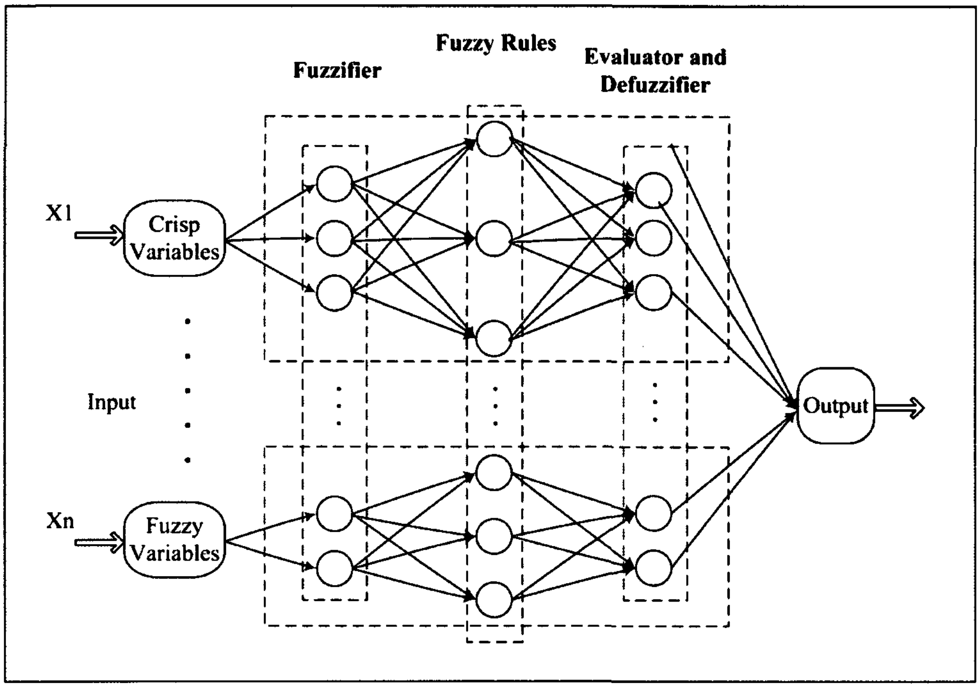


Figure III.2 Basic Architecture of Neurofuzzy Network

The input data of an HDD project will be clustered according to the eight identified input factors; see Figure (III.3). These eight input factors are clustered into four levels. The first level identifies the working soil type. The model soil types are limited to clay, rock and sand due to limitation of collected data. The second input cluster level defines pipe condition and operational conditions. The third level, pipe length and diameter, represents pipe conditions and drilling bit capabilities, machine condition, site/weather conditions and operator/crew skills, which represents the operational conditions. The last input cluster is the HDD project productivity that represents the targeted model output.

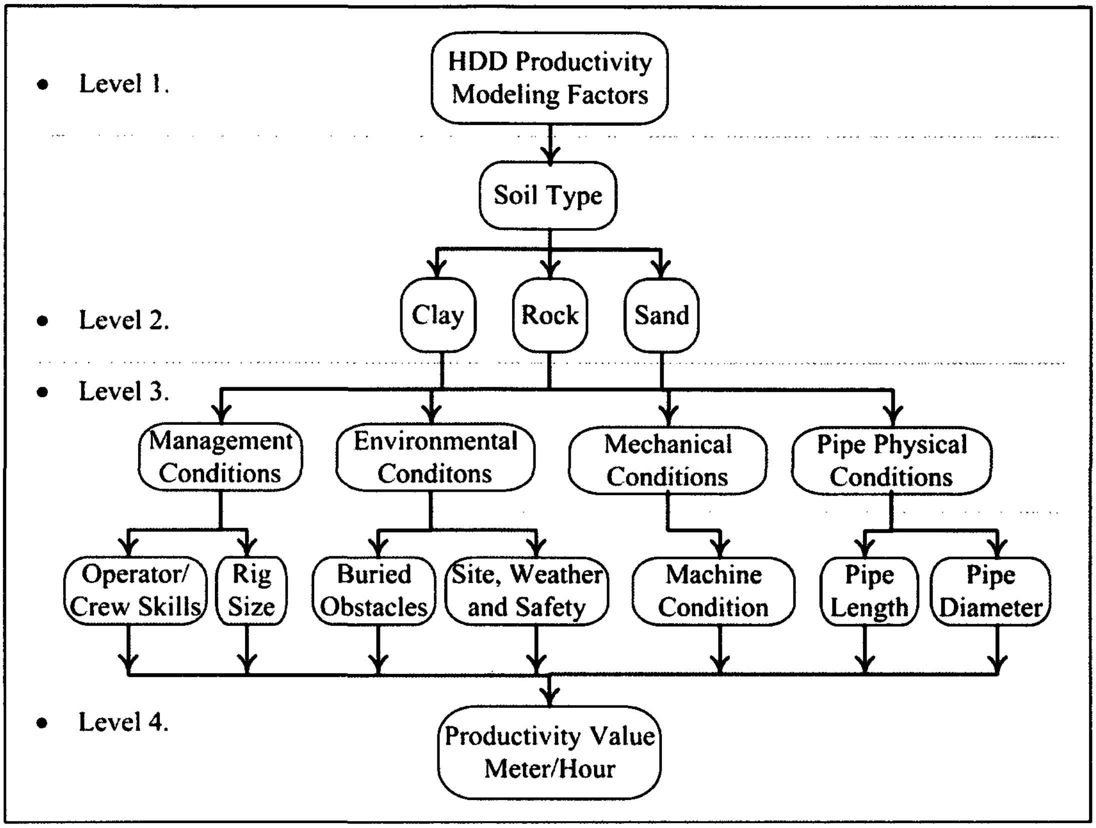


Figure III.3 Data Clustering

III.5.1. Model Training

The model implementation is divided into training and validation phases. The training phase starts by both qualitative and quantitative data entry in terms of factor weights, cycle time, and production rate, respectively. The model was developed by using MatLAB® version 7.0 using the Adaptive Neurofuzzy Inference Systems toolbox ANFIS. The training process starts by data fuzzification where the degree of each factor is determined. The data then proceeds to the training phase via ANN. The fuzzy outcome is then deffuzified, where the crisp input factor variable is determined given its degree of membership. In other words, the functions performed by the neurofuzzy networks are to fuzzify systems inputs, develop a structure weight that properly represent the nonlinear relationships among the model inputs and outputs, and to defuzzify model outputs. This system is able to build a relationship between the factors affecting the HDD process and the overall productivity. Therefore, the model can predict HDD process productivity given a specified set of project input variables (factors) with an adequate percent error. This research utilized the neurofuzzy technique as a credible approach for predicting or estimating HDD technique productivity, because of their fault tolerance, ability to model nonlinearity and their systematic procedure for modeling qualitative variables.

III.5.2. Model Validation

The developed model is tested during the modeling phase, in which the neurofuzzy technique can split the modeling data into training and testing data. However, twenty percent of the total collected data points will be unexposed to the neurofuzzy system during modeling phase and is used for validation purposes afterwards. Validation will be performed according to Zayed and Halpin (2005) model, which will be described in Chapter V.

III.6. MODELING CASE STUDIES

After developing the neurofuzzy models for HDD, three case studies are implemented using the developed clay, rock and sand NF models. After running the models and obtaining output (production rate), each case study is validated and the results are compared to actual calculated onsite productivity.

III.7. SENSITIVITY ANALYSIS

After model validation and achieving robust results, sensitivity analysis will take place to observe how independent factors (e.g. crew and operator skills, pipe diameter, length) affect productivity of HDD. Sensitivity analysis will be carried out for the case study of each soil type, in which the studied HDD factor is kept at actual values while other factors are kept at their constant average values. Sensitivity results are achieved using MatLAB® (ver. 7.6.0.324) and the developed NF models.

III.8. AUTOMATED HDD PRODUCTIVITY PREDICTION DECISION SUPPORT TOOL

An automated decision support tool will be designed for the developed HDD productivity model. The purpose is that the model provides a significant tool to assist HDD professionals in predicting project production rates and aid them in the determination of project cost and duration according to Figure (III.4). In this section, a descriptive example of clay study case will be demonstrated.

A typical prediction of productivity starts usually by recalling data from previous work done and collecting data related to constraints and requirements of any project. A HDD user-friendly interface software is developed to help both experienced and new contractors, engineers, consultants and field experts to establish an estimation of hourly rate progress in HDD projects. This, in turn, leads to a better understanding of the actual cost and duration required for the HDD project. The user is required to enter a simple set of input data that illustrates the project details, environment and user requirements. The system is then performed and derived from the input data. MatLAB starts calling the developed neurofuzzy system. A report is engendered illustrating the hourly production rate of the targeted project.

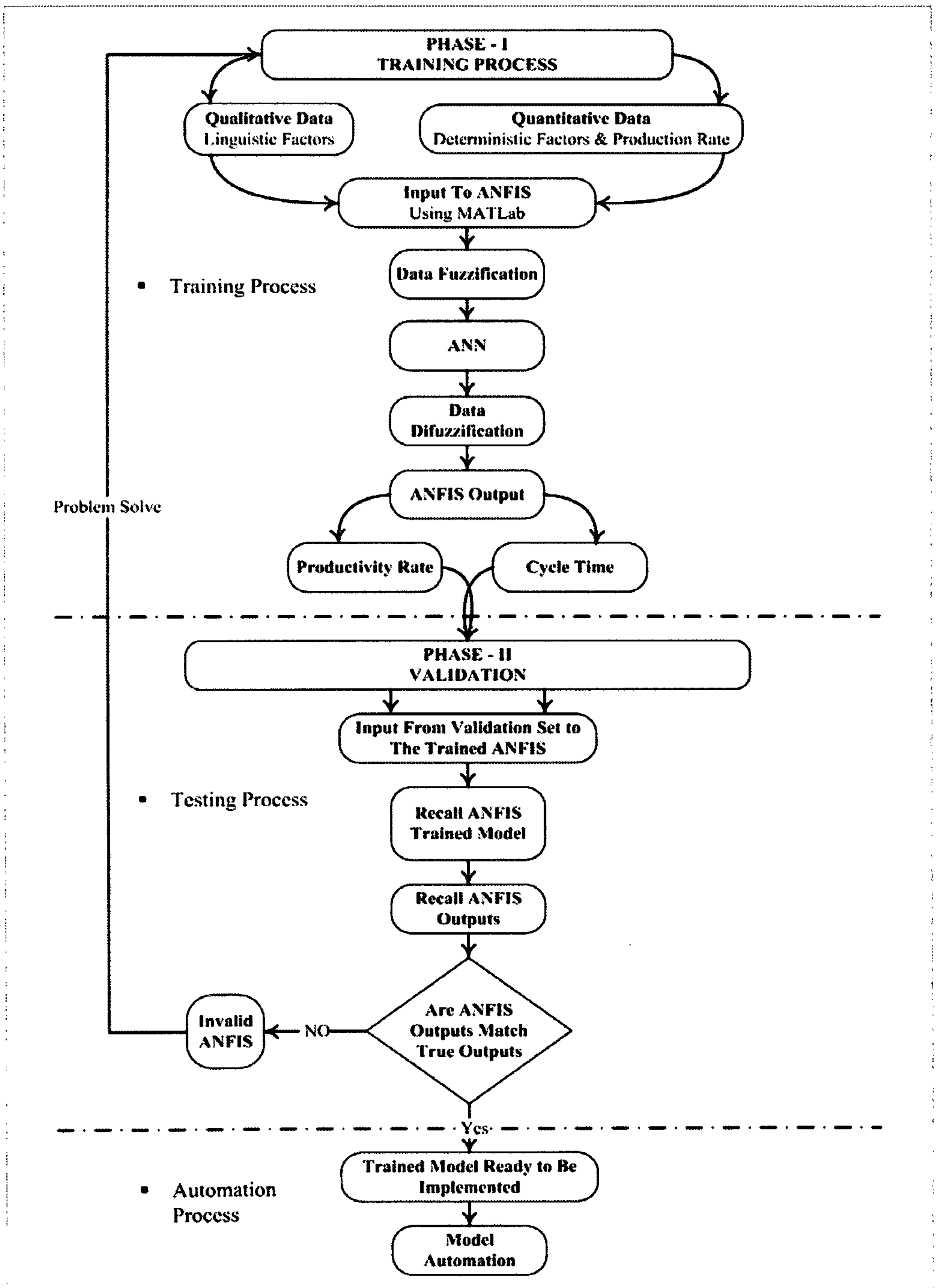


Figure III.4 Output Input HDD Productivity Prediction Model Mechanism

III.9. SUMMARY OF CHAPTER III

The methodology of this research work is presented, in which it illustrates the following steps:

(1) Literature review was carried out on all main disciplines that are necessary to predict the productivity of HDD construction method. The review defines the problem, and provides an overview of the HDD technique, factors affecting the HDD productivity and the neurofuzzy modeling technique.

(2) Collection of data, this includes real-time project cycle time and affect of qualitative and quantitative factors on productivity in comprising production rate information.

(3) Use of analytical hierarchy process to establish the relative importance of each modeling factor; this section ranks the factors according to their effect on productivity and helps in reorganizing the input factors.

(4) Use of neurofuzzy systems to address prospect of input data. This section defines main criteria of neurofuzzy systems and use of MatLab 7.0 software that is used to develop the model,

(5) HDDPP model development; where training, validation and case study application for each soil type are implemented.

(6) Performing sensitivity analysis to achieved results for three case studies of each soil type, which studies the effect of the variability of the main input factors to the analysis of the final predictions.

(7) Generation of the HDD-PP automated user-friendly interface software and the presentation of the clay case study.

CHAPTER IV

DATA COLLECTION

Data collection is the main driving force to this research work. Almost, 220 trenchless technology contractors in Canada and USA were contacted to obtain real time HDD project data. An online questionnaire was designed and created to help engineers and professionals easily respond and complete the questionnaire. In addition, traditional electronic formats and hard questionnaire copies were collected.

IV.1. DATA COLLECTION AND ORGANIZATION

Data are collected through two methods: direct and questionnaire. Direct data collection is done using onsite interviews, field visits and phone calls. The second technique is through an online questionnaire. A questionnaire was designed based on literature review and interviewing construction industry professionals to investigate the most effective factors on HDD productivity. The survey was sent to professionals, consultants, contractors and equipment operators in relation to HDD technique, as depicted in Figure (IV.1 and IV.2). The first part was designed to collect the participant and project information, in addition to pipe dimensions and soil characteristics. The second part of the questionnaire was designed to collect the HDD cycle time duration and productivity information. The last part of the questionnaire was designed to collect the effect of qualitative factors on HDD productivity using a unified fuzzy performance scale from (1-5), (see Figure IV.3). Approximately, 220 questionnaires were sent to TT professionals in North America with response rate of 12% (28 projects). All replies represent the new pipe/cable installations using HDD in clay, sand, and rock soils.

Almost 20% of data are excluded from the modeling phase in order to be used for validation purposes.

QUESTIONNAIRE

I. Personale Information :

Name:	
Email:	
Phone:	

II. Time and Pipe Information:

Please select ***one previously completed project for each questionnaire*** you will be completing and answering the following questions.

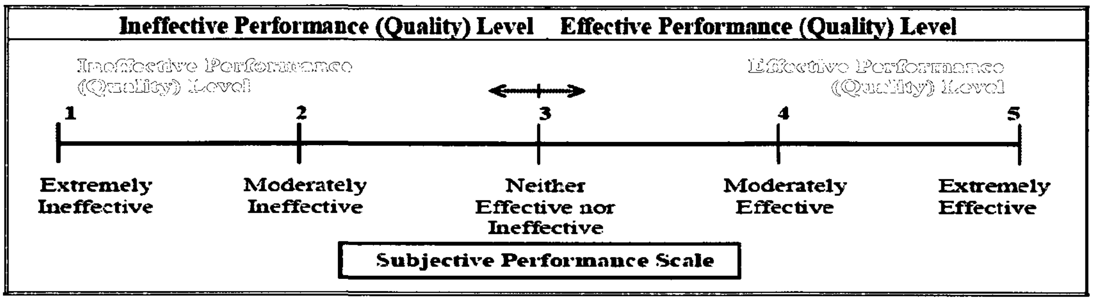
Project Start Date:	Project End Date:	
No. of Actual Working hours/day:	Pipe/Cable Length (m):	
Pipe/Cable Type:	Pipe/Cable Depth (m):	
Pipe/Cable Diameter (mm):	Soil Type:	
Drilling Rig Size: □ Small	□ Medium	□ Large
Project Place:		

III. Activities Information:

A. Estimate most probable **duration** of each HDD **activity cycle time** for the selected project.

	Activities	**Estimated Time (Minutes)** **Most Probable**
Major	Site Preparation	
	Pilot hole drilling	
	Reaming	
	Final pipe pulling	
Minor	Angle adjusting at bit entrance	
	Drill pipe segments joining	
	Reamer with shackle attaching for pre-reaming	
	Pipe/Cable segments connection and layout	
	Pipe swivel assembly for pipe pullback	
	All tracking activities	
	All Assessment Activities	

Figure IV.1 Questionnaire



B. According to the above scale, please, rate the **effect** of the following factors **on HDD process productivity**.

	Questions	Scale 1	2	3	4	5
Management Conditions	Drilling rig operator and crew skills?					
	Rig size/drilling bit capabilities?					
	Safety regulations?					
Mechanical Conditions	Machine condition?					
	Slurry flow rate and slurry recycle equipment?					
	Steering problems? (Correction in direction)					
Environmental Conditions	Soil type?					
	Unseen buried obstacles?					
	Site and weather conditions?					
Pipe Conditions	Pipe type?					
	Pipe length?					
	Pipe depth?					
	Pipe diameter?					

Figure IV.2 Questionnaire Continued

The collected data are organized and analyzed according to the various soil types so that they would be ready for neurofuzzy modeling. In this study, both qualitative and quantitative data are needed, in which qualitative data are collected via part II of the questionnaire and the quantitative data were collected via part I and III.

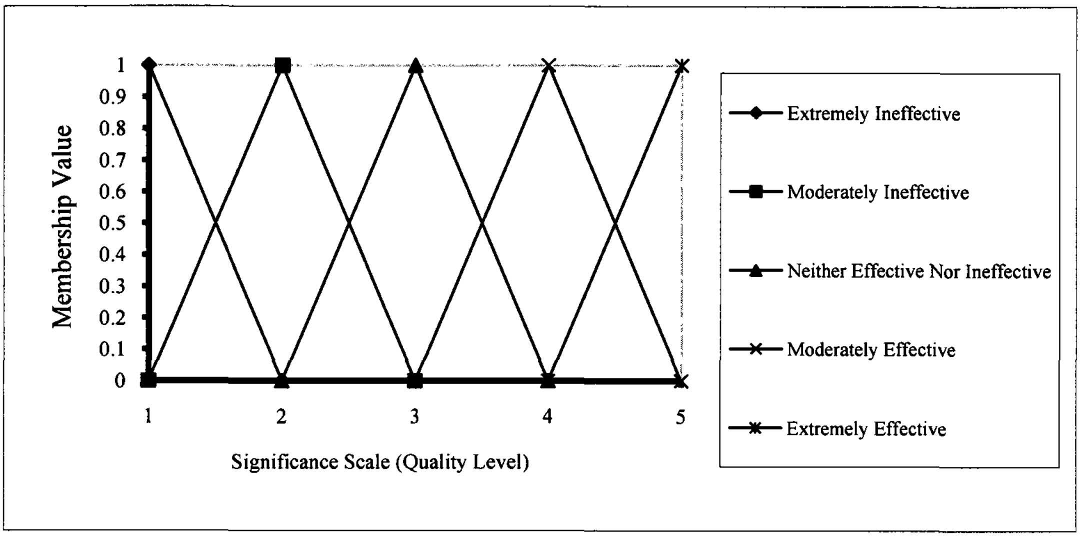


Figure IV.3 Representation of the Fuzzy Performance Scale

IV. 2. QUESTIONNAIRE SURVEY ANALYSIS

As stated before, approximately 220 questionnaires; hard copies, soft copies or online copies; were sent to HDD contractors, consultants, field technicians and individual experts in North America. However, only questionnaires for 28 projects were received (12.73%) as shown in Figure (IV.4).

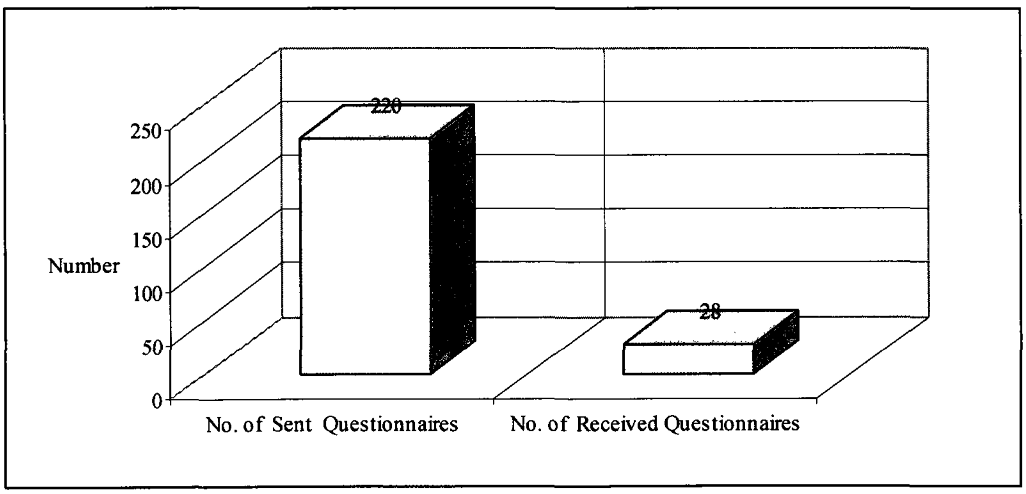


Figure IV.4 Number of Questionnaires

Collected questionnaires are classified according to soil types. Figure IV.5 shows that clay, sand and rock soil types are represented by 11, 9 and 8 questionnaires, respectively. The various pipe diameters (d) that were indicated in the questionnaire replies are classified into three main categories: 1) small (25% of collected data), 2) medium (18% of collected data) and 3) large (57% of collected data), with diameter range of (d) ≤ 150mm, 150mm < (d) ≤ 250mm , (d) > 250mm , respectively. Figures (IV.6 - IV.8) shows the classification of pipe diameter size for the projects collected for each soil type.

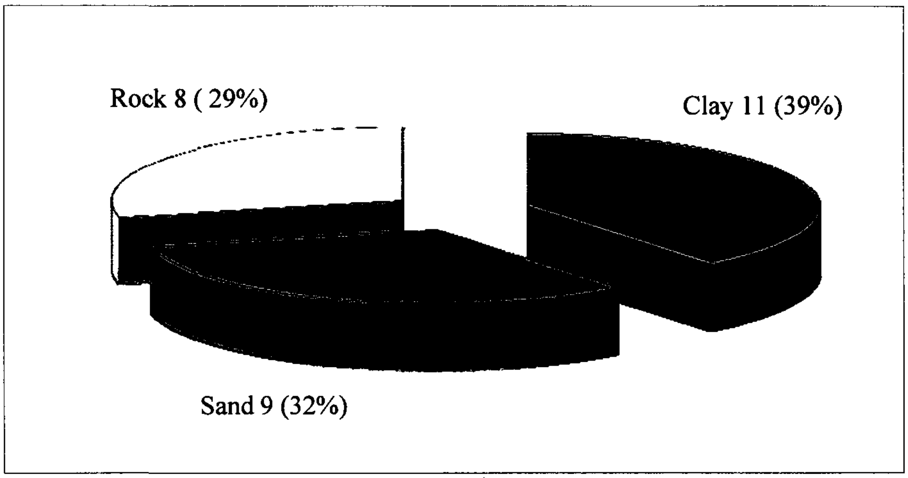


Figure IV.5 Number of Projects Collected for Each Soil Type

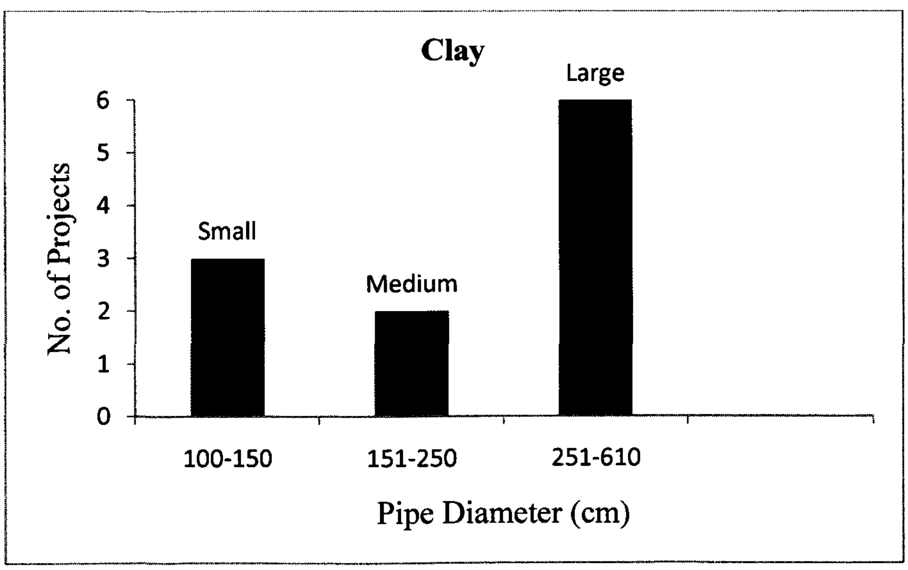


Figure IV.6 Distribution of Pipe Diameter According to Collected Data; Clay Soil

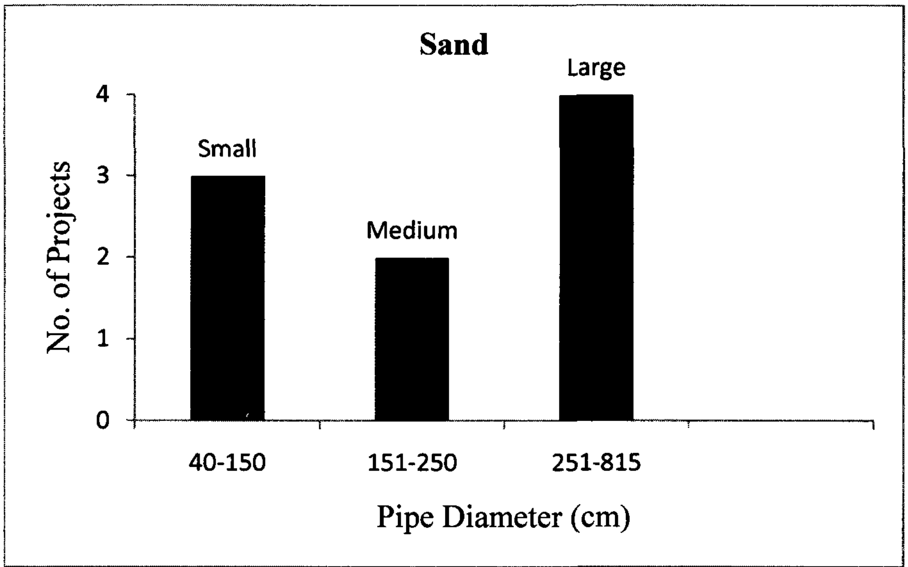


Figure IV.7 Distribution of Pipe Diameter According to Collected Data; Sandy Soil

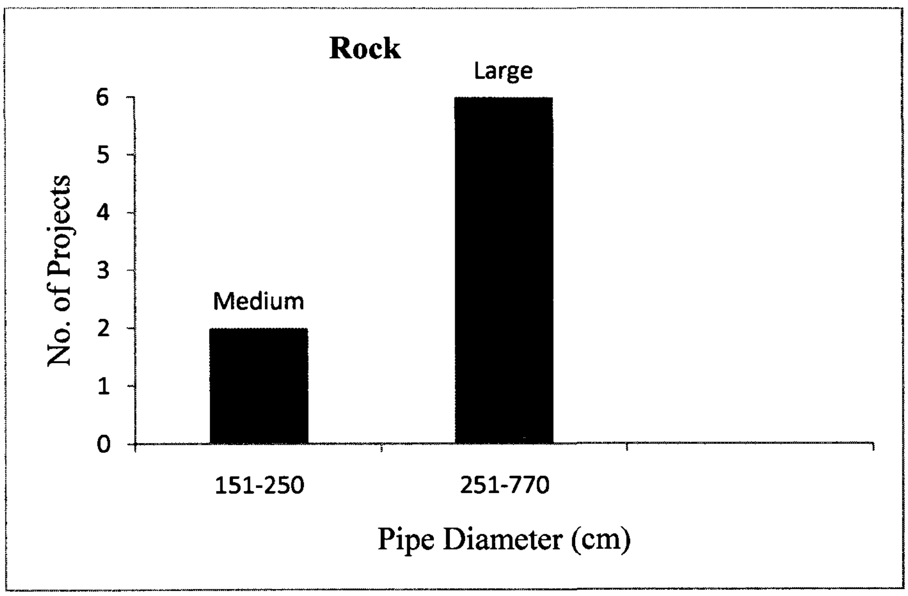


Figure IV.8 Distribution of Pipe Diameter According to Collected Data; Rock Soil

By analyzing pipe diameter, and its relation with the calculated onsite productivity, it was found that the larger the diameter, the lower the productivity due to the need of multi-reaming process.

Manufacturers have classified horizontal directional drilling (HDD) rigs into three main categories: 1) small, 2) medium and 3) large according to their capabilities (maximum torque (ft-lb)), small rigs < 4000 ft-lbs, medium rigs 4000 – 20000 ft-lbs and large rigs > 20000 ft-lbs. The collected data was limited to utilizing medium and large rigs only. Data analysis showed that medium and large rigs represent 68% and 32% of collected data, respectively, as shown Figure IV.9. Each rig category is capable of installing certain lengths and diameters of pipe product based on their respective thrust/pullback and rotational torque. Experts indicated that HDD industry is dominated by medium rigs, as dictated by need to increase production rates and due to project size and environment. The small drilling bit capabilities have a respectable market; however, it was not involved in this study due to data limitations. Collected HDD projects data indicates that 82% of HDD operations in clay utilized medium rigs and 18% utilized large rigs, while 75% of HDD projects in rock utilized large rigs and 25% only utilized medium rigs. In addition, all HDD projects in sands utilized medium rigs.

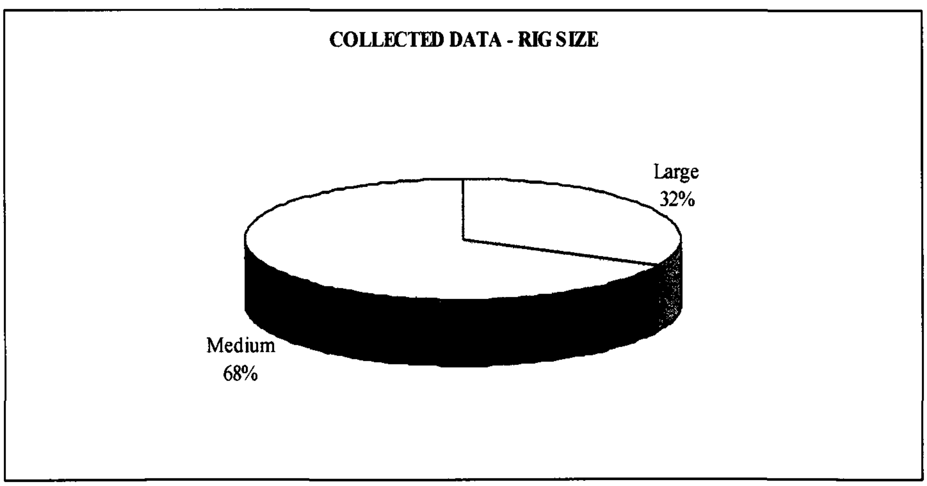


Figure IV.9 Drilling Bit Sizes

The current research studied a wide range of pipe lengths, which varied from 84 to 2300 meters. Pipe length was classified into short, medium and long length according to Good

Practices Guidelines, (2004). Figure (IV.10 - IV.12) shows various lengths of installed pipes for different soil types; short (L) ≤ 300m; 300m < medium (L) ≤ 500m; and long (L) > 500m. The shortest pipe installation was found to be in sandy soil with a length of 85 m, while the longest installation was in rock soil (2300 m).

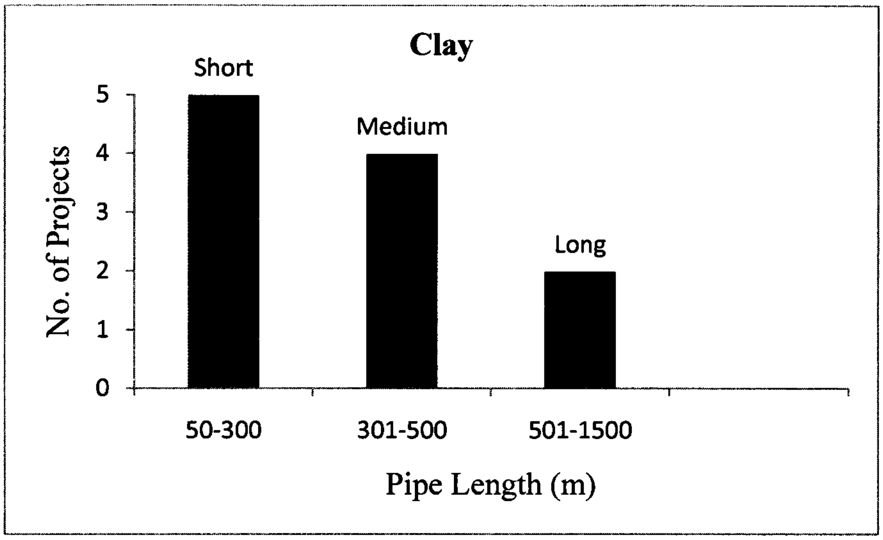


Figure IV.10 Distribution of Pipe Length According to Collected Data; Clay Soil

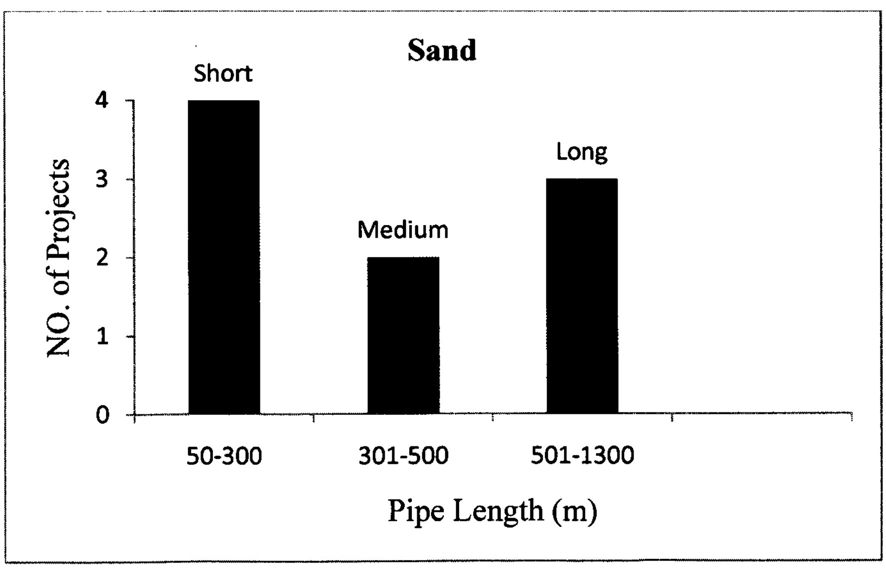


Figure IV.11 Distribution of Pipe Length According to Collected Data; Sandy Soil

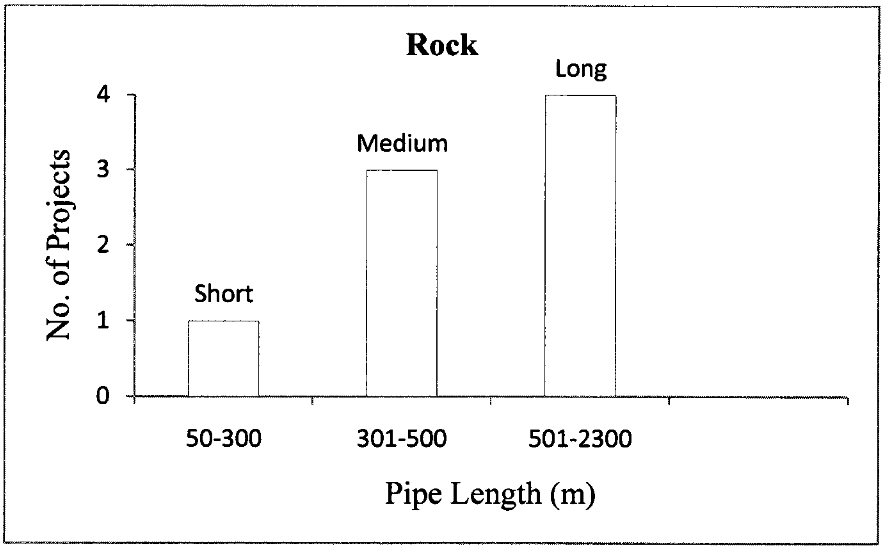


Figure IV.12 Distribution of Pipe Length According to Collected Data; Rock Soil

Two pipe types were utilized in this study: steel and HDPE. It is worth to mention that HDPE is mostly used in HDD applications due to its high workability and flexibility. Figure IV.13 shows that seventy-one percent of the collected projects data utilized HDPE pipes, while 29% utilized steel pipes. Collected HDD projects data indicates that 82% of HDD operations in clay utilized HDPE pipes and 18% utilized steel pipes, while 50% of operations in rock utilized HDPE and 50% utilized steel pipes. Operations in sand utilized almost 78% HDPE pipes and only 22% steel pipes.

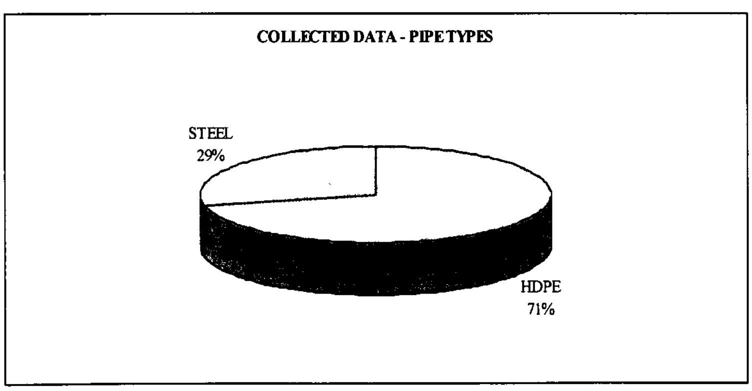


Figure IV.13 Percentage of Pipe Types

IV.3. CASE STUDY PROJECTS

One comprehensive HDD project was selected for clay, rock and sand soil to be implemented and validated through the developed productivity prediction NF models. After data analysis and preparation, both qualitative and quantitative factors were identified and prepared as inputs to developed models. Data for modeling, testing, validation and case studies were collected from specialized HDD companies (e.g. Fordirect, Johnston-Vermette, Directed Technologies Drilling Inc. and Golder Associates). However, company and personnel data were not presented in this study due to privacy and confidentiality agreements that were made during data collection.

In this research, HDD Activities are classified into major and auxiliary drilling activities. Major drilling activities include the three main drilling steps pilot hole drilling, back reaming, pipe pull back (Good Practices Guidelines, 2004) and site preparation. While, all other activities are considered as auxiliary drilling activities. Pipe connection & layout time is considered as auxiliary activity because in some projects its time is neglected if it was done parallel to site preparation, however, in some projects (long pipe installations) pipe connection time may exceed any major activity time.

IV.3.1. Clay Case Study

A 300 m long water main was installed at 3 m depth in clay soil. The pipe was 200 mm in diameter and made of HDPE. The project was implemented by utilizing a medium drilling rig size (maximum torque; 4000 - 20000 ft-lb), a highly skilled operator and crew, moderate machine condition, with moderate expectations of unseen buried obstacles. In addition, a moderate site, weather and safety conditions were also implemented. The onsite project work was done in 2 working days based on a 10 hour work day. Table (IV.1) shows the clay case study activities duration filled by the HDD expert and collected from the questionnaire.

Table IV.1 Clay Case Study Activity Duration

Drilling Activity		Duration (min)
Major	Site preparation (SP)	45
	Pilot hole drilling (PH)	210
	Reaming (R)	210
	Pipe Pull Back (PP)	30
Auxiliary	Pipe connection & layout	430
	Angle adjusting	15
	Drill pipe segments joining	30
	Attaching reamer/shackle	30
	Pipe swivel assembly	30
	Tracking activities	60
	All assessment activities	60

IV.3.2. Rock Case Study

A 440 m long water main was installed at 4.5 m depth in black shale (rock) soil. The pipe was 139.7 mm in diameter and made of HDPE. The project was implemented by utilizing a large drilling rig (maximum torque > 20000 ft-lb), a highly skilled operator and crew, very good machine condition, with low expectations of unseen buried obstacles and bad site, weather and safety conditions. The job was accomplished in 4 working days based on a 12 hour work day. Table (IV.2) shows the rock case study activities duration filled by the HDD expert and collected from the questionnaire.

Table IV.2 Rock Case Study Activity Duration

Drilling Activity		Duration (min)
Major	Site preparation (SP)	180
	Pilot hole drilling (PH)	180
	Reaming (R)	0
	Pipe Pull Back (PP)	120
Auxiliary	Pipe connection & layout	1140
	Angle adjusting	15
	Drill pipe segments joining	90
	Attaching reamer/shackle	120
	Pipe swivel assembly	270
	Tracking activities	180
	All assessment activities	180

IV.3.3. Sand Case Study

A 660 m long water main was installed at 2.5 m depth in sandy soil. The pipe was 101.6 mm in diameter and made of HDPE. The project was implemented by utilizing a medium drilling rig size (maximum torque; 4000-20000 ft-lb), a highly skilled operator and crew, moderate machine condition, with high expectations of unseen buried obstacles, and good site, weather and safety conditions. The job was accomplished in 7 working days based on an 8 hour work day. Table (IV.3) shows the sand case study activities duration filled by the HDD expert and collected from the questionnaire.

IV.4 RELIABILITY OF COLLECTED DATA

Miaoulis and Michener (1976) stated the main factors that need to be specified to determine a representing sample size as: 1) study purpose, 2) population size, 3) precision level (sampling error), 4) confidence level and 5) degree of variability in the measured attributes. Yamane (1967) has provided a simple formula to calculate a reliable sample size with a confidence level of 95% and 50% level of accuracy (degree of variability), which is usually used to determine a general level of accuracy for a known sample size, as shown below:

$$n = \frac{N}{1 + N(e)^2}$$

Equation VI.1

Where, (n) is the sample size, (N) is the population size, and (e) is the level of precision.

According to NASTT (2007), there are 220 TT contractors (population size) operating in Canada and USA. There for the margin of error of collected data is found to be 17.34%. Therefore, the more collected projects data the less the margin of error, which may improve the current research application results.

Table IV.3 Rock Case Study Activity Duration

Activity		Duration (min)
Major	Site preparation (SP)	600
	Pilot hole drilling (PH)	960
	Reaming (R)	720
	Pipe Pull Back (PP)	360
Auxiliary	Pipe connection & layout	600
	Angle adjusting	60
	Drill pipe segments joining	360
	Attaching reamer/shackle	60
	Pipe swivel assembly	60
	Tracking activities	60
	All assessment activities	120

IV.5. SUMMARY OF CHAPTER IV

This chapter covers procedure of data collection and a description of tools used. Both direct data collection and questionnaires were utilized in the study. Two-hundred and twenty (220) questionnaires were sent to four countries. Only 12.73% of the questionnaires received with replies. The collected data have been sub-divided into three main categories; clay, rock and sandy soils. Furthermore, three data projects were selected in order to be applied by the developed productivity prediction NF models (one project for each soil type). These projects help validate and understand model mechanism.

CHAPTER V

MODEL DEVELOPMENT AND RESULTS

This chapter covers the ranking system used for the HDD productivity factors, the development of the NF models for each soil type, and the validation process. This includes the relative importance of each factor, a schematic representation of input and output variables, and the process of system adaptation and training. Furthermore, the chapter presents the productivity factor sensitivity curves.

V.1. HDD PRODUCTIVITY FACTORS RANK

The purpose of establishing the input factor ranking is to highlight the relative importance of the factors used to model HDD productivity. The AHP technique is utilized to determine the relative importance of each of the previously investigated HDD productivity factors. The investigated factors that affect HDD productivity are divided into four major levels as shown in Figure (V.1). A pair-wise comparison matrix was developed considering the thirteen factors, as shown in Table (V.1). In order to assign priorities, the AHP methodology is applied to these matrices in order to determine each factor's weight.

The eigenvector or weighting vector (W_i) for each pair-wise matrix is then established using Saaty's methodology (1982), as shown in Table V.2. Each of these weights represent its relative importance among the other factors, therefore the total weight value of each matrix is equal to one. Table V.2 shows the weight of factors (Wi) using respondent # 1 in which operator and crew skills, steering problems and soil type have the highest priority and effect on HDD productivity (0.1136). Safety regulations and unseen obstacles have the lowest effect of (0.0227).

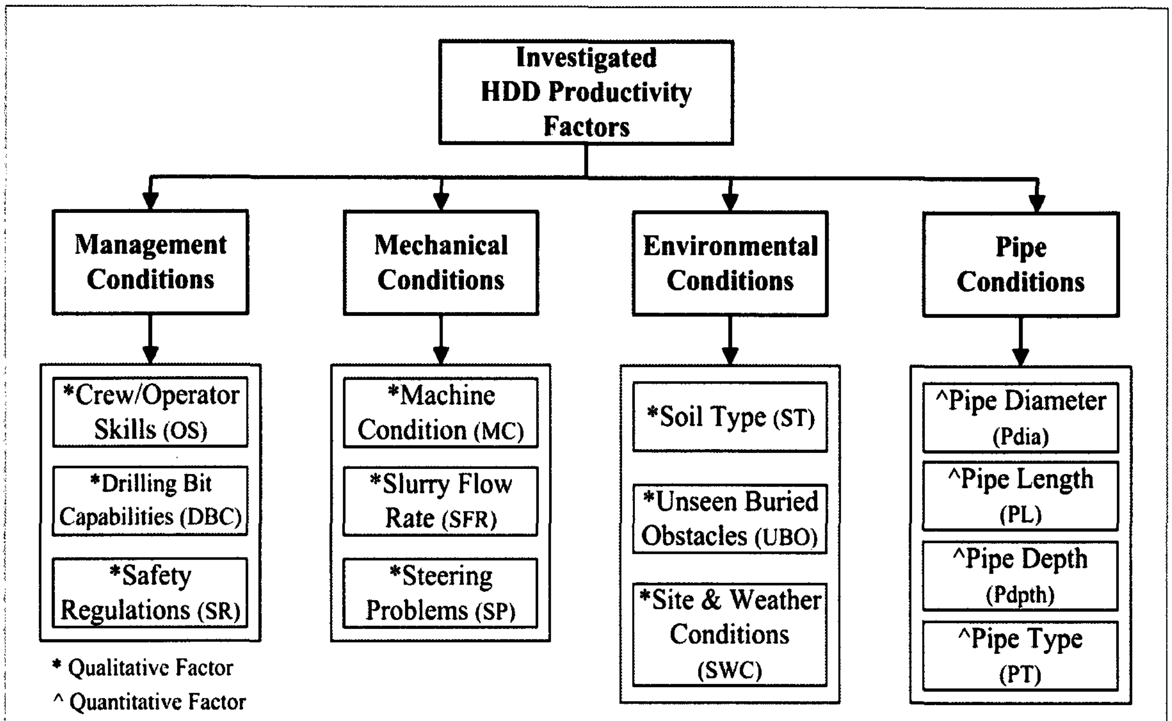


Figure V.1 Investigated HDD Factors

Table V.1 Pair-wise Comparison Matrix (Respondent No. 1)

	OS	DBC	SR	MC	SFR	SP	ST	UBO	SWC	PT	PL	Pdpth	Pdia
OS	1	1.25	5	1.25	1.25	1	1	5	1.25	2.5	2.5	2.5	1
DBC	0.8	1	4	1	1	0.8	0.8	4	1	2	2	2	0.8
SR	0.2	0.25	1	0.25	0.25	0.2	0.2	1	0.25	0.5	0.5	0.5	0.2
MC	0.8	1	4	1	1	0.8	0.8	4	1	2	2	2	0.8
SFR	0.8	1	4	1	1	0.8	0.8	4	1	2	2	2	0.8
SP	1	1.25	5	1.25	1.25	1	1	5	1.25	2.5	2.5	2.5	1
ST	1	1.25	5	1.25	1.25	1	1	5	1.25	2.5	2.5	2.5	1
UBO	0.2	0.25	1	0.25	0.25	0.2	0.2	1	0.25	0.5	0.5	0.5	0.2
SWC	0.8	1	4	1	1	0.8	0.8	4	1	2	2	2	0.8
PT	0.4	0.5	2	0.5	0.5	0.4	0.4	2	0.5	1	1	1	0.4
PL	0.4	0.5	2	0.5	0.5	0.4	0.4	2	0.5	1	1	1	0.4
Pdpth	0.4	0.5	2	0.5	0.5	0.4	0.4	2	0.5	1	1	1	0.4
Pdia	1	1.25	5	1.25	1.25	1	1	5	1.25	2.5	2.5	2.5	1

The weights (Wi) for all factors will be similarly calculated for the 28 respondents. Table V.3 shows the average of the calculated factors' weights (Wi) for the 28 respondents. Operator and crew skills, soil type and pipe diameter are the most important factors where their values are 0.1024, 0.0988 and 0.0905, respectively, while pipe depth and pipe length have the least weight of 0.0578 and 0.0575, respectively.

Table V.2 Weight Vector for each Pair-Wise Matrix "Respondent No.1"

	Factors	**Weight (Wi)**
1	Operator and crew skills	0.1136
2	Drilling bit capabilities	0.0909
3	Safety Regulations	0.0227
4	Machine Condition	0.0909
5	Slurry Flow Rate	0.0909
6	Steering Problems	0.1136
7	Soil type	0.1136
8	Unseen Obstacles	0.0227
9	Site/weather conditions	0.0909
10	Pipe type	0.0455
11	Pipe length	0.0455
12	Pipe depth	0.0455
13	Pipe diameter	0.1136

The factors relative importance were then introduced and discussed with five HDD professionals. After these discussions, a new factor layout was developed, as shown in Table (V.4). Safety regulations (Wi=0.0623) and site/weather conditions (Wi=0.0604) were merged due to the fact that they are a parallel-performed activity in the HDD industry. Site/weather and safety conditions were then assigned a weight of 0.0614. Steering problems (Wi=0.0854) and slurry flow rate (Wi=0.0785) were considered as a subcategory of the machine condition (Wi=0.0852). According to HDD Good Practices Guidelines, (2004) the change of pipe type has no effect on pipe installation time.

Therefore, pipe type and pipe depth were eliminated in the modeling phase due to their low effect on productivity.

Table V.3 Average Weight Values (Wi) for All Respondents

	HDD Productivity Investigated Factors	**Weight (Wi)**
1	Operator and crew skills	0.1024
2	Soil type	0.0988
3	Pipe diameter	0.0905
4	Drilling bit capabilities	0.0875
5	Steering Problems	0.0854
6	Machine Condition	0.0852
7	Slurry Flow Rate	0.0785
8	Unseen Obstacles	0.0702
9	Pipe length	0.0635
10	Safety Regulations	0.0623
11	Site/weather conditions	0.0604
12	Pipe type	0.0578
13	Pipe depth	0.0575

Table V.4 The Weight (Wi) of Modified Factors' Layout

	Modified Factors Layout	**Weight (Wi)**
1	Operator and crew skills	0.1024
2	Soil type	0.0988
3	Pipe diameter	0.0905
4	Drilling bit capabilities	0.0875
5	Machine Condition (Steering Problems, Slurry Flow Rate)	0.0830
6	Unseen Obstacles	0.0702
7	Pipe length	0.0635
8	Site/Weather Conditions (Safety Regulations)	0.0614

V.2. NEUROFUZZY MODEL ARCHITECTURE

In the previous section, eight productivity input variables were identified to have the largest impact on HDD productivity in pipe/cable installation, Figure (V.2). Therefore, this research considered these eight factors in developing a model to measure the pipe/cable installation productivity when utilizing the HDD technique. Neurofuzzy systems were utilized in developing this productivity prediction model. To improve system adaptation and training, three neurofuzzy networks were designated NF_{clay}, NF_{rock} and NF_{sand}. Each of the three structures was employed to deal with one soil type, based on seven input variables I1, I2… I7 (Figure V.3).

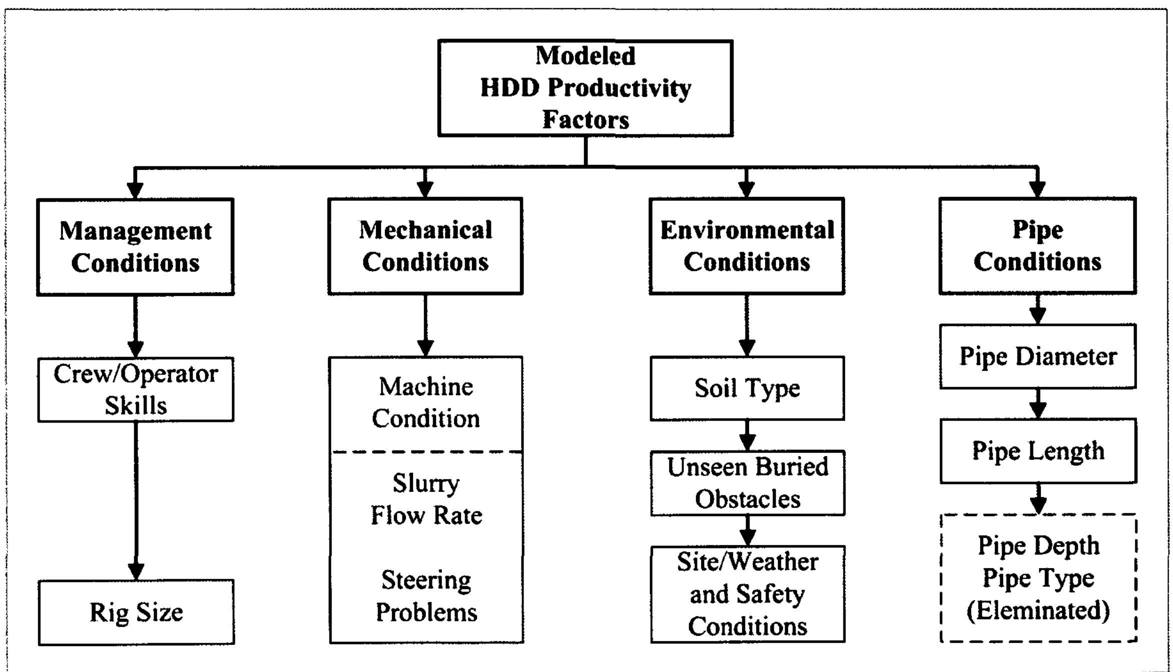


Figure V.2 Modeled Factors Affecting Productivity of HDD Operations

The functions of the neurofuzzy network are to fuzzify the system inputs, defuzzify the system outputs and develop a weight structure that suitably represents the non-linear relationships between the system inputs and outputs. To follow a proper NF system training, the neurofuzzy system is able to generalize the relationships between the inputs and outputs using actual industrial project data. Accordingly, the developed system can be used for predicting HDD productivity, given a specified set of project input variables, to an acceptable error level.

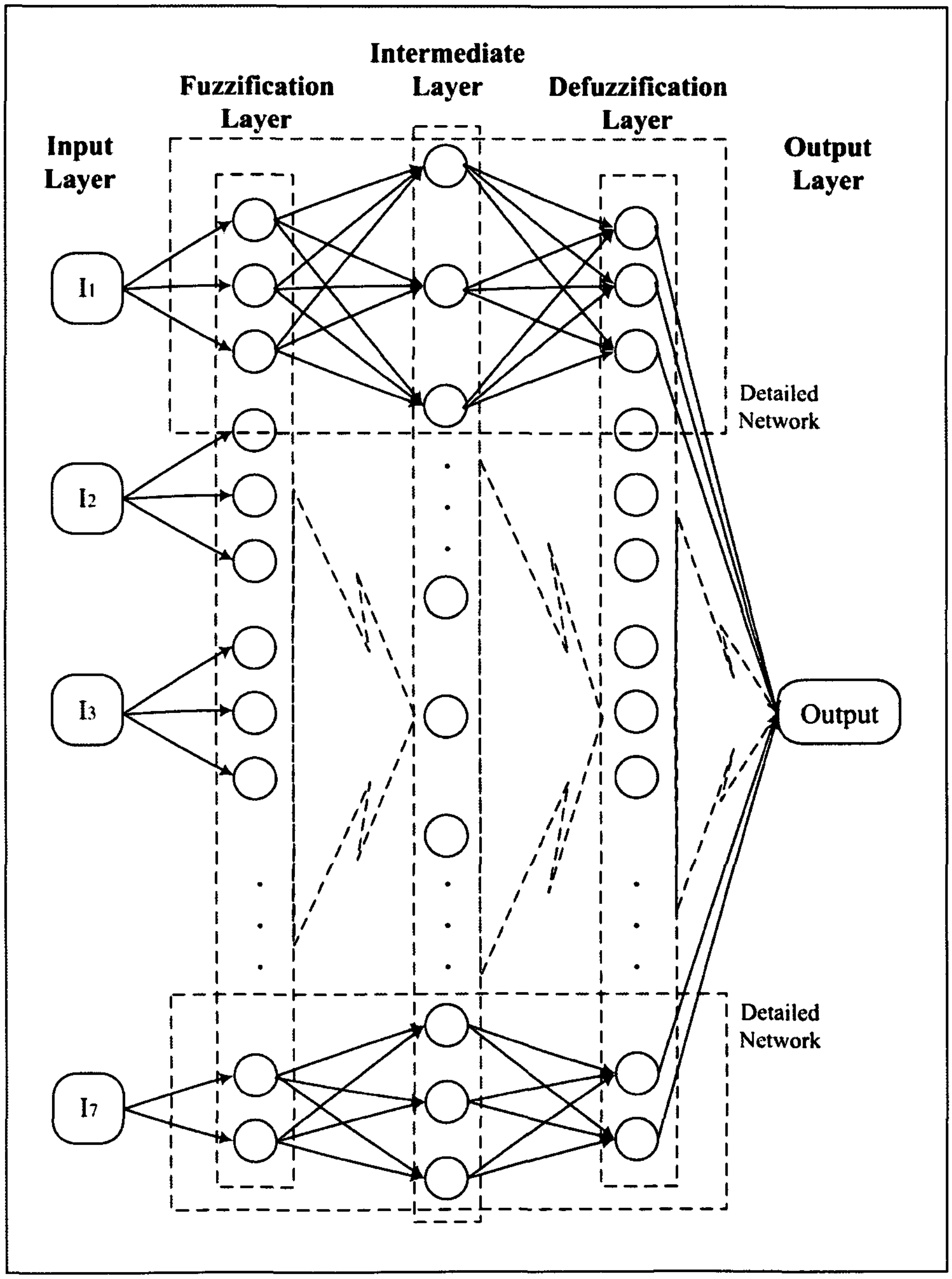


Figure V.3 Schematic Representation of the Utilized NF Architecture

V.3. NEUROFUZZY MODEL DEVELOPMENT

The current research developed three NF productivity prediction models for clay rock and sand. The reason of developing three models (clay and rock considered 7 factors, sand considered 5 factors) instead of just one model (considering 11 factors) is due to neurofuzzy system limitation. As the number of NF system inputs and outputs increase, designing of fuzzy rule base becomes complicated, dramatically increase number of fuzzy rules, needs longer run time and special computer hardware specifications (memory size). The neurofuzzy network model development involves the training and adaptation of three different structures for clay, rock, and sand. Questionnaire survey, Appendix C, was used for acquiring real time industrial project data relevant to the eight project input variables and one single output. The model mechanism was divided into training and validation phases. The training starts with both qualitative and quantitative data entry in terms of factor weights and cycle time/production rate, respectively. The model was developed using MATLAB® (ver. 7.6.0.324) using the Adaptive Neurofuzzy Inference Systems toolbox (ANFIS). The data entry layer takes both crisp and fuzzy factors and processes all factors to the training process, which starts by data fuzzification where the degree of each factor is determined. The data are then sent to be trained via ANN. The fuzzy outcome is then defuzzified, where the crisp input factor variable is determined given its degree of membership. In other words, the functions performed by the neurofuzzy networks are to fuzzify system inputs, defuzzify model outputs and develop a structure weight that properly represent the nonlinear relationships across the model inputs and outputs, Figure (V.3). This system is able to build relationships between the factors affecting the HDD process and the overall productivity. Therefore, the model can predict HDD process productivity given a specified set of project input variables (factors), with an adequate percent error.

V.3.1. Identifying Input Factors

The neurofuzzy system inputs represent a wide range of deterministic and linguistic variables. The modeled linguistic (non-numerical) variables are soil type, drilling rig size (capabilities), operator and crew skills, machine condition, unseen buried obstacles and site and weather conditions. On the other hand, the deterministic model variables are pipe length and pipe diameter. Linguistic variables generally have higher levels of uncertainty than deterministic variables. However, this degree of uncertainty defines the fuzziness in variable description.

For appropriate neurofuzzy system functionality, both deterministic and linguistic variables need to be described in a fuzzy form, as shown in Figures V.4 to V.10. Deterministic variables usually have exact or near-exact values. Therefore, they have low levels of uncertainty associated with them. Hence, a triangular membership function is used in the representation of deterministic fuzzy variables because of their steep change. Triangular or π membership functions centered at the particular value can be used for describing these linguistic terms. Nevertheless, the triangular membership function is commonly used in practical applications due to its mathematical simplicity. Therefore, this model employed the triangular form to present the input variable membership functions.

Allouche *et al.*, (2000) and Najafi M., (2004), classified the pipe diameter into three main categories; 50-100 mm (72% of the HDD market), 150-300 mm (16% of the HDD market) and >300mm (12% of the HDD market). It was found that the largest HDD market share is for the installation of 50-100 mm pipe diameters. Products in this diameter range are mostly used in the telecommunication industry (e.g. fiber-optic), natural gas distribution systems, electrical conduits and environmental applications. This is followed by the 150-300 mm diameter range, which is typically utilized in crude oil and natural gas delivery systems, municipal applications (i.e. water and sewer pipelines) and industrial applications. Diameters of greater than 300 mm are mainly used for utilizing water trunk lines, sewers, and transmission lines. This research considered this classification in designing the membership functions for pipe diameter for all soil types according to the maximum diameter collected (see Figure V.4 as an example). Membership function for the small pipe category is designed from 50-200 mm, medium from 100-300 mm and large consisting of diameters >200 mm.

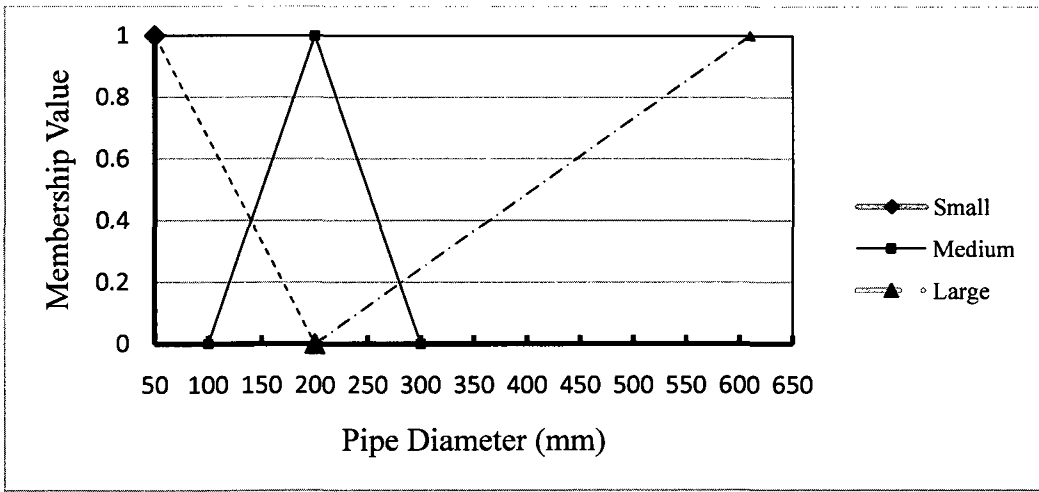


Figure V.4 Fuzzy Representation of Numerical Variables "Pipe Diameter-Clay"

According to Good Practices Guidelines (2004) the pipe length (L) was classified for the collected clay soil project data in to three main categories (short, medium and long), it was found that 45% of the clay projects is (L) $\leq$ 300m, 35% 300m $<$ (L) $\leq$ 500m, and 20% (L) $>$ 500m. Accordingly, pipe length membership function of clay soil was designed, see Figure (V.5).

According to drilling rig manufacturers and Good Practices Guidelines (2004), HDD rigs are classified into small, medium and large rigs according to their maximum torque (ft-lb). Therefore, three membership functions were developed to present their fuzzy values for clay, sand and rock, as shown Figure V.6; Small rigs $<$ 4000 ft-lbs, Medium rigs 4000 – 20000 ft-lbs and large rigs $>$ 20000 ft-lbs.

The fuzzy presentation of qualitative factors was based on their data collection fuzzy scale. Five membership functions were designed for each qualitative factor and named according to the factor quality. However, due to data limitations, the collected data were limited to some parts of the factor membership functions. Clay and rock models were trained based on skilled and highly skilled operator and crew, modeling inputs vary between skilled and highly skilled membership functions only. The sand model was limited only to a highly skilled operator and crew, (Figure V.7). Machine condition inputs vary from poor to very good for all models (Figure V.8), while very poor does not have any input as it is not ideal to use a very poor condition rating unless the machine is repaired, since it might cause a loss of track and a waste of time.

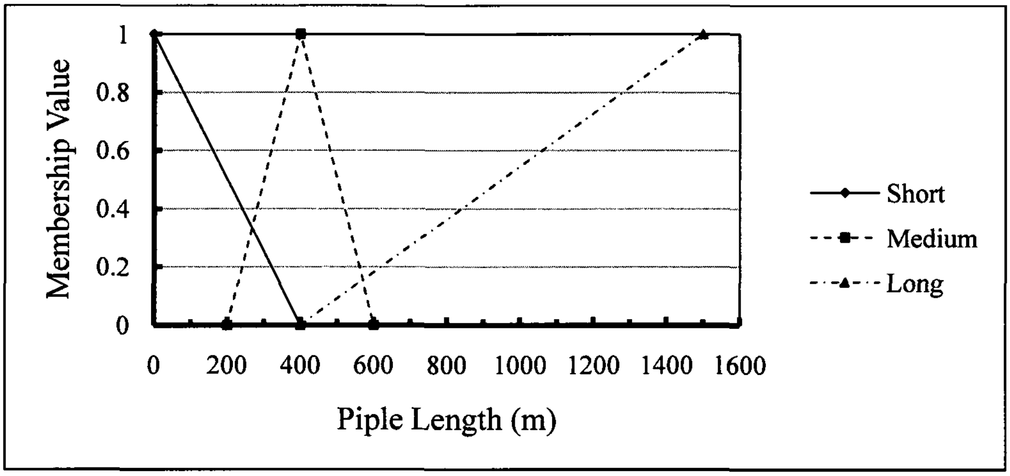


Figure V.5 Fuzzy Representation of Numerical Variables “Pipe Length-Clay”

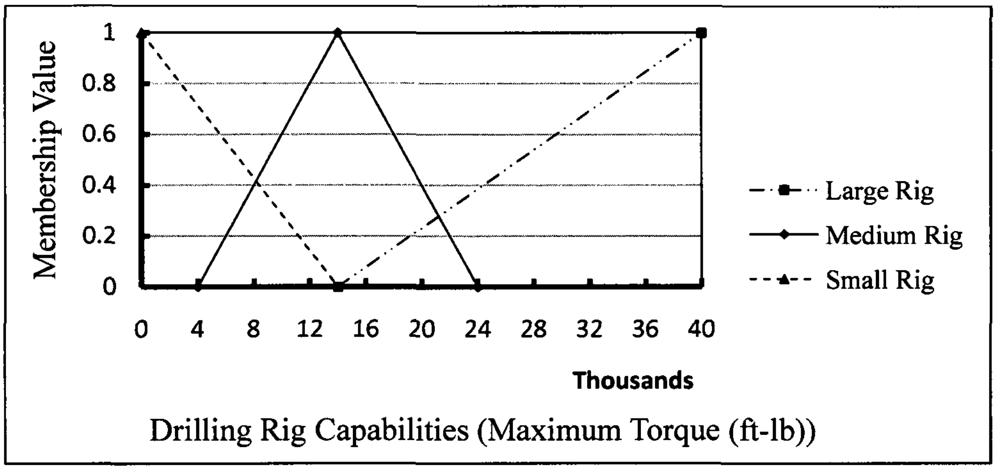


Figure V.6 Fuzzy Representation of Numerical Variables “Rig Size; all soil types”

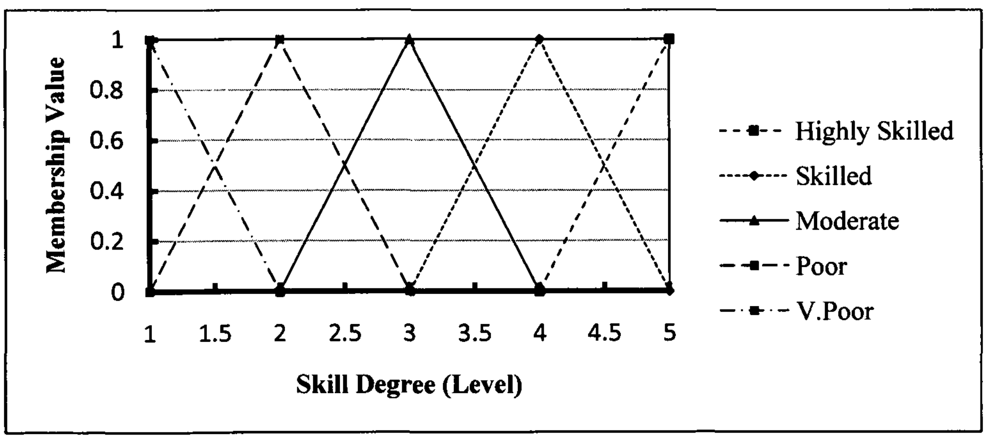


Figure V.7 Fuzzy Representation of Linguistic Variables

“Drilling Rig Operator & Crew Skills”

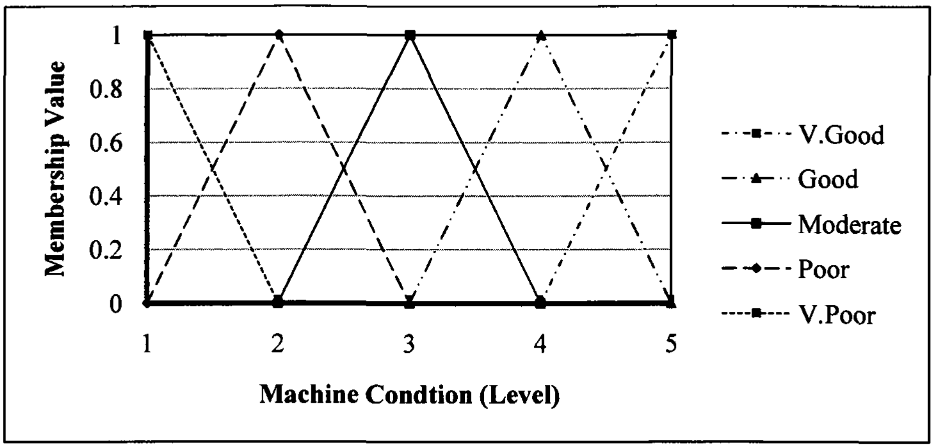


Figure V.8 Fuzzy Representation of Linguistic Variables "Machine Condition"

As shown in Figure V.9, unseen obstacles and site, weather and safety condition modeling inputs are limited to four membership function areas. Very low expectation of underground obstacles does not have inputs because HDD are commonly used in urban and crowded areas, in which there are many buried infrastructure services (e.g. telephone lines, water mains and internet cables). Weather, site and safety does not have very good condition, (see Figure V.10).

V.3.2. Calculating Output (Productivity (m/hr))

Based on the surveys and five personal meetings with HDD professionals, finding a universal deterministic productivity rate for the overall HDD construction process was not possible. Contractors, engineers, consultants and field experts rarely keep track of the overall project production rate on their database; however, they keep track of small activity production rates (i.e. pilot hole drilling, back reaming). Moreover, working hours per day vary from one contractor to another and may be unique for each project.

Contractors may work eight, ten or twelve hours per day, while other contractors perform longer operations on crew shift basis.

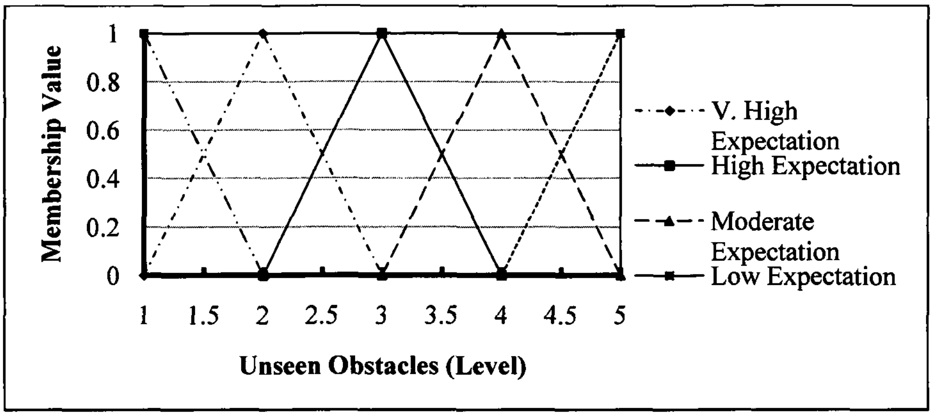


Figure V.9 Fuzzy Representation of Linguistic Variables "Unseen Obstacles"

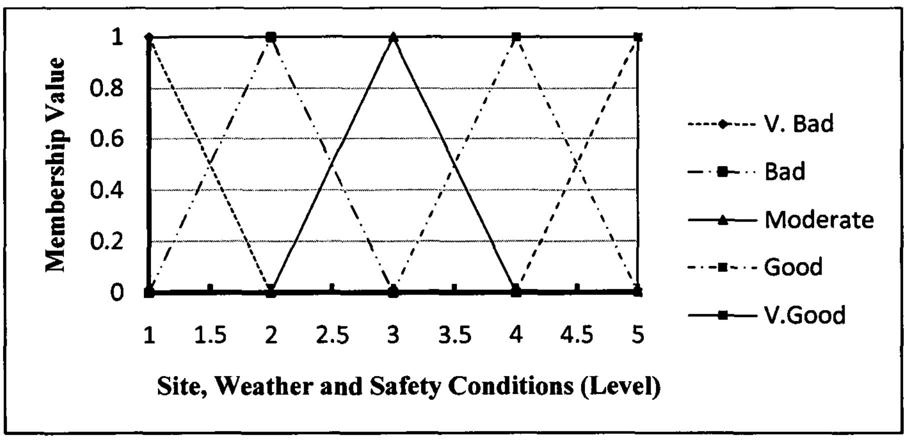


Figure V.10 Fuzzy Representation of Linguistic Variables "Site, Weather and Safety Conditions"

This research attempts to break down the HDD construction process into small activities and calculate the most probable time for each activity, in order to find the process production rate in m/hr for each project. The time for each HDD process is calculated in minutes, based on the surveyed data. HDD processes are defined according to major and auxiliary activities as follows:

Major Drilling Activities & Site Preparation Time (T_j):

1. Site preparation (T_{sp})
2. Pilot hole drilling (T_{ph})
3. Reaming (T_r)
4. Final pipe pulling (T_{pp})

$$T_{major} = T_{sp} + T_{ph} + T_r + T_{pp}$$

(Equation V.1)

Auxiliary Drilling Activities and Pipe Connection Time (T_x):

1. Angle adjustment at bit entrance (T_{adj})
2. Joining of drill pipe segments (T_{sj})
3. Reamer with shackle attaching for pre-reaming (T_{sh})
4. Pipe/cable segment connection and layout (T_{sc})
5. Pipe swivel assembly for pipe pullback (T_s)
6. All tracking activities (T_{tr})
7. All assessment activities (T_{ass})

$$T_{auxiliary} = T_{adj} + T_{sj} + T_{sh} + T_{sc} + T_s + T_{tr} + T_{ass}$$

(Equation V.2)

Accordingly, the modeling output is achieved based on the formula shown below:

$$\text{Productivity (m/hr)} = \frac{\text{Total Pipe Length (L)}}{(\text{Tmajor} + \text{Tauxiliary})/60}$$

(Equation V.3)

Note: All activities durations (T_{major} & $T_{auxiliary}$) include idle time.

V.4. HDD PRODUCTIVITY MODEL FOR CLAY SOIL

V.4.1. Clay Model Training

The Clay NF model considered seven input factors: 1) operation and crew skills, 2) pipe diameter, 3) rig size, 4) machine condition, 5) site and weather conditions, 6) pipe length and 7) unseen obstacles, where each factor has its own number of membership functions according to its data range, (see Figure V.11). Data for the clay projects, acquired through the questionnaire, were used for the neurofuzzy system development, verification and validation. The clay model was trained and tested via 80% and 20% of the collected data points, respectively. Furthermore, the clay NF model was developed based on 1992 nodes (fuzzification layer 22 nodes, Intermediate layer 1948 nodes and defuzzification layer 22 nodes), 32 training data pairs, and 972 fuzzy rules, see Figure (V.12). As shown in Figure V.13, 30 training cycles (epochs), are used for the clay soil model training. The training process engages the tuning of the network weight structure for more precision, thereby producing the target output for the network. Neurofuzzy systems use back-propagation algorithm to minimizing the error, which is the difference between the target and calculated output.

The developed model was then tested after the modeling phase, where the neurofuzzy system splits the modeling data into training and testing data. Twenty percent of the total collected data points were unexposed to the neurofuzzy system during the training phase and were used for testing and validation purposes. The testing data set was then used to predict productivity and compare the results with the real time productivity, (Figure V.14).

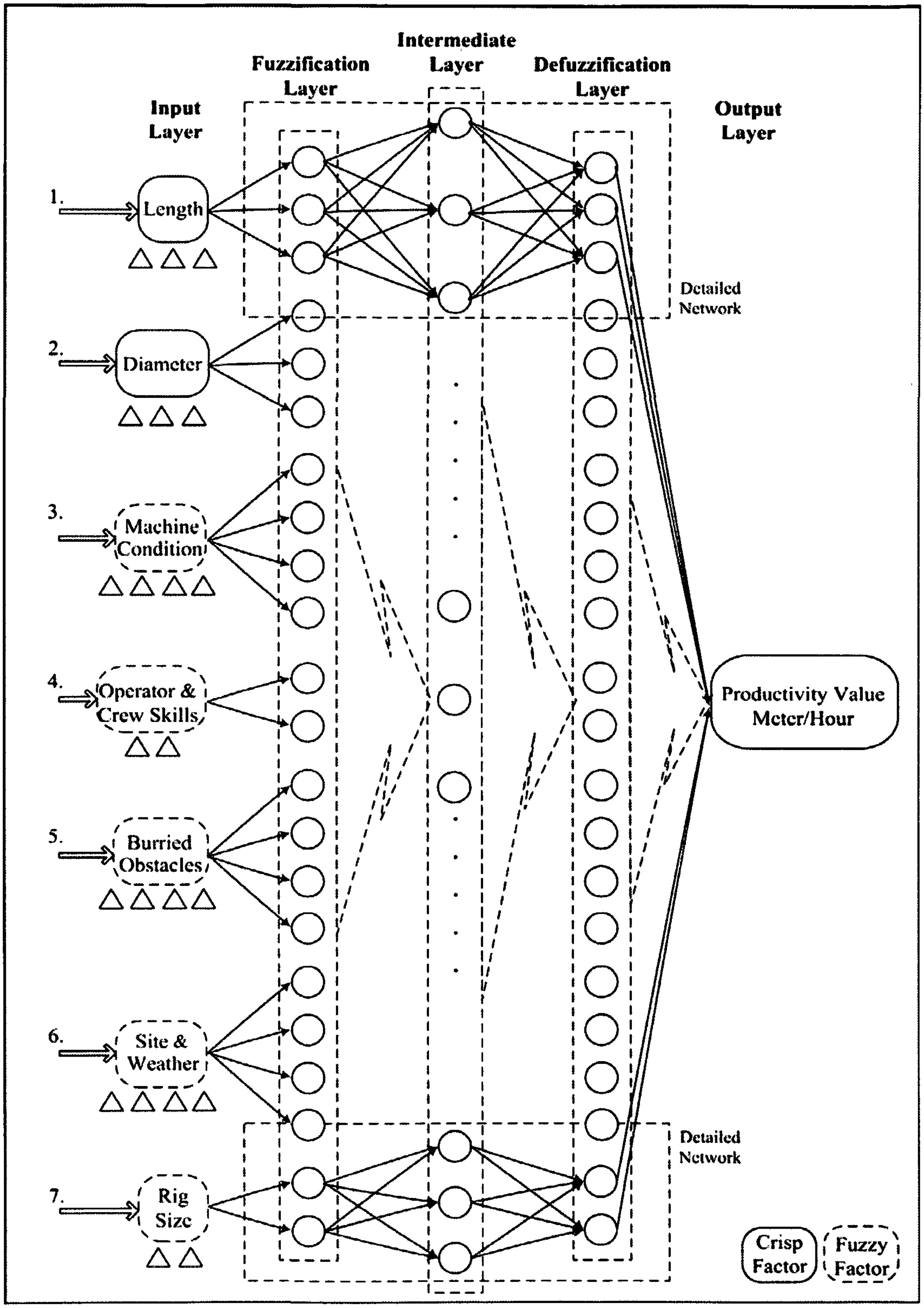


Figure V.11 Basic Architecture of Clay and Rock NF Model

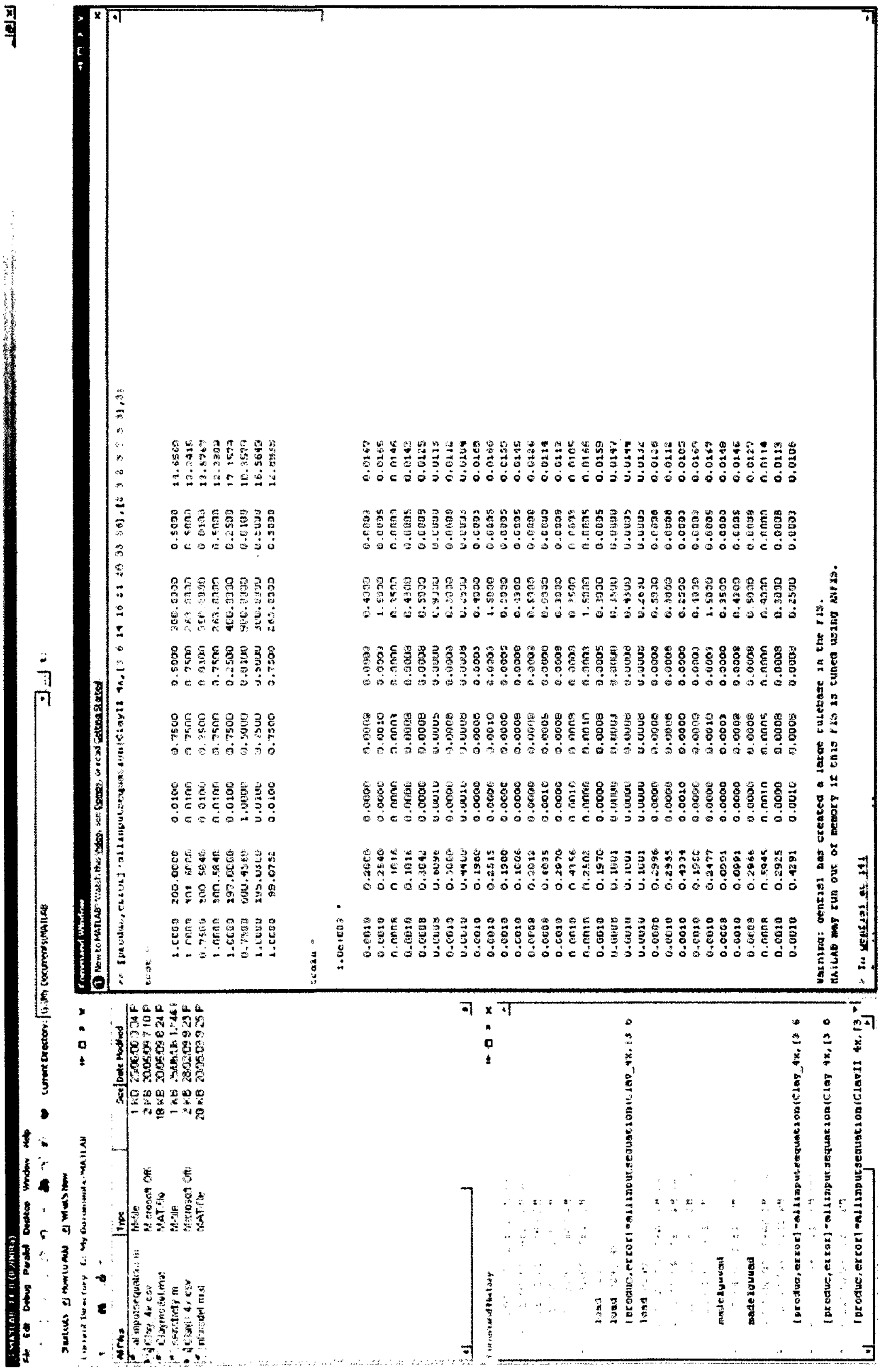


Figure V.12 Training and Validation Data Sets; Clay NF Model

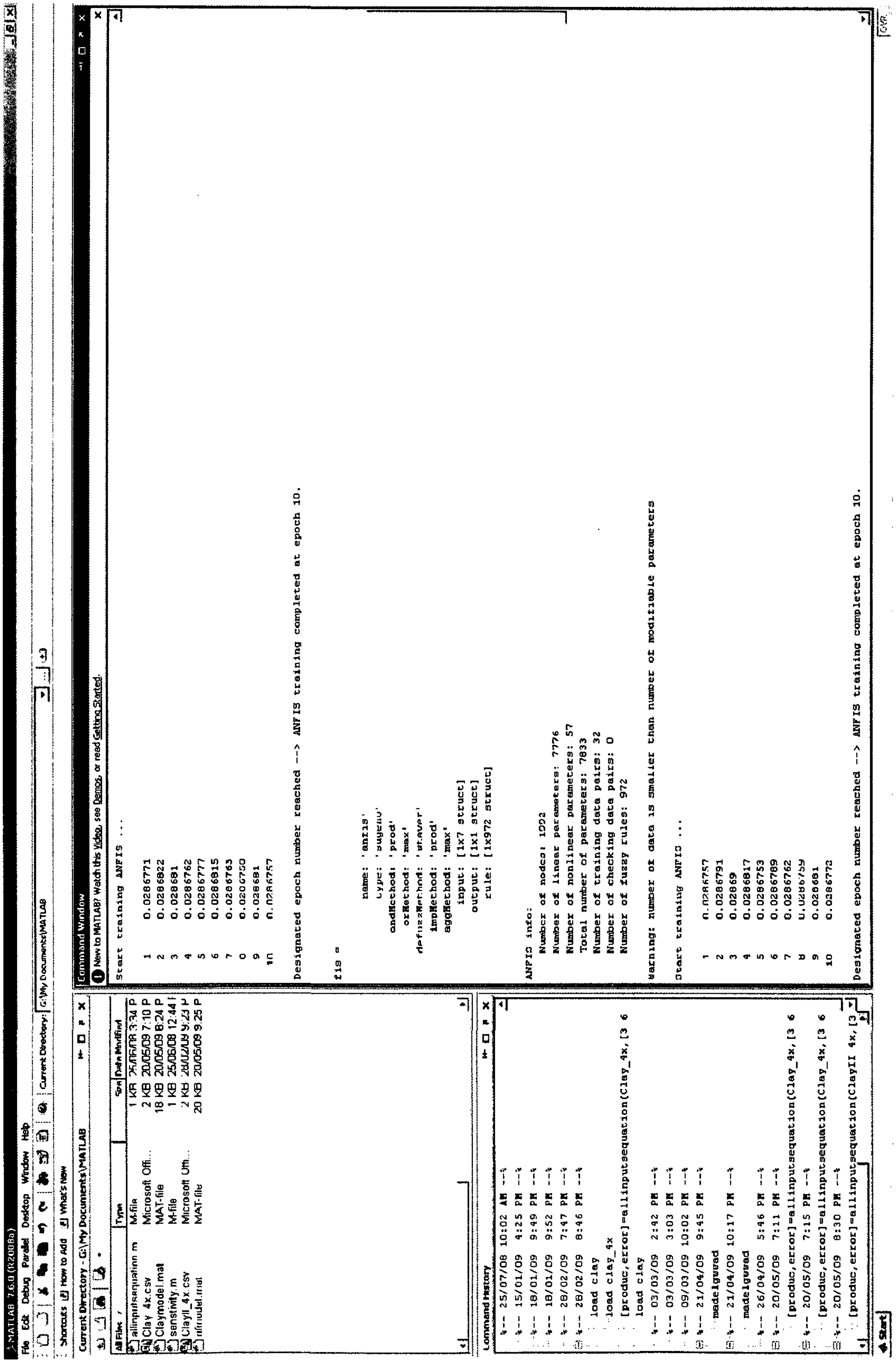


Figure V.13 Sample of Training Cycles (Epochs); NF Clay Model Training

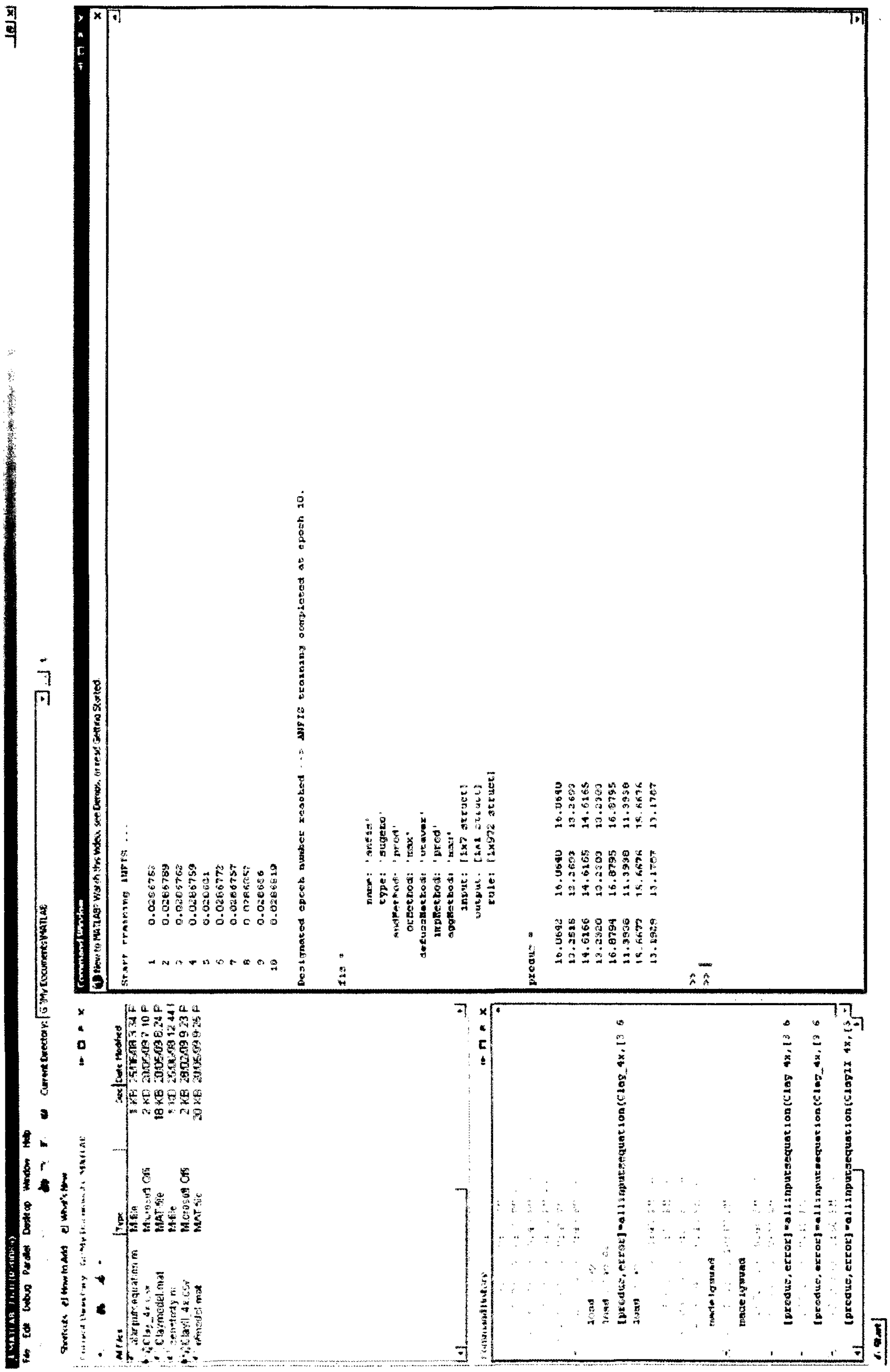


Figure V.14 Clay NF Testing Data Set Results

V.4.2. Clay Model Validation

The model was tested by utilizing a portion of project data already used in system training to verify the network adaptability for the proper estimate of its inputs. Furthermore, system functionality was investigated and validated utilizing a sample project data (20% of clay data) not previously employed in system training. The validation process of the developed models was performed as shown in the following sections.

i. Average Invalidity and Validity Percent (Clay)

A mathematical validation diagnostic was utilized for model validation. According to Zayed and Halpin, (2005), the average invalidity and validity percents are calculated for validation data using the following formulas:

$$AIP = \frac{\sum_{i=1}^{n}\left|1-\left(\frac{Ei}{Ci}\right)\right|}{n} \times 100 \qquad \textit{(Equation V.4)}$$

and

$$AVP = 100 - AIP \qquad \textit{(Equation V.5)}$$

Where, AIP represents the average invalidity percent, AVP is the average validity percent, E_i is the predicted value, C_i is the actual calculated value and n is the number of observations. The AVP varies between 0 and 1. As the AIP value approaches zero, the better the model fits the data. Similarly, the closer the AIP Value is to one, the more inappropriate is the model. Therefore, for a satisfactory validation results, the AVP should be closer to one. For the clay productivity prediction model, the values were as follows:

- AIP = 5.5611 %
- AVP = 94.4389 %

The validation process shows that the developed model could predict the actual outputs with accuracy of almost 94.7%. The AVP value obtained could be considered as a satisfactory validation result. Therefore, the clay prediction model could be utilized for HDD prediction.

V.4.3. Case Study Description and Application of Clay Model

A water main is to be installed underground at 3 m depth (Project 1, which is located in Saint lazarre, Montreal West). An HDPE pipe with a diameter of 200 mm is to be used. The pipe is to be laid at a distance of 300 m in clay soil. A medium size rig is utilized for job implementation. The job is accomplished in 2 working days based on a 10 hour work day. Tables V.5 and V.6 show the major and auxiliary activities' durations for the case study in hand. Based on productivity calculation equations V.1, V.2 and V.3 mentioned earlier in this chapter, the total activity time T_j, T_x and productivity were calculated.

$T_j = 495\text{min}$ and $T_x = 655\text{min}$

Then, Calculated Productivity (m/hr) $= \frac{300}{(495 + 655)/60} = 15.65\, m/hr$

Table V.5 Major Activities Durations (Clay Case Study)

Major Drilling & Site Preparation Activities	Duration (min)
Site preparation (SP)	45
Pilot hole drilling (PH)	210
Reaming (R)	210
Pipe Pull Back (PP)	30
Total Major Activities Duration	495

Table V.6 Auxiliary Activities Durations (Clay Case Study)

Auxiliary Drilling & Pipe Connection Activities	Duration (min)
Pipe connection & layout	430
Angle adjusting	15
Joining of drill pipe segments	30
Attaching reamer/shackle	30
Pipe swivel assembly	30
Tracking activities	60
All assessment activities	60
Total Auxiliary Activities Duration	655

The calculated on site HDD productivity in clay soil is 15.65 m/hr. The project is implemented by utilizing a medium drilling rig size (max torque; 4000-20000 ft-lb), a highly skilled operator and crew, a moderate machine condition, with moderate expectations of unseen buried obstacles and moderate site, weather and safety conditions. The input of the qualitative factors is based on their membership functions as shown in Figures V.6 to V.10. The clay NF model is recalled and processes the project inputs. The predicted productivity by the clay NF model is calculated to be 13.67 m/hr. The predicted result showed a validation of 87.34%.

V.4.4. Clay Model Productivity Curves

Based on the developed NF clay model, a relationship between productivity performance and each productivity factor (sensitivity analysis) was done, for the previously mentioned HDD application in clay soil. This was done in order to predict the HDD production rate based on different management, mechanical, environmental and pipe physical conditions. The performed sensitivity analysis holds the studied HDD factor at actual values while the other factors are kept at their constant average values. Figures V.15 to V.20 show the direct relationship between the production rate and each of the factors affecting the HDD process.

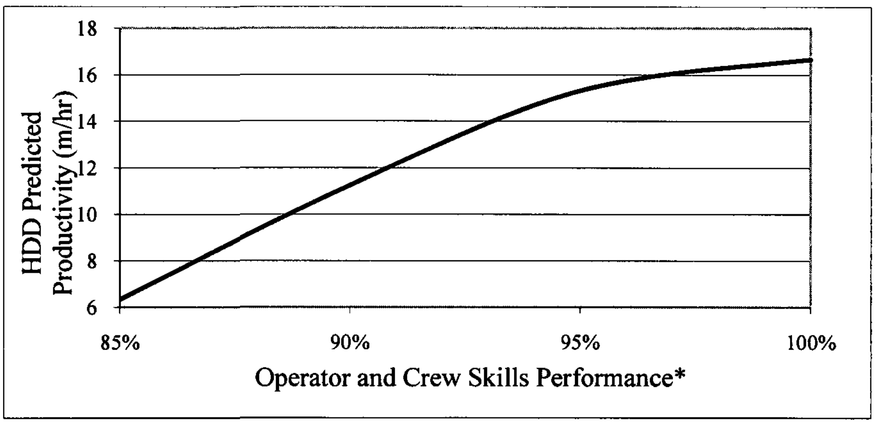


Figure V.15 Productivity Predictions for Operator and Crew Skills; Clay Soil
* 80-100% Highly Skilled, 60-80% Skilled, 40-60% Moderate, 20-40% Poor, 0-20% Very Poor

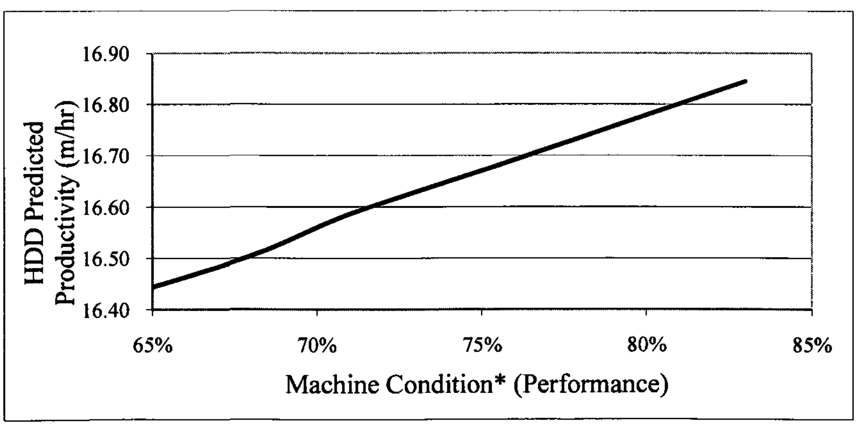


Figure V.16 Productivity Predictions for Machine Condition; Clay Soil
* 80-100% Very Good, 60-80% Good, 40-60% Moderate, 20-40% Poor, 0-20% Very Poor

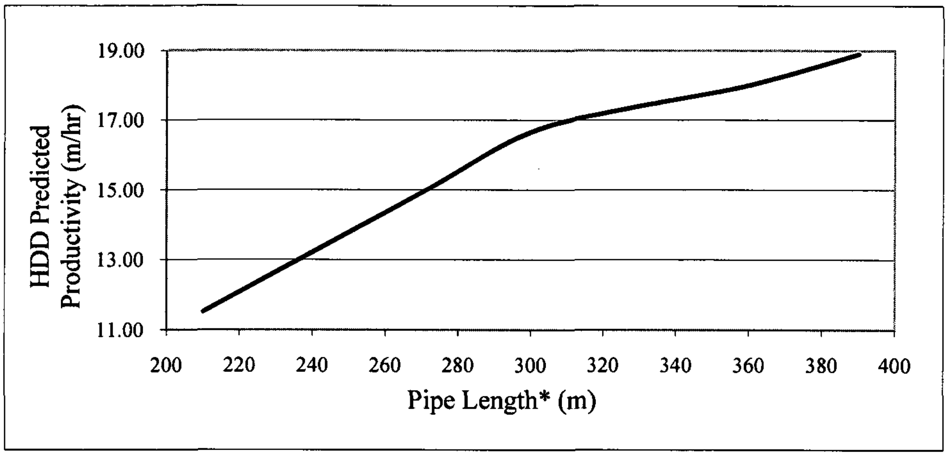


Figure V.17 Productivity Predictions for Pipe Length; Clay Soil

* L< 300m short, L= 300-500m, L> 500 Long

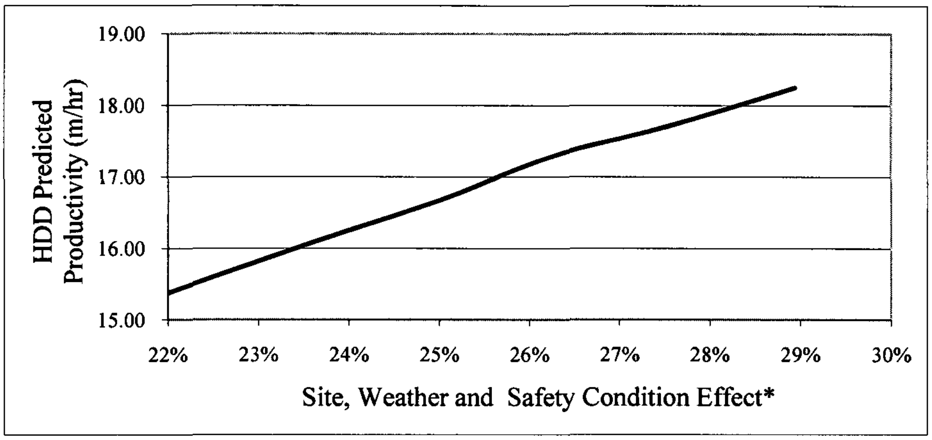


Figure V.18 Productivity Predictions for Site, Weather and Safety Conditions; Clay Soil

* 80-100% V. Good, 60-80% Good, 40-60% Moderate, 20-40% Poor, 0-20% V. Poor

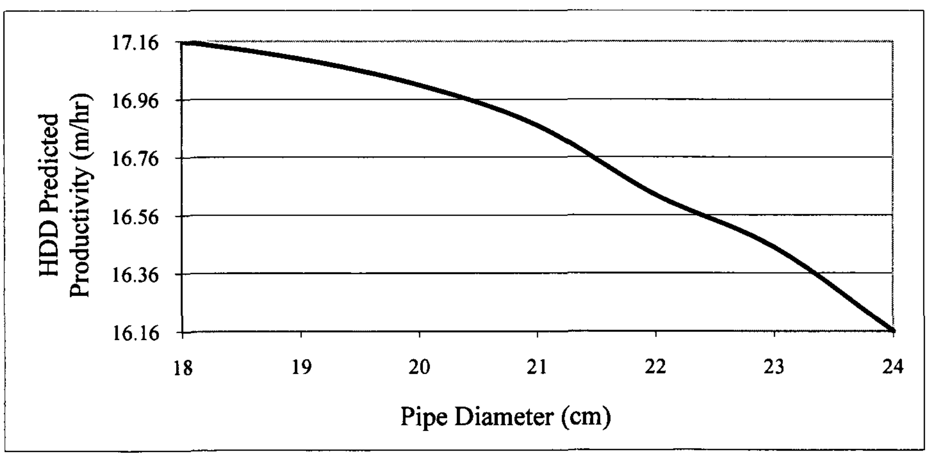


Figure V.19 Relation between Productivity Rate and Pipe Diameter; Clay Soil

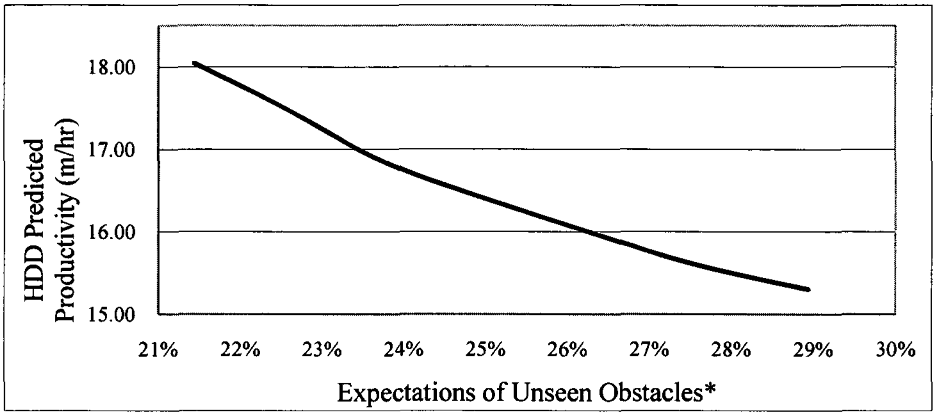


Figure V.20 Relation between Productivity Rate and Buried Obstacles; Clay Soil
* 80-100% V. High Expectation, 60-80% High Expectation, 40-60% Moderate, 20-40% Low Expectations, 0-20% V. Low Expectations

It can be seen that operator and crew skills, machine, site, weather and safety conditions and pipe length figures show a direct relationship with productivity rate. The slope of the productivity and pipe length has inclination at 300m as it is the transition point between short and medium length installations, in which HDD productivity tends to decrease. Pipe diameter and underground obstacles show an inverse relationship with productivity rate.

V.5. HDD PRODUCTIVITY MODEL FOR ROCK SOIL

V.5.1. Rock Model Training

Similar to the Clay NF model, the Rock NF model considered seven input factors, (operation and crew skills, pipe diameter, rig size, machine condition, site and weather conditions, pipe length and unseen obstacles) as shown in Figure (V.11), where each factor had its own number of membership functions according to its data range. Data for rock projects, acquired through the questionnaire, was examined for consistency and completeness. The rock model was trained and tested via 80% and 20% of the collected data points, respectively. The rock NF model was developed based on 1992 nodes (fuzzification layer 22 nodes, Intermediate layer 1948 nodes and defuzzification layer 22 nodes), 27 training data pairs, and 972 fuzzy rules. Thirty training cycles (epochs) were used for rock soil model training. The training process engaged the tuning of the network weight structure for more precision, thereby producing the target output for the network. It should be noted that neurofuzzy systems use a back-propagation algorithm to minimize errors, which is the difference between the target and calculated output.

The developed model is tested after the modeling phase, where the neurofuzzy system, splits the modeling data into training and testing data. Twenty percent of the total collected data points are unexposed to the neurofuzzy system during the training phase to be used for testing and validation purposes. Afterwards, the testing data set is used to predict productivity and compare the result with the real time productivity.

V.5.2. Rock Model Validation

i. Average Invalidity and Validity Percent (Rock)

Similarly, Equations V.4 and V.5 are utilized to validate the rock NF model. For the rock productivity prediction model, values are as follows:

- AIP = 17.71 % and AVP = 82.29 %

The validation process showed that the values of the predicted outputs are almost 82.3 % accurate. The AVP value can be considered as a satisfactory validation result. Therefore, the rock prediction model can be utilized for HDD prediction.

V.5.3. Case Study Description and Application of Rock Model

A water main is to be installed underground at 4.5 meter depth (Project 2, which is located in seaway, Longuell/Notredame). An HDPE pipe with a diameter of 139.7 mm is used. The pipe is to be laid at a distance of 440 m in black shale (rock) soil. A large size rig is utilized for job implementation. The job was accomplished in 4 working days based on a 12-hour work day. On site productivity was then calculated. Tables V.7 and V.8 show the activities durations. Based on productivity calculation equations V.1, V.2 and V.3, the total activity time T_j, T_x and productivity was calculated.

$T_j = 480min$ and $T_x = 1995min$

Then, Calculated Productivity (m/hr) $= \frac{440}{(480 + 1995)/60} = 10.67m/hr$

Table V.7 Major Activities Durations (Rock Case Study)

Major Drilling and SP Activities	Duration (min)
Site preparation (SP)	180
Pilot hole drilling (PH)	180
Reaming (R)	0
Pipe Pull Back (PP)	120
Total Major Activities Duration	480

Table V.8 Auxiliary Activities Durations (Rock Case Study)

Auxiliary Drilling and Pipe Connection Activities	Duration (min)
Pipe connection & layout	1140
Angle adjusting	15
Joining of drill pipe segments	90
Attaching reamer/shackle	120
Pipe swivel assembly	270
Tracking activities	180
All assessment activities	180
Total Auxiliary Activities Duration	1995

The project was implemented by utilizing a large drilling rig size (max torque > 20000 ft-lb), highly skilled operator and crew, very good machine condition, with low expectations of unseen buried obstacles and bad site, weather and safety conditions. The input of the qualitative factors was based on their membership functions shown in Figures V.6 to V.10. The rock NF model processed the project inputs and the predicted productivity was calculated to be 9.47m/hr. The predicted result showed a validation of 88.75%.

V.5.4. Rock Model Productivity Curves

Similar to clay soil NF model, a NF rock model was recalled and a relationship between productivity performance and each productivity factor (sensitivity analysis) was done. Similar to clay soil, the performed sensitivity analysis holds the studied HDD factor at actual values while the other factors are kept at their constant average values. Figures V.21 to V.26 show the direct relationship between the production rate and each of the factors affecting the HDD process. All factors are directly related to outputs except for pipe diameter and underground obstacles, which are inversely related.

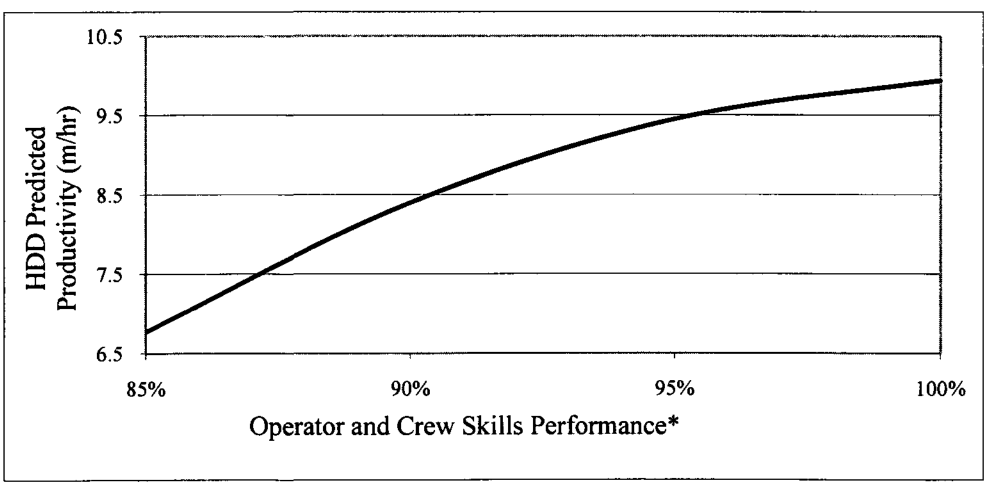


Figure V.21 Productivity Predictions for Operator and Crew Skills; Rock Soil
* 80-100% Highly Skilled, 60-80% Skilled, 40-60% Moderate, 20-40% Poor, 0-20% Very Poor

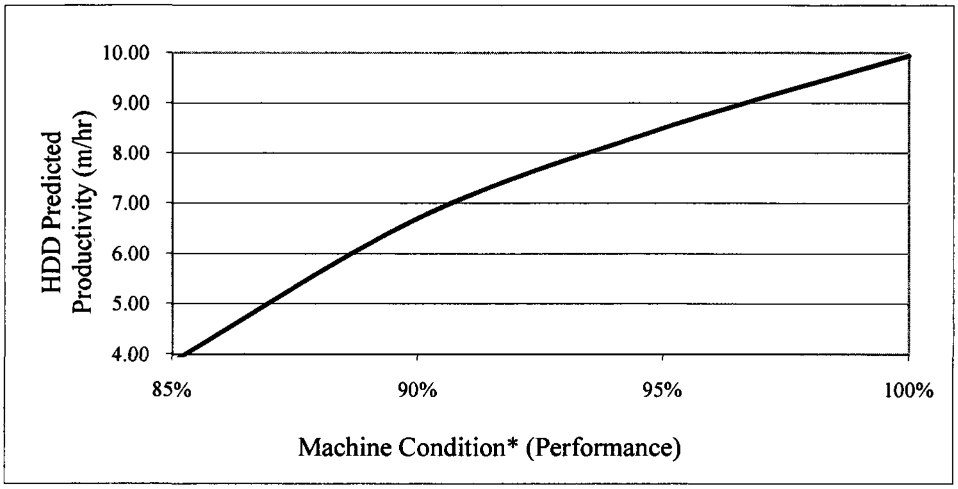


Figure V.22 Productivity Predictions for Machine Condition; Rock Soil
* 80-100% Very Good, 60-80% Good, 40-60% Moderate, 20-40% Poor, 0-20% Very Poor

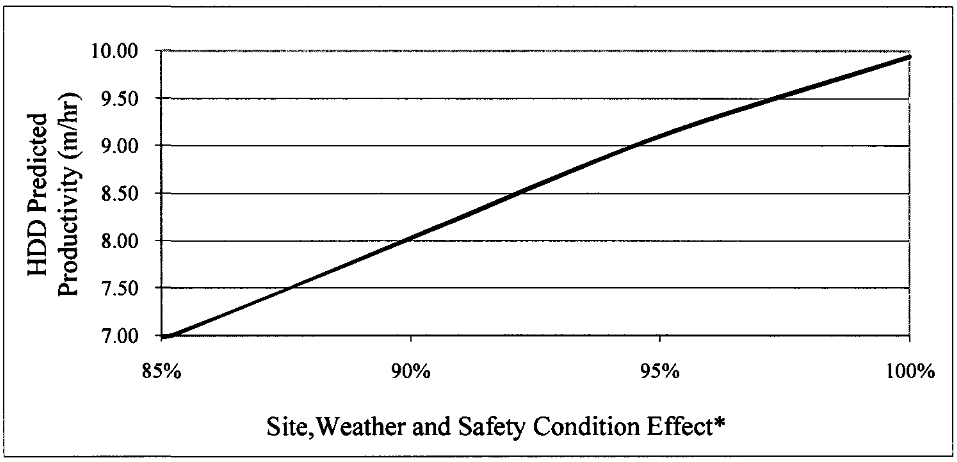


Figure V.23 Productivity Predictions for Site, Weather and Safety Conditions; Rock Soil
* 80-100% V. Good, 60-80% Good, 40-60% Moderate, 20-40% Poor, 0-20% V. Poor

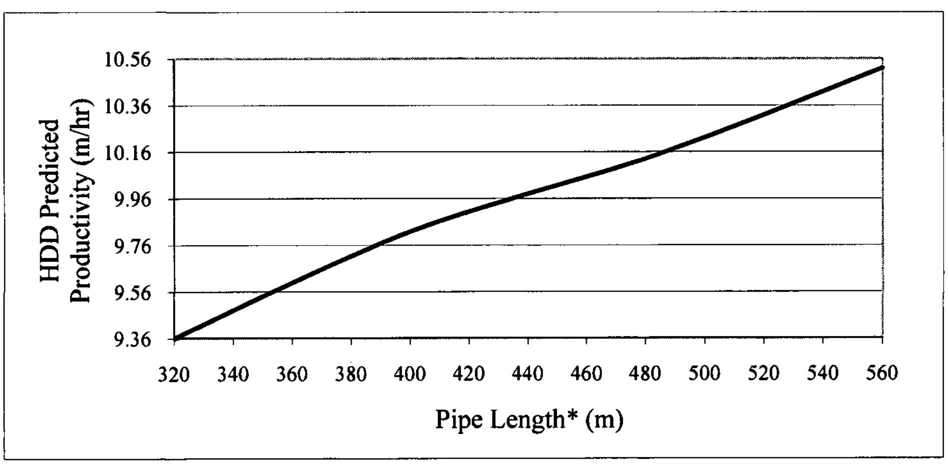


Figure V.24 Relation between Productivity Rate and Pipe Length; Rock Soil
* L< 300m short, L= 300-500m, L> 500 Long

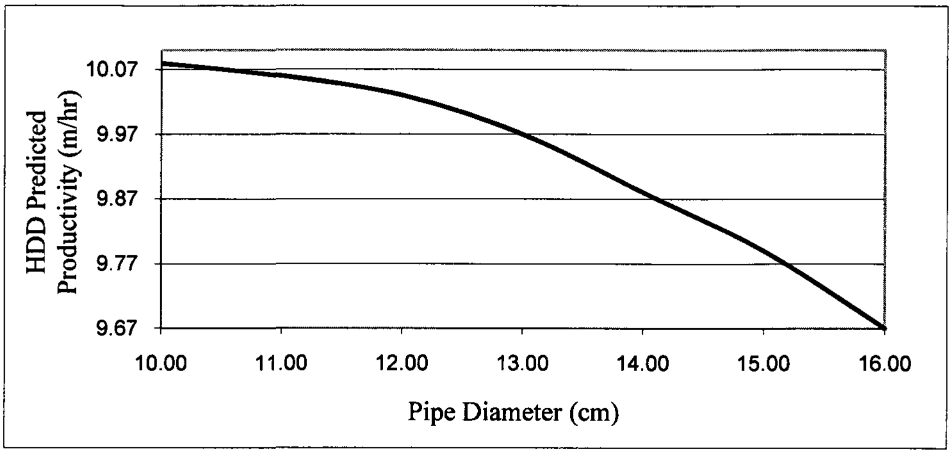


Figure V.25 Relation between Productivity Rate and Pipe Diameter; Rock Soil

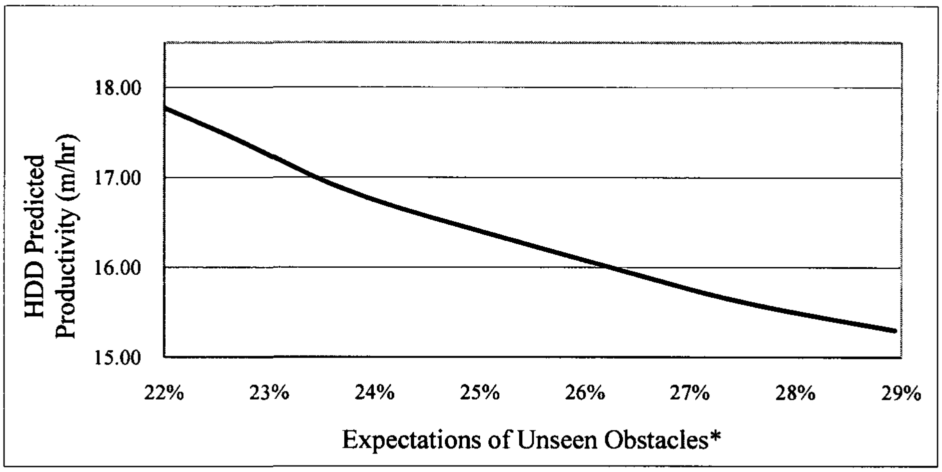


Figure V.26 Relation between Productivity Rate and Underground Obstacles; Rock Soil

* 80-100% V. High Expectation, 60-80% High Expectation, 40-60% Moderate, 20-40% Low Expectations, 0-20% V. Low Expectations

V.6. HDD PRODUCTIVITY PREDICTION MODEL FOR SAND SOIL

V.6.1 Sand Model Training

The sand NF model considered five inputs: 1) pipe diameter, 2) machine condition, 3) site and weather conditions, 4) pipe length, and 5) unseen obstacles, as shown in Figure V.27. Similar to clay and rock models, each factor has its own number of membership functions according to its data range. The sand model was trained via 80% of the collected sand data points, while it was tested by the remaining 20%.

Furthermore, sand NF model was developed based on 360 nodes (fuzzification layer 14 nodes; intermediate layer 332 nodes; defuzzification layer 14 nodes), 30 training data pairs, and 9162 fuzzy rules. Thirty training cycles were used for training the sand soil model. The training process engaged the tuning of the network weight structure for more precision, thereby producing the target output for the network. Twenty percent of the total collected data points were unexposed to the neurofuzzy system during the training phase and were used for validation purposes.

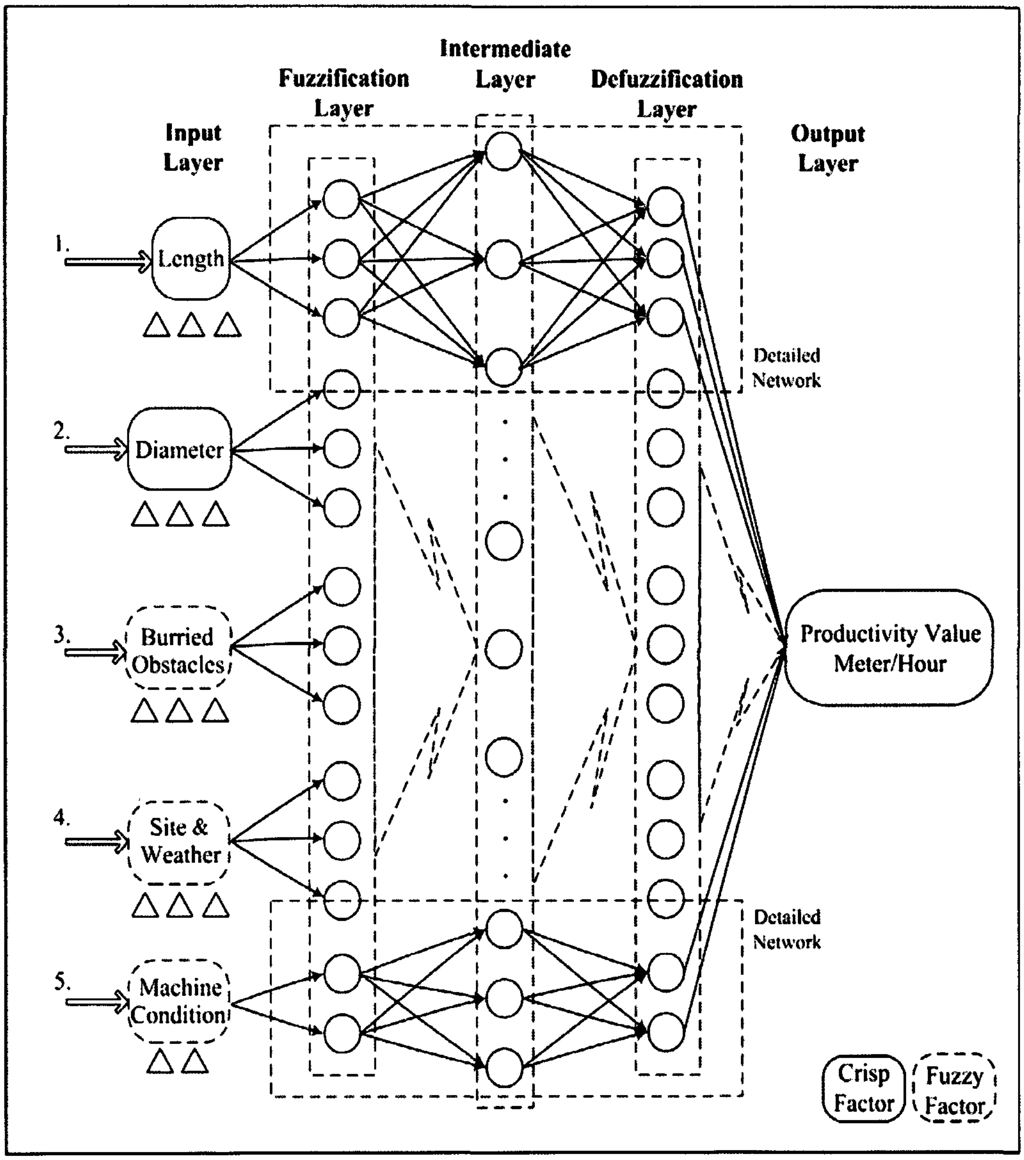


Figure V.27 Basic Architecture of Sand NF Model

V.6.2. Sand Model Validation

i. Average Invalidity and Validity Percent (AIP & AVP)

As previously explained in clay soil, Equations V.4 and V.5 were used to calculate the AIP and AVP for the sand NF model, which shows that AIP = 13.3313 % and AVP = 86.6686 %. The validation process showed that the values of the predicted outputs were almost 86.7% accurate. The AVP value can be considered as a satisfactory validation result and the sand prediction model can be utilized for HDD prediction.

V.6.3. Case Study Description and Application of Sand Model

A pipe is installed underground at 2.5 meter depth (Project 3, which is located in Connecticut, USA). An HDPE pipe is used with a diameter of 101.6 mm. The pipe is to be laid at a distance of 660 m in sandy soil. A medium size rig is utilized for job implementation. On site productivity was then calculated. The job was accomplished in 7 working days based on an 8 hour work day. Tables V.9 and V.10 show the durations of various activities involved in the HDPE installation process.

Table V.9 Major Activities Durations (Sand Case Study)

Major Drilling and SP Activities	**Duration (min)**
Site preparation (SP)	600
Pilot hole drilling (PH)	960
Reaming (R)	720
Pipe Pull Back (PP)	360
Total Major Activities Duration	2640

Table V.10 Auxiliary Activities Durations (Sand Case Study)

Auxiliary Drilling and Pipe Connection Activities	**Duration (min)**
Pipe connection & layout	600
Angle adjusting	60
Drill pipe segments joining	360
Attaching reamer/shackle	60
Pipe swivel assembly	60
Tracking activities	60
All assessment activities	120
Total Auxiliary Activities Duration	1320 - 600 = 720

In this case study, the pipe connection and layout and site preparation was done at the same time. Therefore, the pipe connection and layout time was neglected, as it was already done in parallel with the site preparation time. Based on Equations V.1, V.2 and V.3, the total activity time, T_j, T_x, and onsite productivity was calculated as:

$T_j = 2640min$ and $T_x = 720min$

Then, Calculated Productivity (m/hr) $= \frac{640}{(2640 + 720)/60} = 11.43 m/hr$

The project was implemented utilizing a medium drilling rig size (max torque; 4000-20000 ft-lb), highly skilled operator and crew, moderate machine condition, with a high expectation of unseen buried obstacles, and good site, weather and safety conditions. Based on the above-mentioned input factors, the sand NF model processes the project inputs. The predicted productivity was calculated to be 10.21m/hr. The predicted result showed a validation of 89.32%.

V.6.4. Sand Models Productivity Curves

Similar to the process used on clay and rock, the performed sensitivity analysis for the sand NF model held the studied HDD factor at actual values while all other factors were kept at their constant average values. Figure V.28 shows direct linear relation between the production rate and the machine condition, while Figure V.29 shows inverse linear relation of the pipe diameter with productivity. Furthermore, Figures V.30 and V.31 show direct and inverse exponential relations of site, weather and safety condition, and existence of unseen obstacles, respectively. The HDD productivity and pipe length has a direct relationship in which the longer the pipe installation the more productive the project, see Figure (V.32).

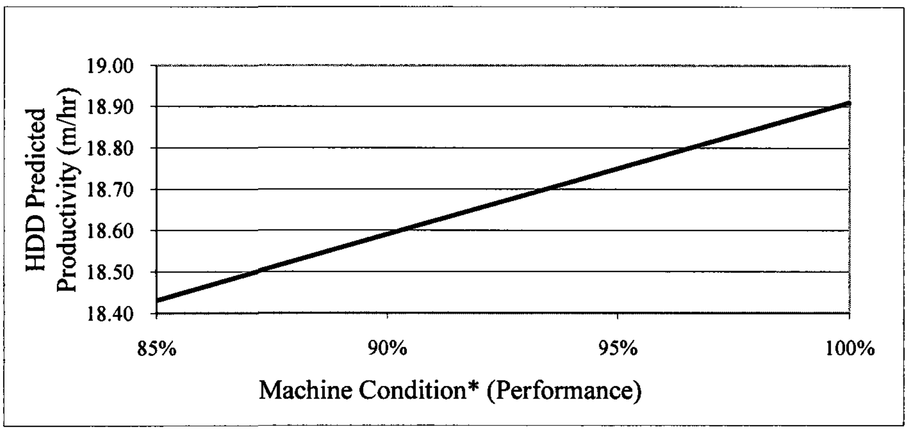


Figure V.28 Productivity Predictions for Machine Condition; Sand Soil
* 80-100% Very Good, 60-80% Good, 40-60% Moderate, 20-40% Poor, 0-20% Very Poor

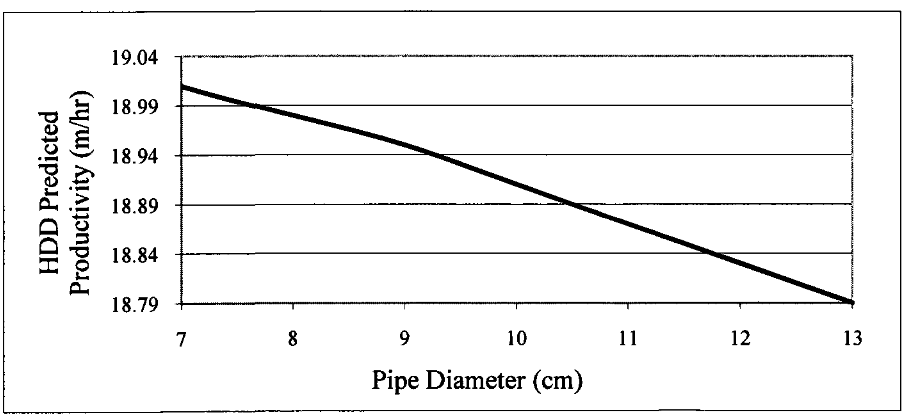


Figure V.29 Relation between Productivity Rate and Pipe Diameter; Sand Soil

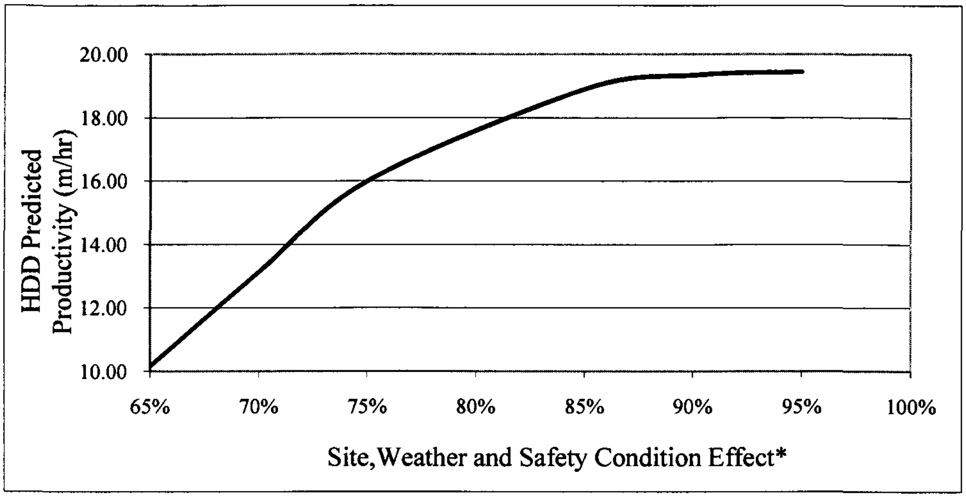


Figure V.30 Productivity Predictions for Site, Weather and Safety Conditions; Sand Soil
* 80-100% V. Good, 60-80% Good, 40-60% Moderate, 20-40% Poor, 0-20% V. Poor

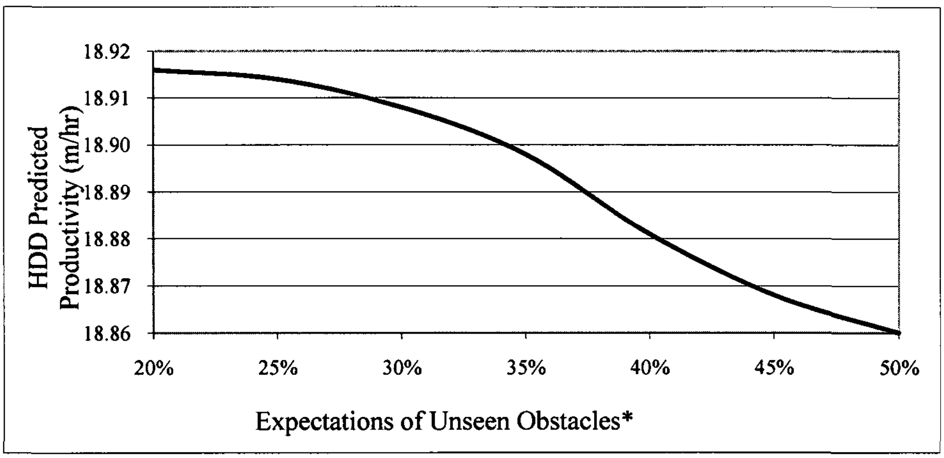


Figure V.31 Relation between Productivity Rate and Underground Obstacles; Sand Soil
* 80-100% V. High Expectation, 60-80% High Expectation, 40-60% Moderate, 20-40% Low Expectations, 0-20% V. Low Expectations

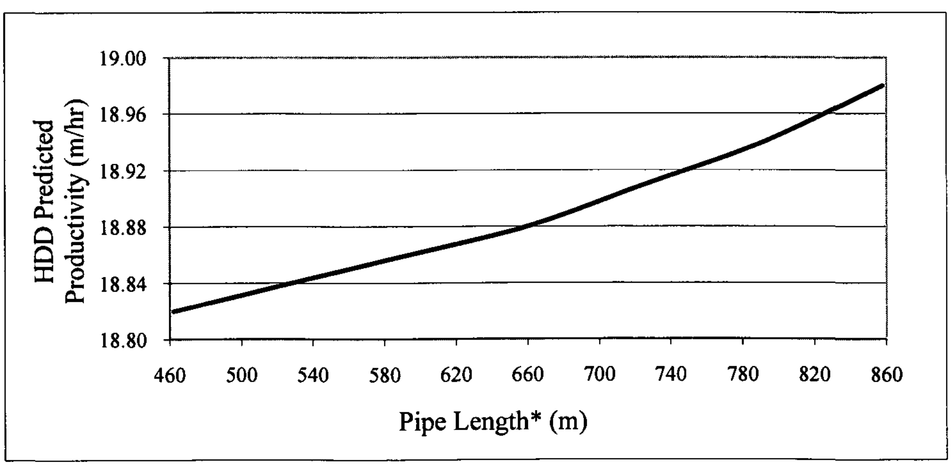


Figure V.32 Productivity Predictions Pipe Length; Sand Soil
* L< 300m short, L= 300-500m, L> 500 Long

V.7. AVERAGE VALIDATION OF THE DEVELOPED HDD-PRODUCTIVITY PREDICTION NF MODELS

Three HDD productivity prediction models were developed and validated in order to help HDD professionals during the pre-construction phase as a decision support tool. Clay, rock and sand models show an AVP of 94.44%, 82.29%, 86.67%, respectively, (see Figure V.33). Accordingly, the total average invalidity percent (TAIP) and total average validity percent (TAVP) are calculated for the developed NF models to be TAIP = 12.2 % and TAVP = 87.8 % as shown in Figure V.34. The developed models display robust validation results.

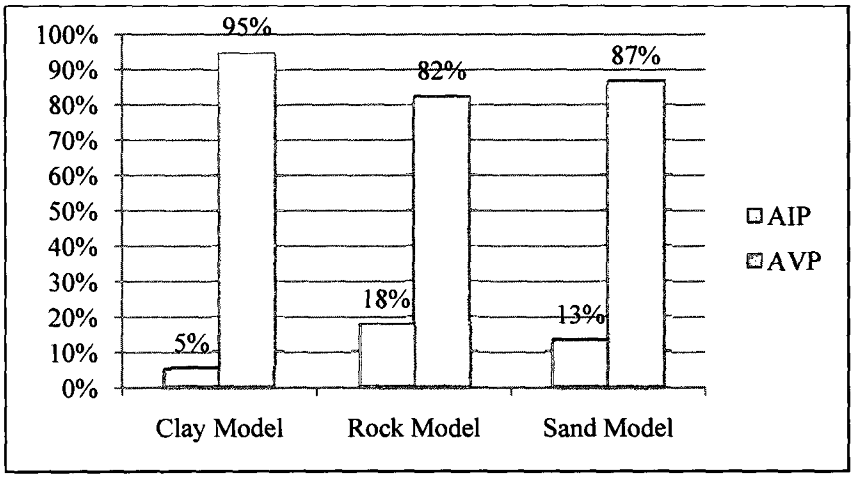


Figure V.33 Clay, Rock and Sand AIP/AVP

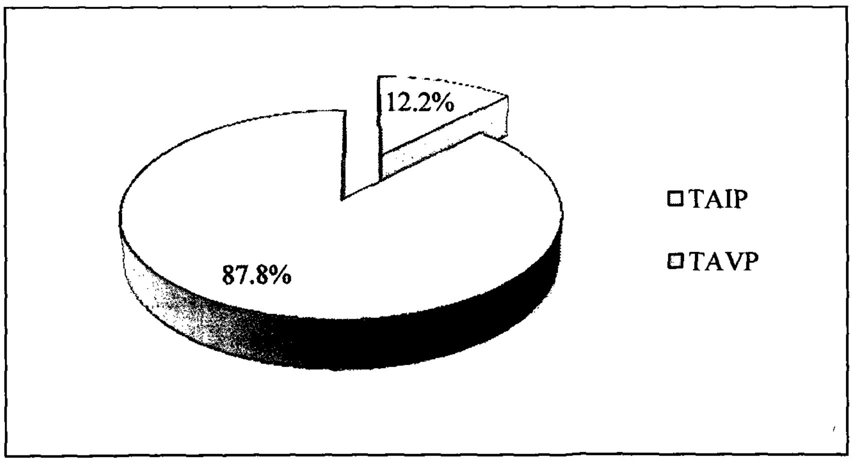


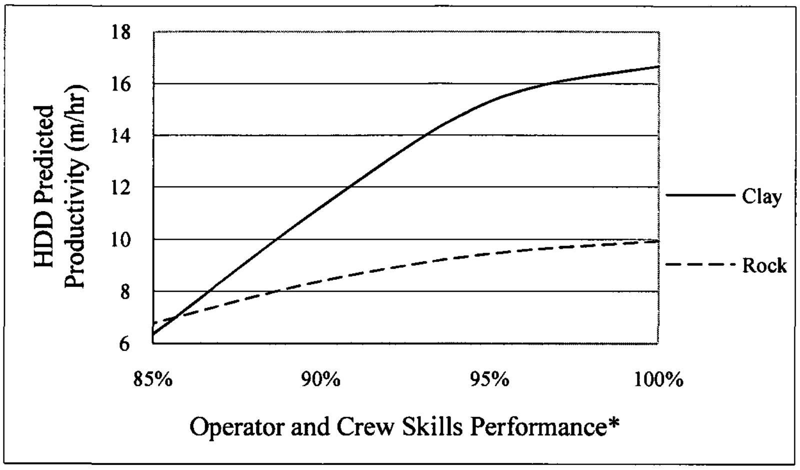
Figure V.34 HDD-PP NF Model TAIP and TAVP

V.8. SOIL TYPE EFFECT ON HDD PRODUCTIVITY

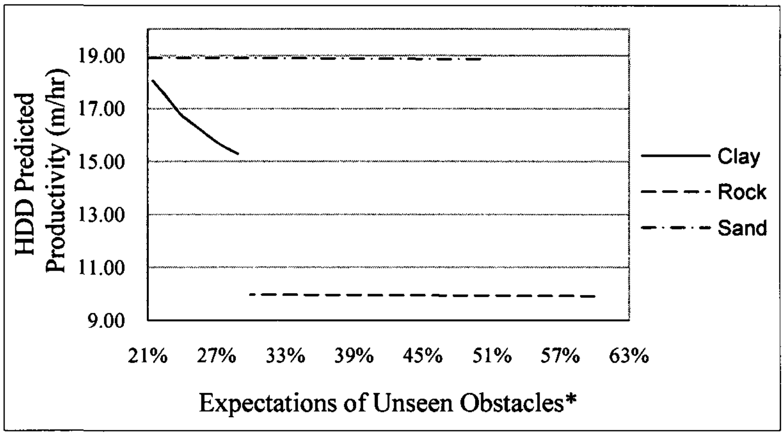
The effect of various productivity factors of HDD operations in clay, sand and rock soils are studied based on the developed NF models. Some of the HDD productivity factors are studied within different ranges of data; however, the study is able to give an idea about the relation between productivity performance and the various soil types according to these studied factors.

Figures V.35a&c show the direct relation between HDD productivity and crew performance and pipe length. HDD productivity is more sensitive to operator and crew skills performance while operating in clay rather than rock soil. This is due to the non-homogenous nature of clay soil conditions and the higher possibility of facing boulders or underground obstacles. In addition, the longer the operation in rock soil the more need to change the drilling head due to fraction, while the longer the drilling process in sandy soil the more need of performing multi-reaming travels due to the heaving nature of sandy soil. Figure V.35b shows the inverse relation of HDD productivity and the presence of underground obstacles while operating in clay soil. This is because clay soil is more likely to have boulders or voids, which might break the drilling head or get stuck. On the other hand, rock and sandy soils show slight inverse relation with HDD productivity because of their homogenous nature and less possibilities of facing underground obstacles (i.e. sandy soil has no voids and rock soil has no boulders) compared to clay soil. Therefore, HDD operations in clay soil are more sensitive to crew skills, pipe length and underground obstacles than operating in rock and sand.

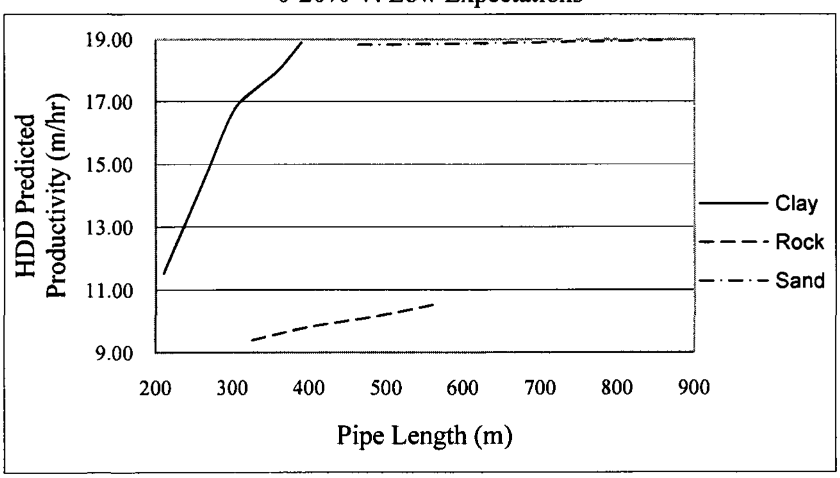
Figures V.35d&f present a direct relation between HDD productivity and machine, site weather, and safety conditions in clay, sand and rock soils. Machine condition is more sensitive to HDD productivity while operating in rock compared to clay and sand soils. The difficulties of operating HDD machine in rock, due to its hard nature and continuous need of changing the drilling head while operating, is significantly affected by the operating machine conditions. Site weather and safety condition effect on HDD productivity is almost similar for various soil types. Figure V.35e shows the inverse relation of pipe diameter to HDD productivity. Pipe diameter has very small effect on HDD productivity in various soil conditions.



(a) Effect of Operator and Crew Skills on HDD Productivity in Clay and Rock Soils
* 80-100% Highly Skilled, 60-80% Skilled, 40-60% Moderate, 20-40% Poor, 0-20% Very Poor

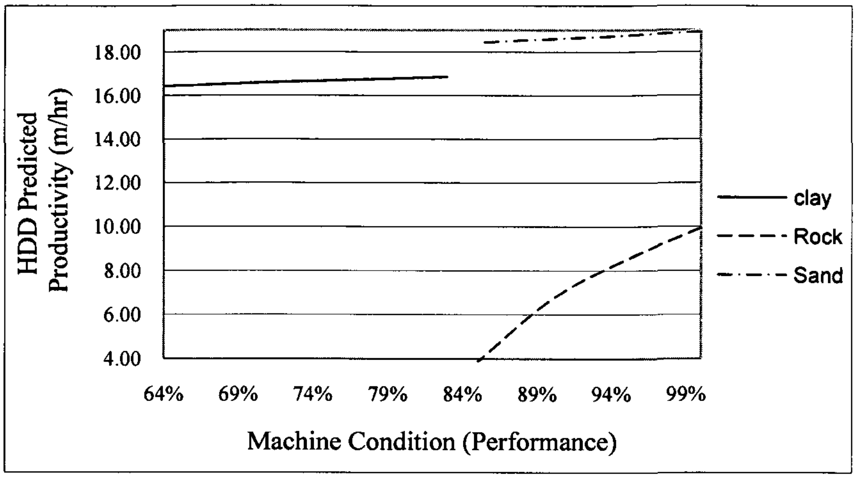


(b) Effect of Underground Obstacles on HDD Productivity in Various Soil Types
* 80-100% V. High Expectation, 60-80% High Expectation, 40-60% Moderate, 20-40% Low Expectations, 0-20% V. Low Expectations

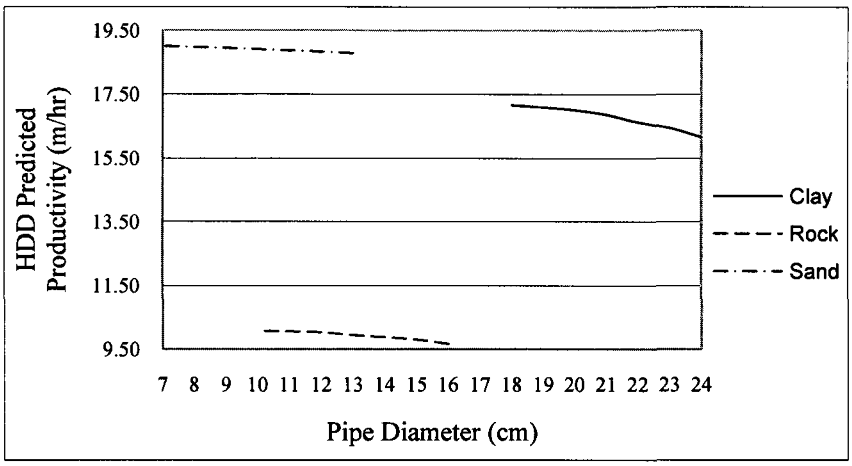


(c) Effect of Underground Obstacles on HDD Productivity in Various Soil Types
* L< 300m short, L= 300-500m, L> 500 Long

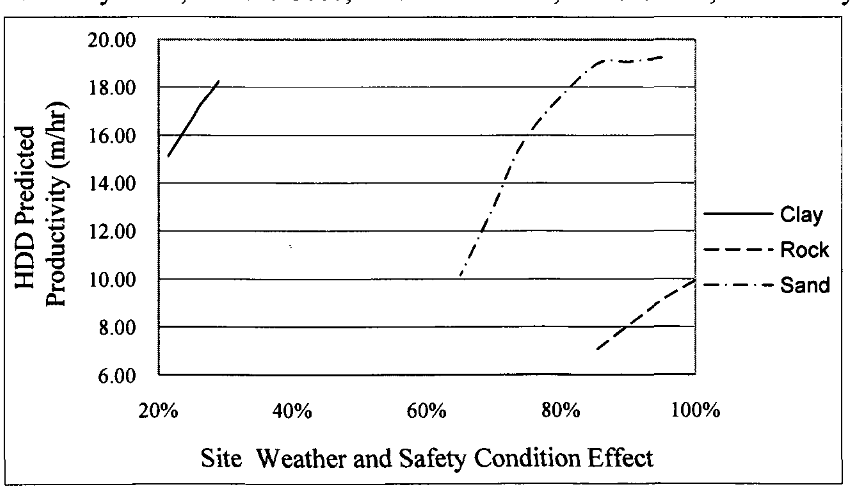
Figure V.35 Effect of Various Factors on HDD Productivity



(d) Effect of Machine Condition on HDD Productivity in Various Soil Types
* 80-100% V. Good, 60-80% Good, 40-60% Moderate, 20-40% Poor, 0-20% V. Poor



(e) Effect of Pipe Diameter on HDD Productivity in Various Soil Types
* 80-100% Very Good, 60-80% Good, 40-60% Moderate, 20-40% Poor, 0-20% Very Poor



(f) Effect of Site Weather and Safety Condition on HDD Productivity in Various Soil Types

Figure V.35 Effect of Various Factors on HDD Productivity (Continued)

V.9. SUMMARY OF CHAPTER V

Eight factors were identified to be the most important factors affecting the HDD construction operation. These factors were then ranked based on their relative importance. Three NF models were developed to predict and assess the productivity of HDD construction operations in clay, rock and sand soils. Eight input factors, i.e. management, mechanical, environmental and pipe conditions and one output factor (i.e. productivity) were used to represent the productivity prediction process. Comparing the NF model results to the calculated on site actual results shows its robustness in predicting the HDD construction operation productivity. The model validation results show that clay, rock and sand models had an average validity percent of 94.44, 82.29 and 86.66, respectively. Therefore, the proposed NF models are robust and can be used to predict the productivity of HDD operations. It should also be noted that operator/crew skills, soil type and pipe diameter are the most influential, while pipe length and site, weather and safety condition are the least influential factors on HDD productivity. Results show an inverse relationship between productivity and pipe diameter and existence of underground obstacles. Results also show a direct relationship with all other factors.

CHAPTER VI

AUTOMATED HDD PRODUCTIVITY PREDICTION MODEL (HDD-PP)

Recent developments in modeling software have resulted in facilitating the use of this software and provided a wide range of applications that can be utilized with other users. This chapter presents a methodology of developing an automated decision support system for productivity prediction of HDD applications. The modeling software (MatLAB, ver. 7.0) provides a graphical friendly user interface to facilitate common use. This system is developed to assist contractors, consultants and engineers in predicting time and cost for HDD applications, in the preconstruction (bidding) phase. The HDD-PP program is developed using the interactive MatLab tools. The program is written by the high-performance MatLAB language that is very similar to C and Fortran programming languages. The following part will demonstrate the clay study case mentioned in the previous section.

VI.1. FRAME WORK OF THE HDD-PP AUTOMATED TOOL

As discussed earlier in chapter III, HDD-PP requires data related to the factors that affect the application process. The results include productivity prediction values in m/hr. A high predicted value indicates a high expected production rate. The flowchart in Figure VI.1 summarizes the function of the proposed automated HDD-PP model. It uses the graphical user interface MatLAB (ver. 7.6.0.324) to import and export data.

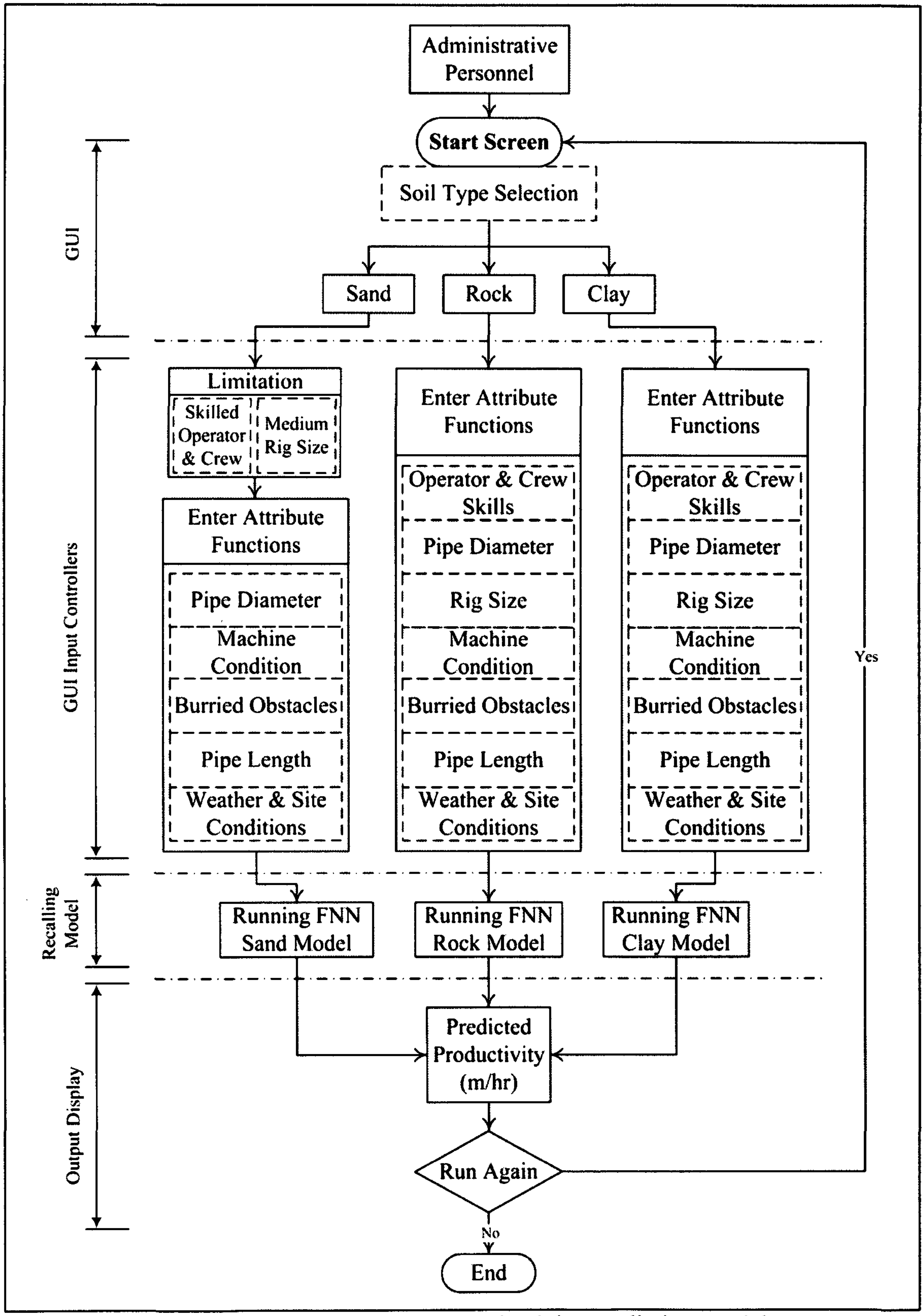


Figure VI.1 Automated HDD Productivity Prediction Model

VI.2. GUI INTRODUCTION

The first graphical user interface page will welcome the user and introduce him to the program as shown in Figure IV.2. The proposed automated decision support tool is called Horizontal Directional Drilling Productivity Predictor (HDD-PP). It applies the principles of neurofuzzy network technique. The HDD-PP will assist contractors and consulting engineers to predict the HDD production rate based on their recourses and project requirements in the preconstruction phase.

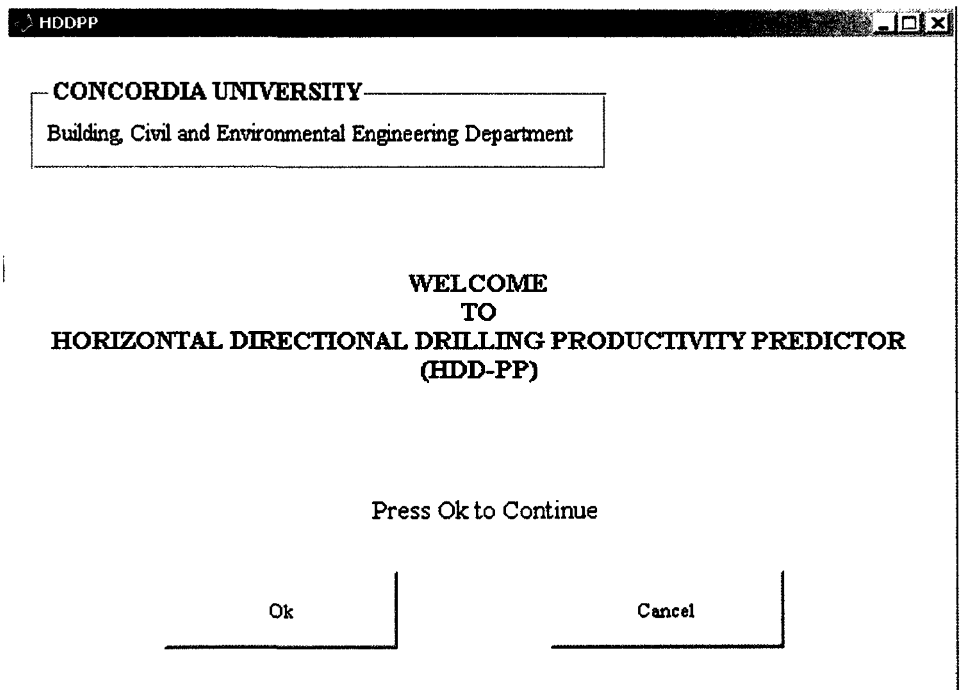


Figure VI.2 HDD-PP Intro (Welcome Page)

VI.3. SELECTION OF SOIL TYPE

The next step allows users to select soil type. Three types of soil could be obtained from this model; Clay, Sand and Rock. The selected model would be recalled by the system, as shown in Figure VI.3. Users may select one soil type at a time.

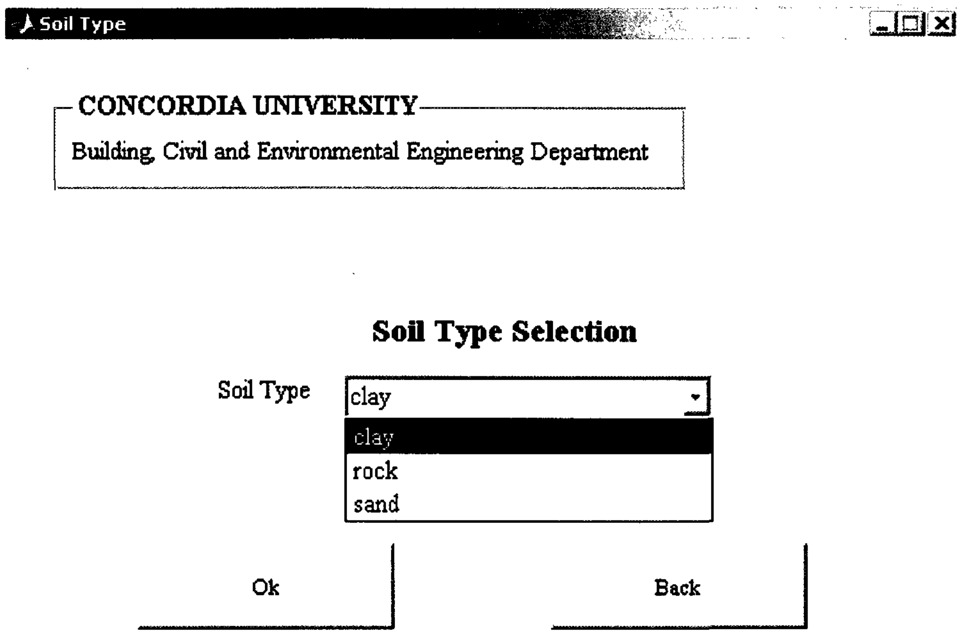


Figure VI.3 Soil Type Selection

VI.4. IMPORTING DATA

The next step for the user is to start inputting project data, as shown Figure VI.4 to VI.10. The level of skill for operator and crew, diameter of installed pipe, capabilities (size) of the rig utilized, condition of machines used, degree of expectations for underground obstacles, length of target installation and site conditions, weather and safety. However, for sandy soil, inputs will be limited to five as the model is developed for a highly skilled operator and crew and medium rig size. This GUI demonstrates the same inputs and values for the clay example explained earlier in the previous chapter. Table VI.1 shows the general limitation of inputs for all models. Nevertheless, the program is designed to display the limit of accepted data values for each input.

Table VI.1 HDD-PP Models Input Limitations

Soil Type	Modeling Factors	Limitations
Clay	Operator & Crew Skills	Good and Very Good
	Pipe Diameter	Between 101.6 mm and 609.06 mm
	Drilling bit capabilities	Medium and Large
	Machine Condition	Poor, Moderate, Good and Very Good
	Unseen Obstacles	Low, Moderate, High and V. High Expectations
	Pipe Length	>250 and <1500 meters
	Site & Weather Conditions	V. Bad, Bad, Moderate and Good
Rock	Operator & Crew Skills	Highly, Moderate and Very good
	Pipe Diameter	From 150 to 762 mm
	Drilling bit capabilities	Medium and Large
	Machine Condition	Moderate, Good and Very Good
	Unseen Obstacles	Low, Moderate, High and V. High Expectations
	Pipe Length	>213 and <2300 meter
	Site & Weather Conditions	V. Bad, Bad and Moderate
Sand	Operator & Crew Skills	Very Good
	Pipe Diameter	From 40 mm to 815 mm
	Drilling bit capabilities	Medium
	Machine Condition	Good and V. Good
	Unseen Obstacles	V. Low Expectations, High Expectations and Very High Expectations
	Pipe Length	85 and 1230 meter
	Site & Weather Conditions	Good, Moderate and Bad

A number of choices are displayed for each qualitative factor based on its input range; i.e. V. Poor, Poor, Moderate, Good and V. Good. The values available for each factor will be active, where the user will be able to select. Other values, which are out of model range, will appear inactive and cannot be selected. Each page carries the name of the target input.

i. Clay Case Study Data Input

The first input factor is operator and crew skill degree and the user should be able to choose between one of two options; Skilled and Highly Skilled, (V. Poor, Poor and

Moderate will appear as inactive). Similarly, in the following steps, the program will ask users to select specific information based on the factors limitation shown in Table VI.1.

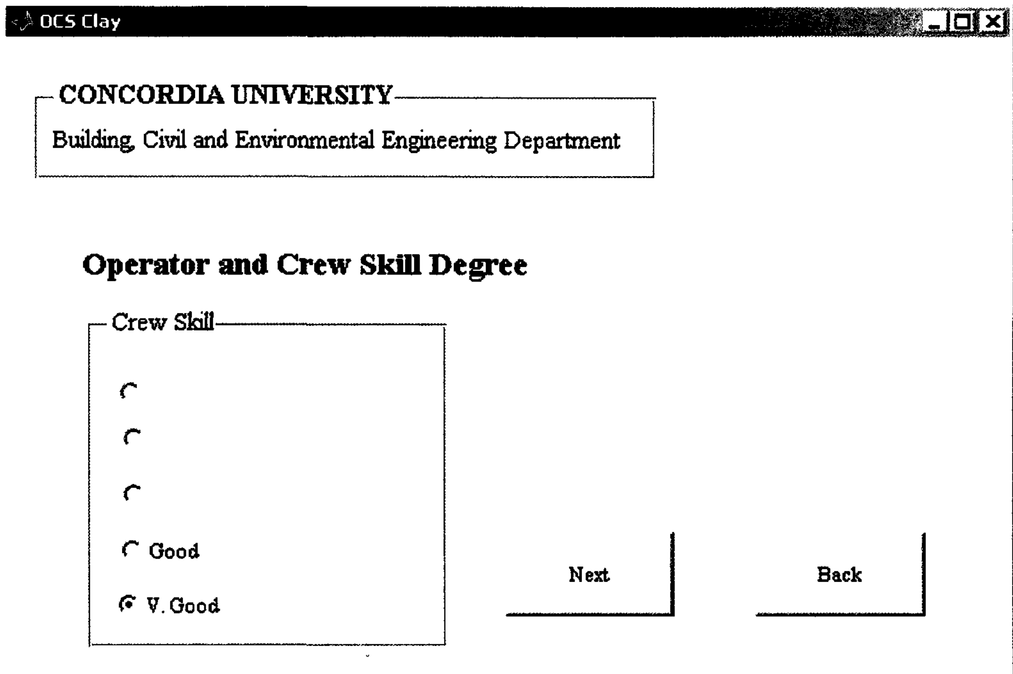


Figure VI.4 Operator and Crew Skills Selection

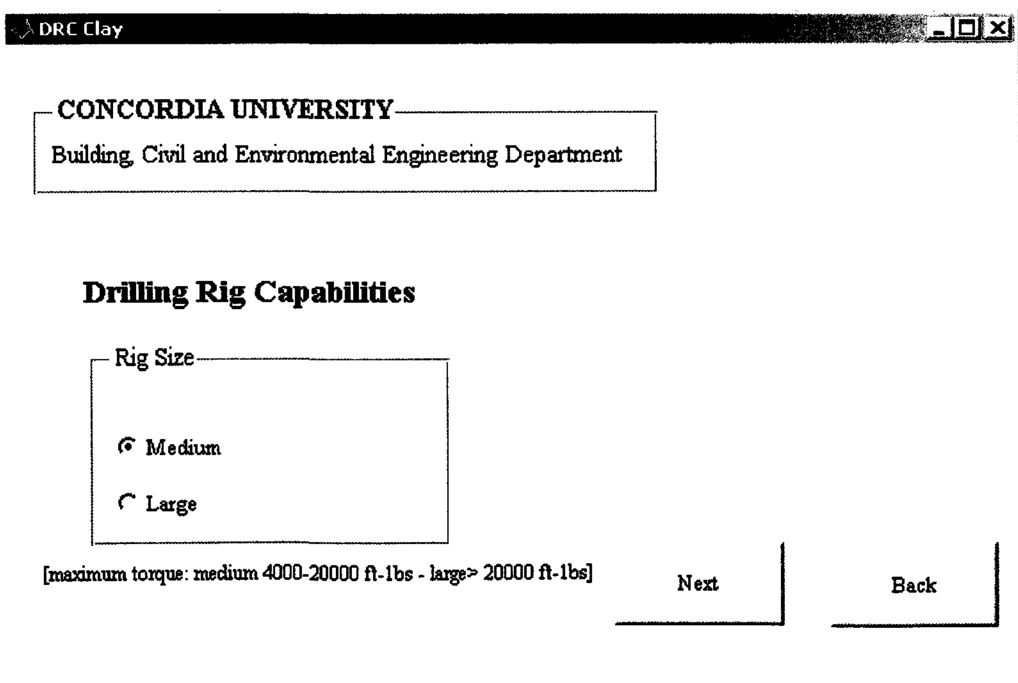


Figure VI.5 Rig Size Selection

Pipe Diameter and Length:

A notice of diameter and length limits will be displayed (i.e. clay model can only accept pipe diameters between 101.6 and 609.06 mm and pipe length between 250 and 1500 meters, see Figure VI.6). If the user entered an out of range value, an error message will appear tagging the error type, see Figure (VI.7).

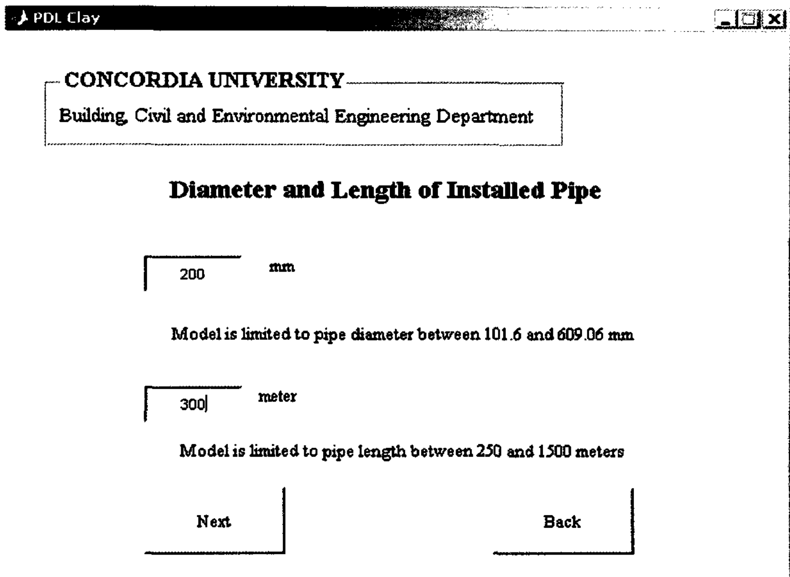


Figure VI.6 Pipe Diameter and Length Selection

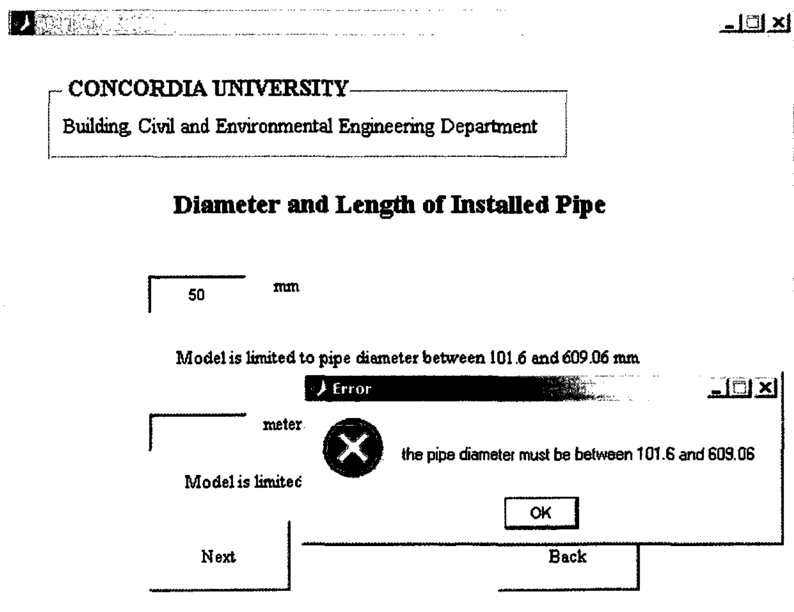


Figure VI.7 Displaying Error; Out of Range Input

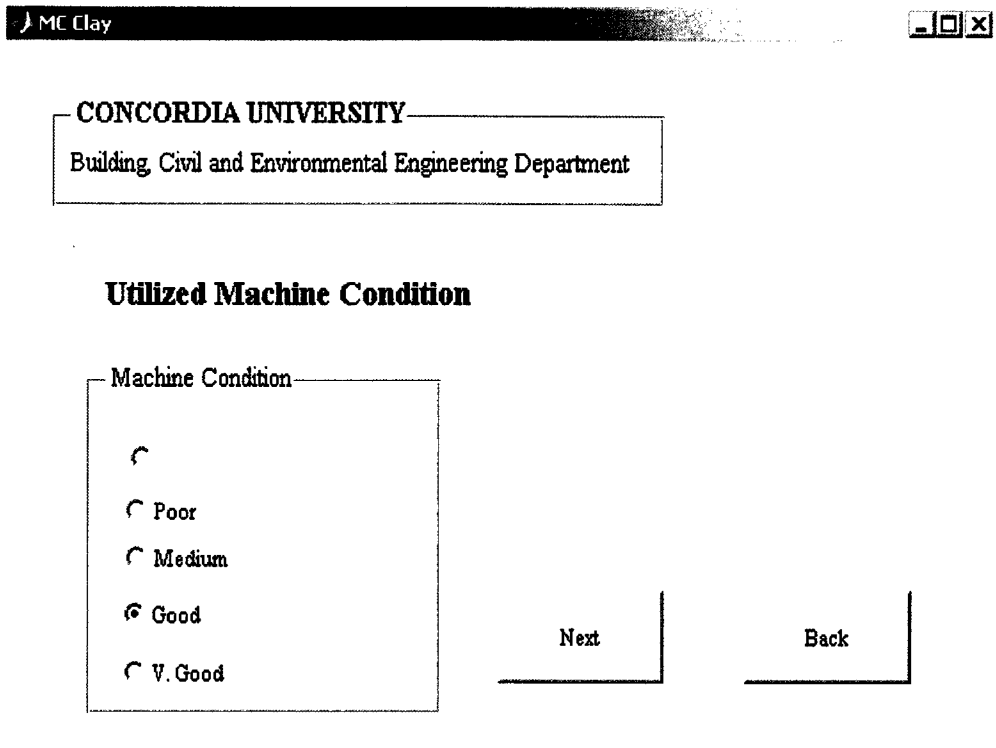


Figure VI.8 Machine Condition Selection

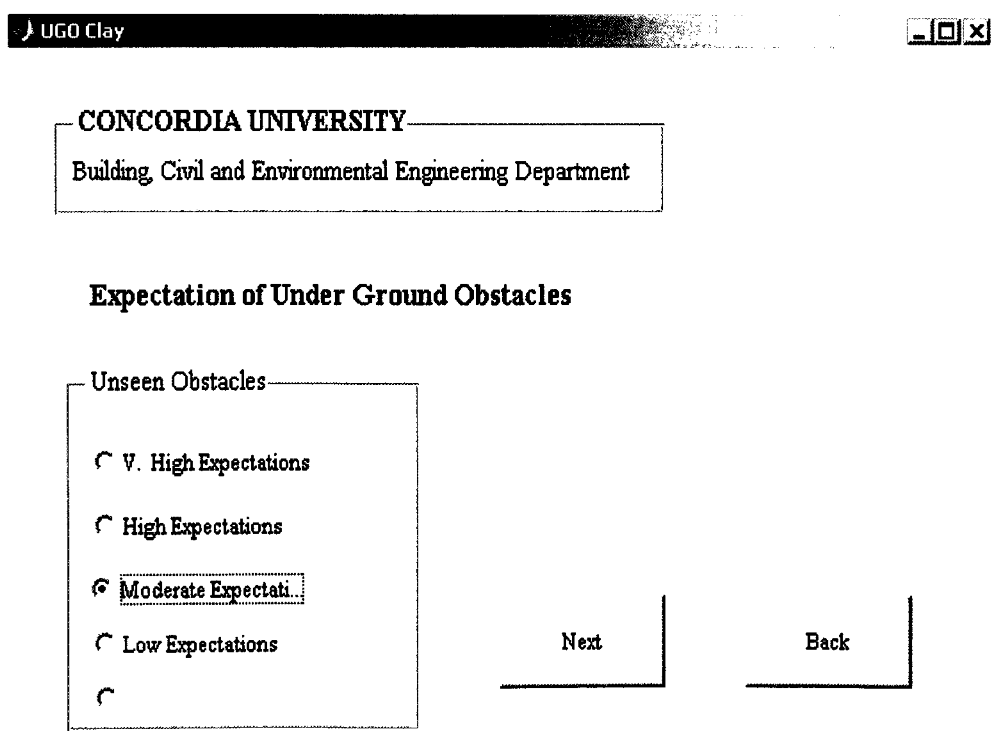


Figure VI.9 Underground Obstacles Expectation Selection

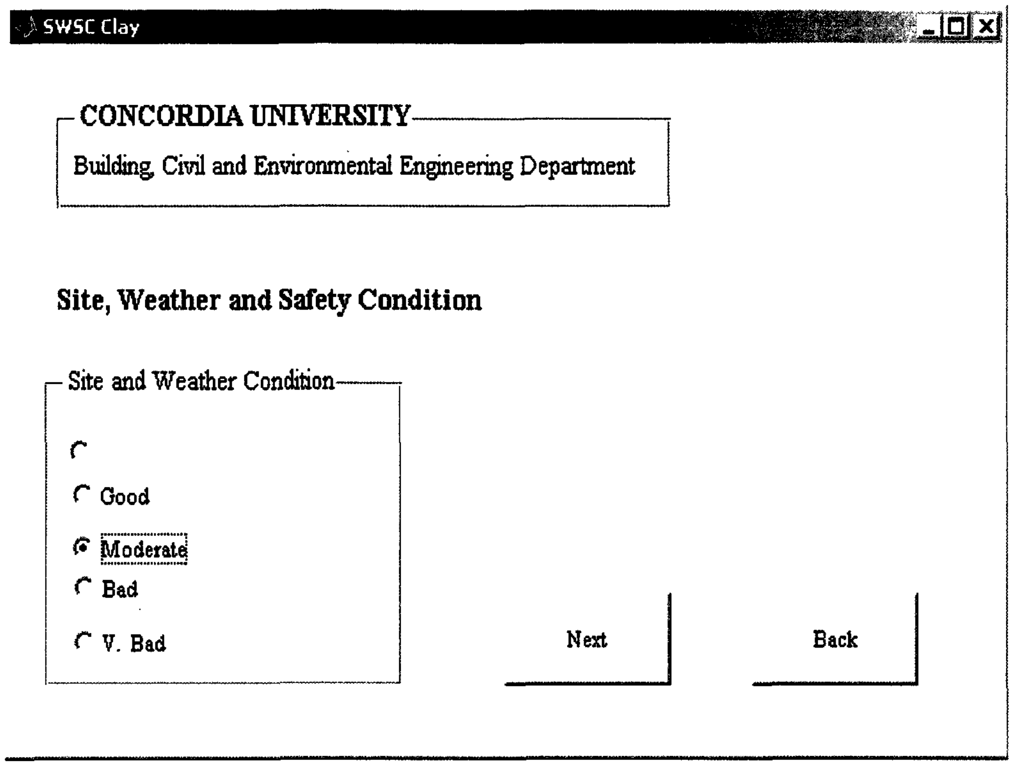


Figure VI.10 Site, Weather and Safety Condition Selection

VI.5. DATA PROCESSING AND RESULTS

Lastly, to achieve the result, the user must click the Productivity Predictor button. The recalled soil type model processes the imported data for calculation of production rate and displays the result as shown in Figure VI.11. For performing another operation, the user can click the "Back Home Button" and model will start over.

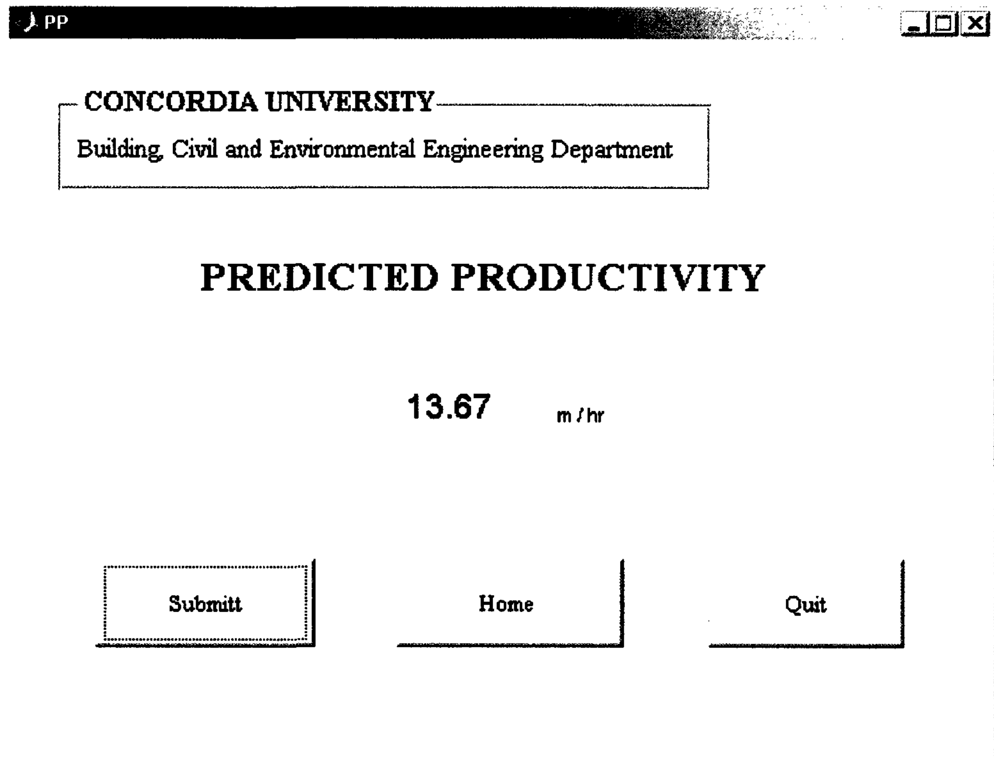


Figure VI.11 Representation of the HDD Predicted Productivity

VI.6. SUMMARY OF CHAPTER VI

The developed automated decision support tool will help the contractor and consulting engineers to have an initial understanding about their target project time and cost. This decision support tool is developed using the same modeling tool (MatLAB®), thereby minimizing errors and bugs that would occur from integrating multiple software. Therefore, the program will provide a robust platform for future research expansion.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

VII.1. SUMMARY AND CONCLUSIONS

HDD has proven itself in the underground construction market as being one of the most effective TT methods for new underground pipe/cable installations. Due to competitive market conditions, client expectations and technological advancements, there is an emergent need for HDD contractors to identify the major factors affecting their project implementation. Utilizing a productivity prediction model helps in managing, projects especially in the bidding phase. Despite the fact that it is one of the most widely used TT techniques applied for new installations, there is little progress in models and software development for the HDD technique.

Current research first investigated and identified main factors that affect HDD pipe/cable installation technique. By means of a thorough literature review, application of AHP technique and discussions with HDD experts, it was found that crew and operator skills, drilling bit capabilities, machine condition, soil type, unseen buried obstacles, site and weather conditions, pipe diameter and pipe length, are the important factors that affect HDD.

In recent years, neurofuzzy technique has been applied to model the productivity of subjective factors. The presented research work used a neurofuzzy approach to predict and assess productivity of HDD based on identified management, mechanical, environmental and pipe conditions in clay, sand and rock soils. Average validity percent (AVP) of the clay, sand and rock models were 94.4%, 86.7% and 82.3%, respectively, which showed their robustness in predicting HDD productivity. It was found that soil type, crew and operator skills and pipe diameter are the most significant factors affecting HDD productivity while weather conditions has the least effect. The developed NF models will help experts to estimate and predict the HDD project duration.

Moreover, a user-friendly interface productivity prediction tool (HDDPP) is developed by using MatLAB® (Version: 7.6.0.324 (R2008a)) based on ANFIS. The proposed tool calculates the productivity of HDD based on different management, mechanical, environmental and pipe factors that are selected by the user. Results are obtained through the MatLAB® GUI and are represented in m/hr.

These models are tools for experts and professionals to help them perform productivity calculation by quantifying the effect of some of the subjective factors. These tools will help them to perform accurate schedules and reliable estimate cost for HDD works. Moreover, they provide researchers and experts with the most significant factors that contribute to HDD installations. The developed neurofuzzy methodology could be used in similar research applications.

VII.2. RESEARCH CONTRIBUTIONS

The current research contributes to the HDD industry on various soil types, in the following areas:

- Identify and study some of the important factors and their effect on predicting HDD operation productivity and combines them with the knowledge of industry experts.
- Develop productivity prediction models to estimate HDD productivity in clay, sand and rock soils considering both quantitative and qualitative factors.
- Develop productivity curves for pipe installation based on the developed models.
- Develop an automated decision support tool (Productivity Predictor), which provides productivity prediction cycle time in order to assist the construction professional to estimate water, sewer and underground pipe installation duration.

VII.3. RESEARCH LIMITATIONS

Due to various data and time constraints, the research scope sustained some limitations as follows:

- Limited number of variables and productivity measures that have an impact on HDD pipe/cable installation.
- The collected data sets are limited due to lack of data and lack of finding a quality database for HDD projects.
- The developed models are limited to clay, sand, and rock soils.

VII.4. RECOMMENDATIONS FOR FUTURE WORK

The integrated nature of HDD projects plays an important role in a successful implementation of the HDD productivity predictor. The presented research work addresses the comprehensive assessment of HDD productivity in such integrated environment. It provides a simple platform to predict the HDD productivity and improve HDD practices. Nevertheless, the timeframe of this research prevented the expansion of the research to enhance factor selection as well as the developed HDDPP model. Various latent research activities can be pursued in the future as follows:

- *Current study enhancement areas:*
  - The collection of life-cycle data of HDD projects is subject to the availability and accuracy of data and whether contractors and consultants keep such type of data or not. With the availability of more data for HDD projects obtained from the same facility type and from various construction fields, the neurofuzzy system could be better trained and generate predictions that are more satisfactory. The validity of the predicted HDD productivity models is still subject to the consolidation of more customized project data.
  - The present research work considered eight input factors. Nevertheless, this list could be refined to only include the most significant factors or add other important factors in order to increase the developed models accuracy. This could reduce the system performance error and improve its results.

- The advantage of the developed methodology is that with some slight modifications in the input factors more outputs could be obtained (i.e. cost, crew size...etc.), which will manifold the usefulness of the model.
- Developing a web-based tool with neurofuzzy engine in order to allow for executable file usage of FNN engine.

➢ *Current study extension areas:*

- Standardize data acquisition tools for contractors that cover more management, mechanical, environmental and pipe physical factors. Integrate the in-house work and the field dissembling time into the developed HDD productivity prediction models.
- The research considered only three soil types (clay, sand and rock), where the investigation into more soil types and calculating HDD productivity within these soil types is subject to more customized data collection.
- Extension of the developed HDD pipelines installation prediction methodology to other HEB trenchless techniques.
- Enhance the developed automated HDD-PP tool in order to provide better representation of the analysis and results. In addition, the developed model GUI can be linked to HDD projects database with the viewpoint of updating the model every time a new HDD project data is acquired. This continuous retraining of the developed model will increase its accuracy and decrease the error.

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APPENDICES

Appendix (A): Trenchless Technology Methods Overview

Trenchless technology systems utilized on underground pipelines fall into two broad categories:

A. Trenchless Construction Methods (new pipelines and services installation)

- Horizontal Earth Boring (HEB)
  - Horizontal Auger Boring (HAB)
  - Horizontal Directional Drilling (HDD)
  - Pipe Ramming (PR); Closed End; Open Face
  - Micro Tunneling (Slurry – Auger)
- Pipe Jacking (PJ)
- Utility Tunneling (UT)

B. Trenchless Rehabilitation Methods (replacement & renovation of existing pipes)

Non-Structural Methods:

- Under Ground Coating & Lining
- Localized Repair (LOR'S) (Point Repair – Sleeves)

Semi-Structural Methods:

- Cured In Place (CIP)
- Slip Lining (SL)
- Thermoformed Pipe (TP)
- Close Fit pipe (CFP)

Structural Methods:

- In Line Replacement
  - Pipe Bursting (PB) and Pipe Removal (PV)

A. Trenchless Construction Methods (new pipelines and services installation)

1. Horizontal Earth Boring

Based on the mode of operation, the Horizontal Earth Boring could be subdivided into four major groups depending on how excavated material are transported either by slurry or by auger, and how excavating is achieved either by boring, hammering or manually.

i. Horizontal Directional Drilling.

There are three main steps for achieving a successful pipe installation using HDD technique (Ariaratnam and Allouche, 2000).

Pilot Bore

Firstly, is making the pilot hole by using the drilling rig and start drilling from the earth surface at a pre-determined angle and along a defined path using drilling rig, drill bit, the steering tool and the bentonite slurry injection under high pressure, as shown in Figure (A.1). Steering is controlled by rotating the drill head and pushing the drill string forward until the required direction is obtained, forth while drilling is continued along the realigned path.

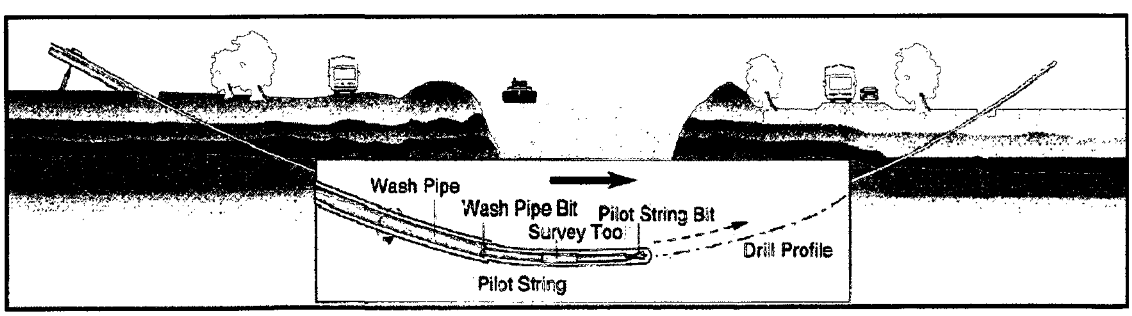


Figure A.1 Pilot Hole (Adapted from Richard, 2004)

Reaming/Hole Enlargement

Once the drill bit exits the other end of the drill hole, the drill bit and steering tool, are detached and a reamer is fastened to the drill string, as shown in Figure (A.2). Depending on the pipe diameter to be installed, several reaming times could be applied to reach the determined diameter. During the reaming process, bentonite-drilling mud is pumped, under high pressure to the reamer. While pulling back the reamer by the drill rig, drill pipe is attached continuously behind the reamer for the successive scrub and pipe pulling operations (Good practices, 2004)

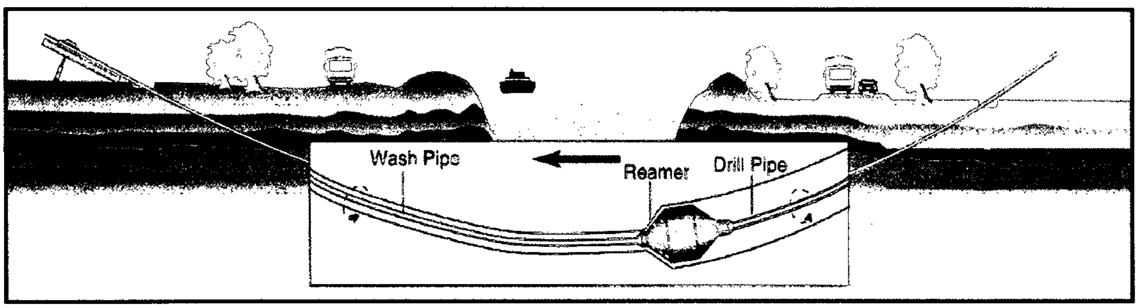


Figure A.2 Pre-Reaming (Adapted from Richard, 2004)

Pipe Pullback

On the finish of the hole reaming, the swab, where the high pressure drilling mud is pumped, is pulled through the hole. Then the pulling head is connected, to the drill string via a swivel. The swivel isolates and prevents the pipe from rotation during the pullback, as shown in Figure (A.3). The pipe is then pulled back toward the entrance hole by the drill rig. Once the pipe has been fully pulled in, usually hydrostatically is tested by the client (Good practices, 2004).

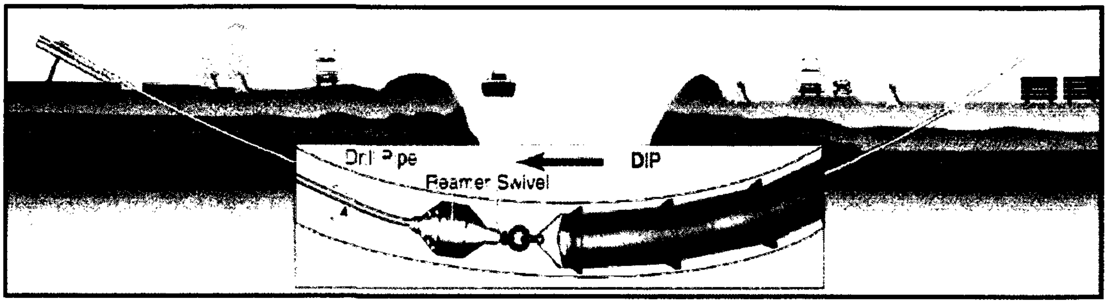


Figure A.3 Pull Back (Adapted from Richard, 2004)

Layout and Site Preparation

Permanent access to the entrance and exit sites for the HDD must be constructed prior to starting the job, and a hard standing area for the drilling operation prepared at each of these points as shown on Figure (A.4) and (A.5).

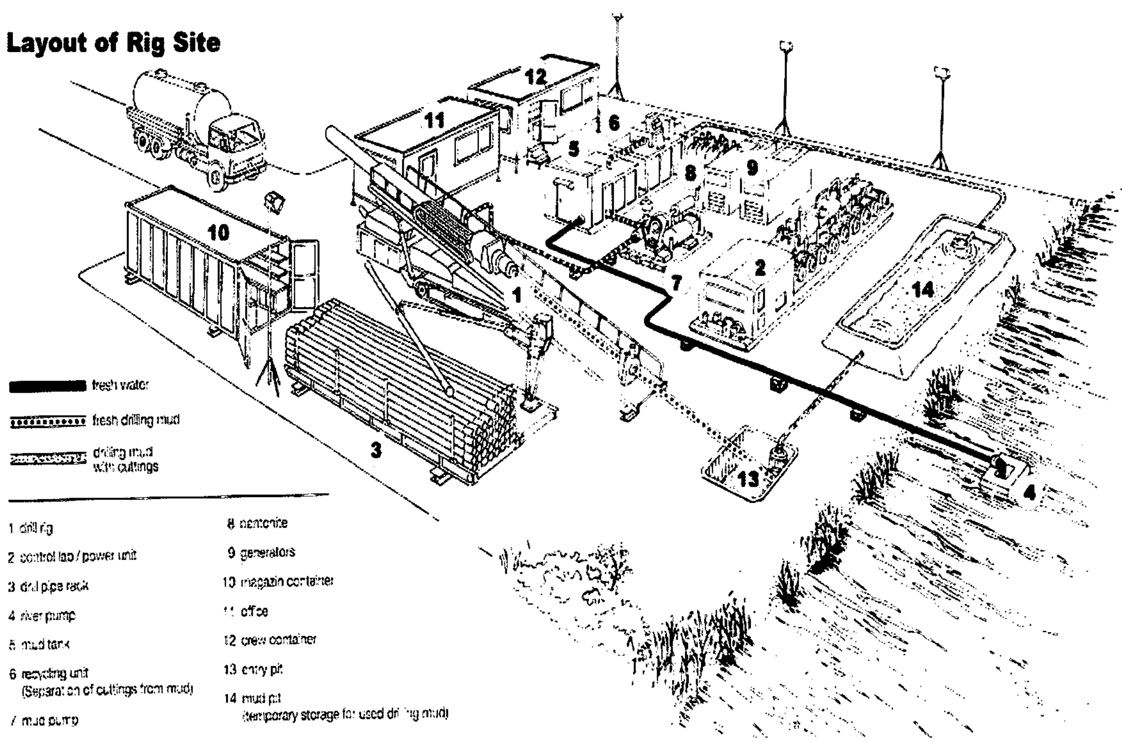


Figure A.4 Rig Site Layout (Adopted from Laney Directional Drilling, 2007)

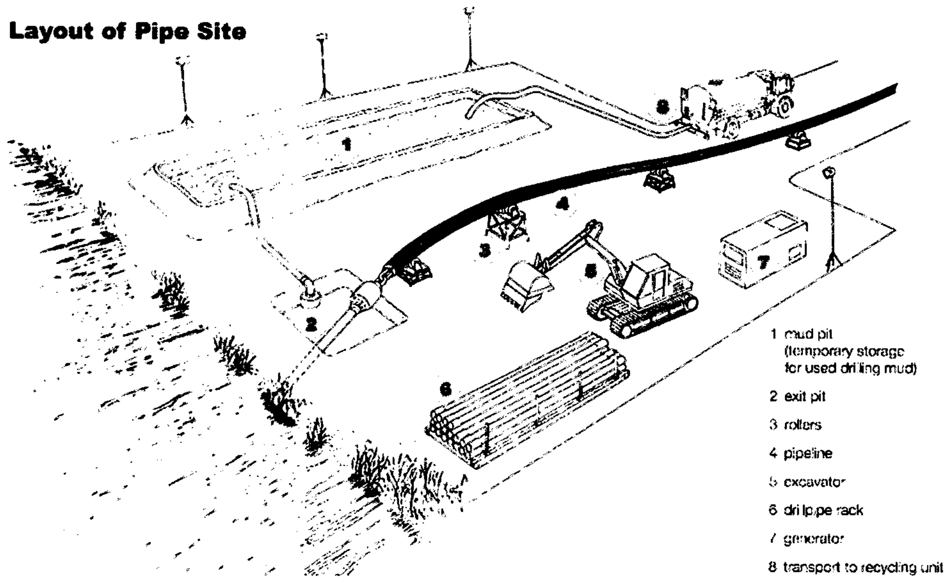


Figure A.5 Pipe Site Layout (Adopted from Laney Directional Drilling, 2007)

For an effective and safely implementation of any HDD operation, a sufficient space based on the drilling bit capabilities is required on the rig side. A large river crossing unit requires a minimum working area of 30 x 50 m, whereas a mini-rig may requires a working space of about 3 x 3 m. As a safety factor, same as the rig space dimensions should be required on the pipe side in case there is a need to move the rig on the other side and attempt drilling from this end of the crossing. In addition, to conduct a productive single continuous pullback operation, a sufficient space should be provided at the pipe side to fabricate the product pipeline into one string (Ariaratnam and Allouche, 2000).

ii. Horizontal Auger Boring (HAB)

Auger Boring is accomplished with an Auger Boring Machine by jacking a casing pipe through the earth while at the same time removing earth spoil from the casing by means of a rotating auger inside the casing. The typical Auger Boring installation begins with the installation of bore pits at the beginning and end of the proposed bore. Bore pit dimensions vary depending on the size and length of the casing being used, and on the depth of the boring. Generally, the length varies from 26 to 40 feet long and 8 to 12 feet wide (Najafi M., 2005).

iii. Pipe Ramming (PR)

Pipe ramming is a trenchless method of installing a steel pipe or casing using a pneumatic tool to hammer the pipe or casing into the ground. The pipe could be rammed with the leading edge either open or closed. Pipes up to 8 inches could be rammed with the end closed; however, this method is more difficult and is not normally recommended.. This method is frequently used under railway and road embankments for installation of medium to large diameter pipes. Steel pipe is used for the casing, as no other material is strong enough to withstand the impact forces generated by the hammer.

iv. Micro-tunneling (Slurry – Auger)

Micro-tunneling has been increasingly used for installing new pipe construction. According to ASCE's "Standard Construction Guidelines for Micro-tunneling," Micro-tunneling can be defined as "a remotely controlled and guided pipe jacking technique that provides continuous support to the excavation face and does not require personnel entry into the tunnel". There are two major types of Micro-tunneling; (1) slurry method and (2) auger method. In the slurry-type method, slurry is pumped to the face of the MTBM. Excavated materials mixed with slurry are transported to the driving shaft, and discharged at the soil separation unit above the ground. In an auger-type method, excavated materials are transported to the drive by the auger in a casing pipe, and then hoisted to the ground surface by a crane (Najafi M., 2005 and Karmer et al. 1992).

2. Pipe Jacking

As a specific installation technique, pipe jacking is the process of installing an underground prefabricated pipe from a drive shaft to a reception shaft. When referred to as a process it is a tunneling operation using thrust boring and pushing pipes with hydraulic jacking forces (http://www.inliner.net/index.php, March 24, 2007, 16:37). It could be applied to other trenchless technologies such as auger boring and micro-tunneling. The Pipe Jacking as a specific installation technique is a cyclic procedure that uses the thrust power of hydraulic jacks to force the pipe into the soil. As the pipe is pushed the ground is excavated and the spoil is transported through the pipe to the drive shaft where it will be disposed from. After the successful installation of a pipe the rams of the jacks are retracted so that another pipe could be installed using the same cycle again (Iseley and Gokhale, 1997), see Figure (A.6).

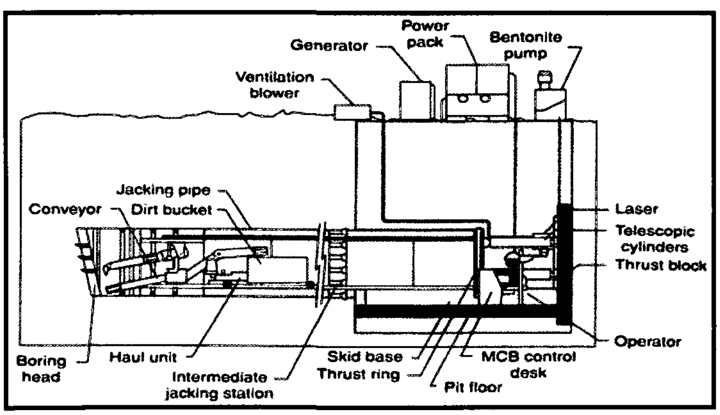


Figure A.6 Typical Components of A Pipe Jacking Operation (Iseley and Gokhale, 1997)

3. Utility Tunneling

Utility tunneling is different from other general tunneling in virtue of the tunnel size and applications. Utility tunnels are used as conduits for utilities and pipelines rather than traffic passages. The method of excavation for utility tunneling and pipe jacking are similar with one difference which is the lining. The pipe is the lining for the pipe jacking method while in utility tunneling special liner plates or rib and lagging systems are used to support the ground temporarily, as shown in Figure (A.7), (Najafi, 2005 and Iseley and Gokhale, 1997).

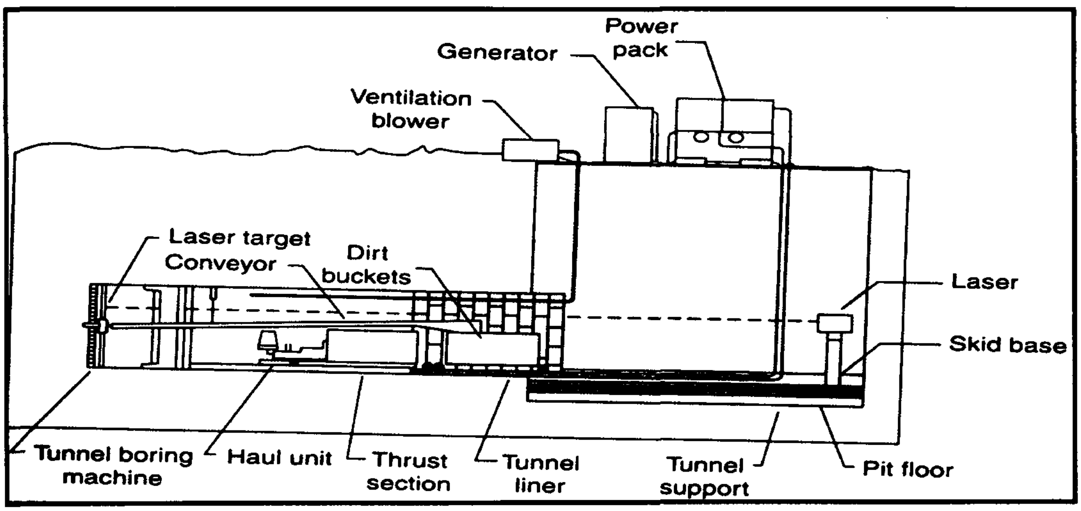


Figure A.7 Typical Components of Utility Tunneling System Techniques

(Iseley and Gokhale, 1997)

The main characteristics of the horizontal directional drilling for new pipeline installation technique among other HEB pipe installation systems are shown in Table (A.1).

Table A.1 Main Characteristics of HDD Among Horizontal Earth Boring Systems

Method		Diameter Range (in)	Max Installation (ft)	Pipe Material	Typical Application	Accuracy
Horizontal Directional Drilling	Mini	2 – 12	Up to 600	PE, Steel, PVC Clay, FRP	Pressure pipe Cable	Varies
	Midi	12 – 24	Up to 1000 H	PE, Steel Ductile iron	Pressure pipe	Varies
	High	24 - 48	Up to 6000 H	PE, Steel	Pressure pipe	Varies
Horizontal Auger Boring	Auger Boring	4 – 6	600	Steel	Road & rail crossing	(+/-)1% of bore length
	AB Steered on grade	4 – 6	600	Steel	Pressure & gravity pipe	(+/-) 12 inch
	AB Steered on line grade	4 – 6	600	Steel	Pressure & gravity pipe	(+/-) 12 inch
Pipe Ramming		Up to 120	400	Steel	Road & Rail Crossing	Dependent on set up
Micro Tunneling		10 - 136	500 – 1500	RCP,GRP,VCP DIP, Steel, PCP	Gravity Pipe	(+/-) 1 inch

B. **Trenchless Rehabilitation Methods** (Replacement & Renovation of Existing Pipes)

1. **Non Structural Methods** (Najafi, 2005)

i. Underground Coatings and Linings

A method of pipeline renewal is spraying the pipe with a thin mortar or a resin coating to protect it against corrosion and improve its hydraulic characteristics. Such treatment is suitable for pipes that are less than 48" in diameter (Najafi, 2005). Structural integrity is not well enhanced with this method but sealing joints and leak prevention are suited. The materials used can be categorized into four categories: cementitious, polymers (epoxies and polyesters), sheet liners (PVC) and cured in place liners (polymer epoxy), these material types could also be used together.

ii. Localized Repair:

Localized Repair is when the pipe defects are repaired temporarily and/or locally without renewal of the whole pipe section. Localized repair (LOR) or point source repair (POR) are used to different problems such as cracks, broken pipes, hammer taps, root intrusion, infiltration, debris, soil erosion, ex-filtration and misaligned pipe sections. LOR uses different techniques to fix these problems such as: robotic repair, grouting, cured in place pipe (CIPP), internal seal and shotcrete. The repair is done by spraying the pipe with a thin mortar or a resin coating to protect it against corrosion and improve its hydraulic characteristics.

2. Semi Structural Methods

i. Cured-In-Place Pipelining (CIPP)

Cured-In-Place Process (CIPP) is a trenchless technology invented in England by Insituform Inc. in 1971. It is a unique process for reconstructing deteriorating pipeline systems in various applications. Avoids unnecessary costs associated with digging and replacing buried pipeline. Also, does not require bonding to the host pipe wall to operate successfully (http://www.insituform.com/munsewers/mun_1_01.html, March 24, 2007, 16:37). A new pipe is formed inside the existing conduit; water, steam or ultraviolet is used to install a flexible tube saturated with a liquid thermosetting resin; this process results in a continuous, tight-fitting, pipe-within-a-pipe. The finished cured-in-place pipe liner fit tightly and neatly against the existing pipe walls.

ii. Slip-lining (SL)

In the slip-lining process, a winch cable is inserted through the existing line and then attached to the front of the new liner. The new liner pipe is then pulled into the existing pipe, and the new liner pipe reconnected to the system. If needed, the void between the new and old pipes can be filled by grouting. Slip-lining (SL) is categorized into two categories: continuous and segmental (Dias B. et al, 2007).

iii. Thermoformed Pipe (http://www.nastt.org, March 24, 2007, 16:37)

This type of trenchless pipeline uses PVC or P.E. pipe that can be repeatedly softened by heating and hardened by cooling through a temperature range characteristic of the plastic and that in the softened state can be shaped by flow into articles by molding or extrusion.

iv. Close Fit Pipe (Najafi, 2005)

This method could be used for both structural and non structural purposes, in the first we use the reduced diameter pipe method (4" to 30" dia.) while in the later we use the mechanically folded pipe method (up to 64" dia and 1000' in length).

Reduced diameter pipe method:

The usage is mainly to pressurized pipelines, It involves the use of long butt fused section of P.E. pipe then the diameter of the P.E. pipe is reduced from its original state by thermal method (swage) or mechanically (roll down). After insertion of P.E pipe, it is reverted to its extruded diameter making a close fit with host pipe.

Mechanically folded pipe method:

It is similar to the reduced diameter pipe method but the P.E. pipes are butt fused and mechanically folded at site then after insertion of P.E. pipe it is reverted to its original state by pressurization with water at ambient temperature to form a close fit with the host pipe.

3. Structural Methods

i. Pipe Bursting

Pipe Bursting is a replacement system called also Pipe Cracking, Pipe Splitting and Pipe Eating. This technique is used to replace deteriorated pipes rather than rehabilitating or repairing them. The replacement is performed by crushing the old pipe and removing its fragments to create a void that will be filled with a new pipe. This method is applied only to structural replacements since the old host pipe is broken into bits. (Al-Aghbar A., 2005)

ii. Pipe removal methods: (Najafi M., 2005)

Pipe Reaming: It is used in directional drilling for pipe replacement. The pilot is inserted through the pipe then the existing pipe is pulled back by a reaming tool which grinds it while the new pipe is installed. The excess material from the grinding is carried with the drilling fluid to the reception pit. This method is used for removal of vitrified clay pipe, PVC, and asbestos cement then replaced by HDPE or PVC pipe of equal or larger diameter.

Pipe Eating: It is a modified micro tunneling adapted for pipe replacement. The new pipe installed after the existing pipe is crushed by the micro tunneling boring machine, which is remotely controlled, and laser guided. The particles of the crushed pipe are circulated by the slurry system. The boring machine is launched from the insertion pit and a jacking frame is used to provide a thrust force to push the new pipe and the machine forward.

Pipe Ejection or Extraction: Pipe Ejection is a modified pipe jacking where the jacking frame in the insertion pit pushes out the existing pipe, and Pipe Extraction is a modified static pipe bursting where the extraction machine placed in insertion pit pulls out the existing pipe. The new pipe is installed while the existing pipe is being removed. This method is used only with existing pipes that can withstand the push or pull without being broken

Table (A.2) shows the main characteristics of trenchless rehabilitation methods for existing pipelines.

Table A.2 Main Characteristics of Trenchless Rehabilitation Methods

Method		Diameter Range (in)	Max Installation (ft)	Pipe Material	Typical Application
Cured In Place	Inverted in place	4 - 108	3000	Thermoset resin/fabric composite	Gravity & pressure pipe lines
	Winched in place	4 - 100	1500	Thermoset resin/fabric composite	
Modified Slip Lining	Panel Lining	More than 48 inch	Varies	GRP	Gravity pipe lines
	Spiral Wound	6 – 108	1000	PE, PVC, PP, PVDM	
	Formed In Place	8 - 144	Varies	PVC, HDPE	
Under Ground Coating & Lining		3 - 180	1000	Epoxy,polyster,silicon Vinyl ester, polyurethane & cementations material	Gravity & pressure pipe lines
Slip Lining	Segmental	24 – 160	1000	PE, PP, PVC, GRP (-EP and –Up)	Gravity & pressure pipe lines
	Continuous	4 - 63	1000	PE, PP, PVC, PE/EPDM	
In Line Replacement	Pipe bursting	4 – 48	1500	PE, PVC, PP, GRP	Pressure and gravity pipe lines
	Pipe Removal	Up to 36	300	PE, PVC, PP, GRP	
	Pipe Insertion	Up to 24	500	Clay, Ductile Iron	
Close Fit pipe	Structural	3 – 24	1000	HDPE, MDPE	Pressure and gravity pipe lines
	Non-Structural	3 - 36	1000	HDPE, MDPE	
Localized Repair Point source repair	Robotics	8 – 30	NA	Epoxy resins/cement mortar	Gravity
	Grouting	NA	NA	Chemical Gel, Grouts, Cement based grouts	Any
	Internal Seal	4 – 24	NA	Special Sleeves	Any
	Point CIPP	4 - 48	50	Fiber Glass, Polyester	Gravity
Thermoformed Pipe		4 - 30	1500	HDPE, PVC	Gravity & pressure pipe lines

Appendix (B): Horizontal Directional Drilling Equipment

1. Drilling Rigs

Najafi, (2005) classified the drill rigs into three main categories: mini; midi; and high, see Table (B.1). Rigs in each category are able to installing certain diameters and lengths of pipes based on their particular thrust/pullback and rotational torque. The "drill rig" consists mainly of the inclined ramp equipped with a carriage, control cab and the hydraulic power unit as shown in Figure (B.1):

- *Inclined ramp equipped with a carriage*: that can be moved up and down the ramp to advance and retract the drill string. The carriage slide forward on a frame and pushes the pipe into the borehole. The carriage is then retracted and a new pipe segment is attached.
- *Control cab*: houses the controls and personnel necessary to operate the drill rig. *Hydraulic power unit*: provides power to the directional drilling rig. The power unit is typically either mounted on a semi trailer along with the control cab or positioned next to the rig as a stand-alone piece of equipment.

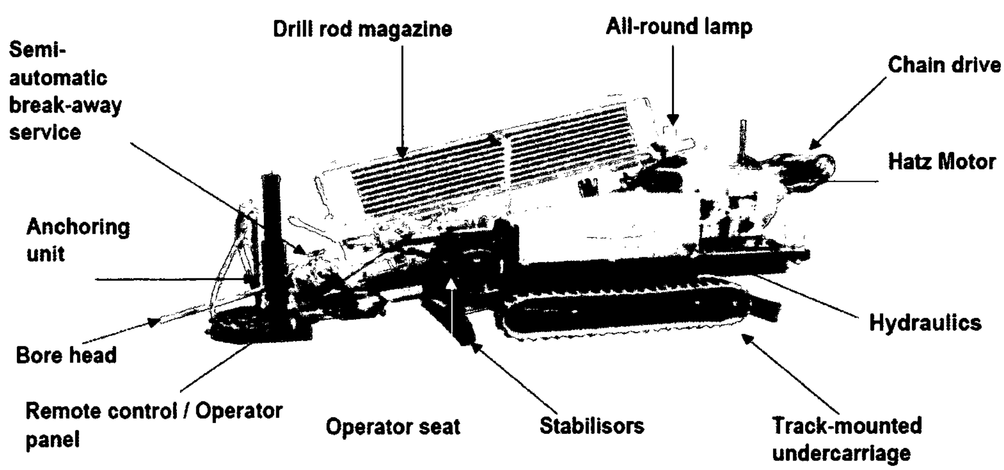


Figure B.1 Basic Component of Bore Rig (Adopted from TT Technologies Inc., 2007)

Table B.1 Classification and Characteristics of HDD Rigs
(Good Practices Guidelines, 2004)

	Small Rigs	**Medium Rigs**	**Large Rigs**
Thrust/Pullback	< 40000 lbs	40000 – 100000 lbs	> 100000 lbs
Maximum Torque	< 4000 ft-lbs	4000 – 20000 ft-lbs	> 20000 ft-lbs
Rotational Speed	> 130 rpm	90 – 210 rpm	< 210 rpm
Carriage speed	> 100 ft/min	90 – 100 ft/min	< 90 ft/min
Carriage drive	Chain, Cylinder, or Rack & Pinion	Chain or Rack & Pinion	Rack & Pinion with or without cable Assist
Drill Pipe Length	5 – 10 ft	10 – 30 ft	30 – 40 ft
Drilling Distance	≤ 700 ft	≤ 2000 ft	≤ 6000 ft
Power source	< 150 hp	150 – 250 hp	> 250 hp
Mud Pump	< 75 gpm	50 – 200 gpm	> 200 gpm
Weight of Drill Rig	< 15000 lbs	< 60000 lbs	> 60000 lbs
Rig Footprint Area (width x length)	3 ft x 10 ft. to 7 ft x 20 ft	7 ft x 20 ft. to 8 ft x 45 ft	> 8 ft x 45 ft.
Recommended Work Area Requirement (width x length)	20 ft x 60 ft	100 ft x 150 ft	150 ft x 250 ft

2. Bore Drilling.

Bore drilling equipments include drill bits, drill pipes, and reamer.

a. Drill Bits

Drill bits are used to facilitate steering and to excavate the soil or rock at the face of the bore, see Table (B.2). Common types of drill bits used in the HDD industry are:

- *Slanted face bits*: These are generally used in unconsolidated soils and soft to medium consolidated soil conditions (i.e. clay, silt, sand and soft sandstone).
- *Slanted face rock bits*: Slanted face rock bits are applicable in harder ground conditions and soft rock that can't be readily penetrated with thrust alone. The face of the tool usually has one or more nozzles emitting pressurized drilling

fluid. In the harder ground conditions, steering is accomplished by wiggling clockwise and counters clockwise

- *Hard rock or Mud motors*: These are utilized in ground conditions ranging from hard soil to medium rock, where an aggressive cutting bits and mud motors are used. This system uses a positive displacement motor, which generates torque and rotation at the drill bit from the flow output of the mud pump.

Table B.2 Drill Bit Types and Application Guidelines (Good practices, 2004)

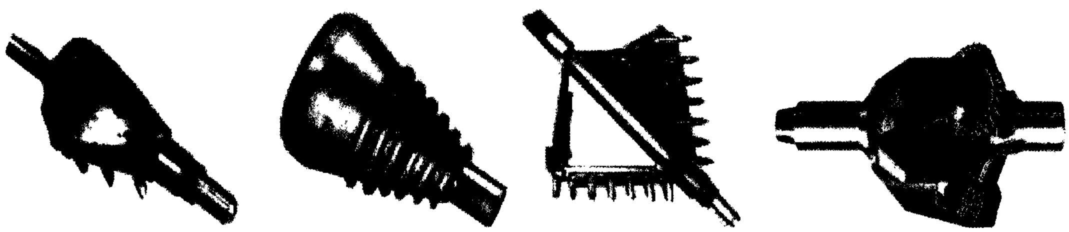
Drill Bit Type	**Applications**	**Comments**
Slanted-Face Bits		
Flat Spade Bent Spade	Clay Sand Organic soils	Increase width, length, and/or angle for more aggressive steering
Modified Spade	Hard Ground conditions	May be modified by adding teeth, tapers, etc. to match conditions
Rock bits	Rock Hard Pan	Small surface steering area; abrasion and impact resistant cutters
Mud Motor Rock Bits		
Roller-cone (Mill tooth)	Soft rock	
Sealed Bearing roller-cone (Tungsten Carbide Inserts)	Medium rock	
Sealed Bearing Roller-cone/Drag bit	Hard rock	
Polycrystal Diamond Compact (PDC) Drag bit	Hard rock formations	Generally too expensive and fragile for HDD applications

Compressive strength of rock types

Soft rock: < 5000 PSI, Medium rock: 5000 – 10000 PSI and Hard rock: > 10000 PSI

b. Back Reamer

Mainly used for enlarging the bore sufficiently to facilitate and fit the pipe installation. The reamer should be able to carry the native material or minimizing it to convenient cuttings, mixing those cuttings with the slurry, and preparing the bore for the pipe installation, see Figure (B.2).



All purposes Compaction Mixing Hole opener.

Figure B.2 various models of back reamers (Adopted from Vermeer, 2007)

3. Drilling Fluid, Delivery, Recovery and Containment System

Drilling fluid system main functions are carrying out spoils, cleaning, cooling, lubricating, stabilize borehole and driving mud motors.

Mixing and delivery system (Ariaratnam and Allouche, 2000)

Proper drilling fluid additives are added to water producing the drilling fluid mixture (slurry) as for the local geological conditions. Mixing system components include a gasoline or diesel powered engine, a hopper for mixing and adding materials, one or more centrifugal pumps, delivery hoses and tanks to minimum of 300 gallons. The mud pump carries out the drilling fluid to the rig at the required flow rate and pressure.

Storage tanks

"Steel Water storage tanks", is a must at locations lacking an adequate source of fresh water. They are located next to the mud system.

Cleaning systems

Cleaning systems are used to remove the cuttings and to recycle the drilling fluids. The drilling fluid enters a shale shaker for initial coarse particle separation, and then the slurry undergoes further cleaning through de-sanding and de-silting units.

4. Bore Tracking Equipments

Tracking systems are required to guide drill bit in the right path and direction of installation. A sensing unit is attached to the rear of the steering tool. It defines the exact location of the drilling tool (position, depth and orientation) for the operator. Accordingly, from this data, the operator identifies the location of the drill bit at all times and fixes the path if needed.

Typical methods of bore tracking *(Ariaratnam and Allouche, 2000; Ariaratnam 2005)*

a. Walkover system

This is the common used system for drilling operation. It consists of transmitter, receiver, and an optional remote monitor, see Figure (B.3). The transmitter is equipped behind the drill bit, in which it transmits the signals to the surface. A hand-held receiver detects these signals on the surface, and analyzes the data. Signals received are displayed in numeric values or graphical forms. The remote monitor reduces drilling time by providing the driller with the required information needed to locate and deduce the reaction of the drill head to the steering and drilling conditions, thus minimizing over steering and miscommunication and increasing productivity

Advantages: In spite of its market price, the only major cost is the batteries and sondes replacement, in addition to its higher productivity among the other systems.

Limitations: Tracking is limited according to the geological and site conditions. i.e.: in case of drilling work across river or freeway, it is not an easy task to walk over.

The signal transmitted from the sonde often interferes with signals from other media such as overhead power lines, traffic signals, rebar in foundation (Ariaratnam and Allouche, 2000; Ariaratnam 2005)

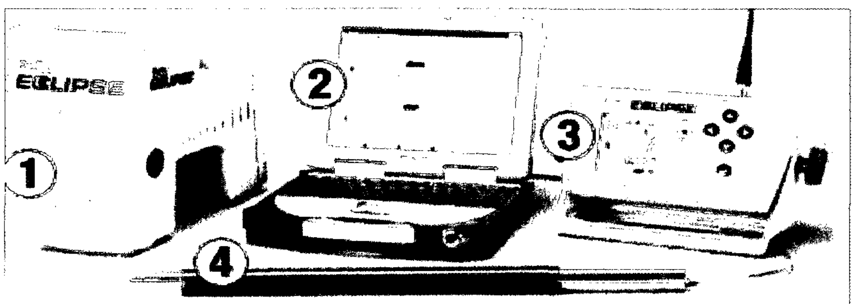


Figure B.3 Bore Tracking Equipment-Walkover System

b. Wire line system

It consists of the probe placed inside a nonmagnetic drill collar near the drill bit, wire connecting the probe to an interface unit on the drill rig, readout box, computer and printer at the driller's station. Therefore, the position can be located with the signal from the transmitter to the receiver through the wire. The remote device displays the position information. The bore path is monitored during the pilot bore by taking periodic readings of the inclination and azimuth of the probe. The probe's accelerometer measures gravity and resolves the tool's vertical-horizontal inclination. A magnetometer measures the earth's magnetic field and dip angle to resolve the tool's relationship to magnetic north.

Information is transmitted to the interface unit, which connects to a laptop computer and printer and provides the driller with constant updates of drill head roll, pitch, and direction.

Advantages: No depth limitation, minimize reading errors, no interference of signal, more efficient versus the time loss in walkover system for battery change.

Limitations: high capital costs and the need for highly skilled operators (Ariaratnam and Allouche, 2000; Ariaratnam 2005).

5. Accessories (Cable/Pipe Pulling Devices/Swivels)

Cable grip: This is attached to the outside of the pipe and can be fixed or bind with embrace or nylon ties at the end to avoid pulling off.

***Pipe pulling devices*:** This consists of the duct puller and pulling head. Duct puller has two sides, one end has one piece for cable connection; the other side has one or many pieces which are used for pipe connection. Pulling heads are made from pre-fabricated heavy steel with a central hole to fasten the swivel.

Swivel: This is utilized to connect the pull section with the leading reaming assembly to reduce the torsion transmitted to the pipe; which could happen with large diameter pipe, by a flexible link with the pulling head.

Appendix (C): Questionnaire Samplers

QUESTIONNAIRE SAMPLE I

I. Personal Information : *(Removed due to confidentiality and privacy Policy)*

Name:	
Email:	
Phone:	

II. Time and Pipe Information:

Please select ***one previously completed project for each questionnaire*** you will be completing and answering the following questions.

Project Start Date: 21/07/07	Project End Date: 23/07/07
No. of Actual Working hours/day: 10	Pipe/Cable Length (m): 200
Pipe/Cable Type: HDPE	Pipe/Cable Depth (m): 10
Pipe/Cable Diameter (mm): 100	Soil Type: Clay
Drilling Rig Size: □ Small	□ **Medium** □ Large
Project Place:	

III. Activities Information:

A. Estimate most probable **duration** of each HDD **activity cycle time** for the selected project.

	Activities	Estimated Time (Minutes) Most Probable
Major	Site Preparation	120
	Pilot hole drilling	240
	Reaming	480
	Final pipe pulling	60
Minor	Angle adjusting at bit entrance	10
	Drill pipe segments joining	5
	Reamer with shackle attaching for pre-reaming	15
	Pipe/Cable segments connection and layout	600
	Pipe swivel assembly for pipe pullback	120
	All tracking activities	60
	All Assessment Activities	90

Ineffective Performance (Quality) Level   Effective Performance (Quality) Level

Extremely Ineffective	Moderately Ineffective	Neither Effective nor Ineffective	Moderately Effective	Extremely Effective
1	2	3	4	5

Ineffective Performance (Quality) Level ← → **Effective Performance (Quality) Level**

Subjective Performance Scale

B. According to the above scale, please, rate the **effect** of the following factors **on HDD process productivity**.

	Questions	Scale 1	2	3	4	5
Management Conditions	Drilling rig operator and crew skills?				X	
	Rig size/drilling bit capabilities?				X	
	Safety regulations?		X			
Mechanical Conditions	Machine condition?				X	
	Slurry flow rate and slurry recycle equipment?			X		
	Steering problems? (Correction in direction)				X	
Environmental Conditions	Soil type?					X
	Unseen buried obstacles?				X	
	Site and weather conditions?		X			
Pipe Conditions	Pipe type?			X		
	Pipe length?				X	
	Pipe depth?	X				
	Pipe diameter?				X	

Thank you for your valuable time…

Questionnaire Sample II

I. Personal Information : *(Removed due to confidentiality and privacy Policy)*

Name:	
Email:	
Phone:	

II. Time and Pipe Information:

Please select ***one previously completed project for each questionnaire*** you will be completing and answering the following questions.

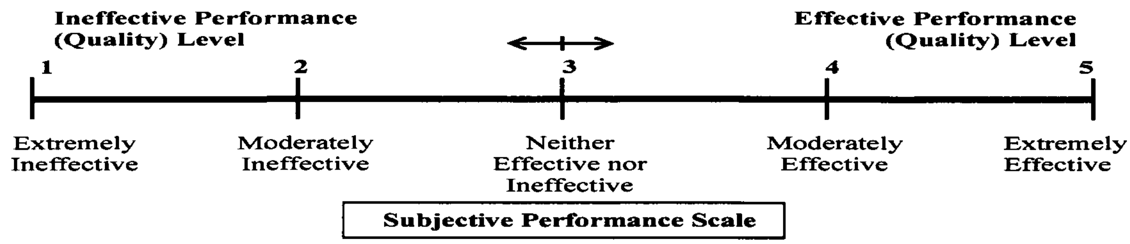
Project Start Date: 9/9/2005	Project End Date: 6/10/2005
No. of Actual Working hours/day: 10	Pipe/Cable Length (m): 600
Pipe/Cable Type: HDPE	Pipe/Cable Depth (m): 4
Pipe/Cable Diameter (mm): 500	Soil Type: Rock
Drilling Rig Size: □ Small	□ Medium □ **Large**
Project Place:	

III. Activities Information:

A. Estimate most probable **duration** of each HDD **activity cycle time** for the selected project.

	Activities	Estimated Time (Minutes) Most Probable
Major	Site Preparation	1200
	Pilot hole drilling	1200
	Reaming	2400
	Final pipe pulling	1800
Minor	Angle adjusting at bit entrance	600
	Drill pipe segments joining	1200
	Reamer with shackle attaching for pre-reaming	120
	Pipe/Cable segments connection and layout	600
	Pipe swivel assembly for pipe pullback	200
	All tracking activities	1200
	All Assessment Activities	300

Ineffective Performance (Quality) Level Effective Performance (Quality) Level



B. According to the above scale, please, rate the **effect** of the following factors **on HDD process productivity**.

Questions		Scale 1	2	3	4	5
Management Conditions	Drilling rig operator and crew skills?					X
	Rig size/drilling bit capabilities?				X	
	Safety regulations?			X		
Mechanical Conditions	Machine condition?				X	
	Slurry flow rate and slurry recycle equipment?				X	
	Steering problems? (Correction in direction)				X	
Environmental Conditions	Soil type?					X
	Unseen buried obstacles?					X
	Site and weather conditions?			X		
Pipe Conditions	Pipe type?		X			
	Pipe length?				X	
	Pipe depth?		X			
	Pipe diameter?				X	

Thank you for your valuable time...

Questionnaire Sample III

I. Personal Information : *(Removed due to confidentiality and privacy Policy)*

Name:	
Email:	
Phone:	

II. Time and Pipe Information:

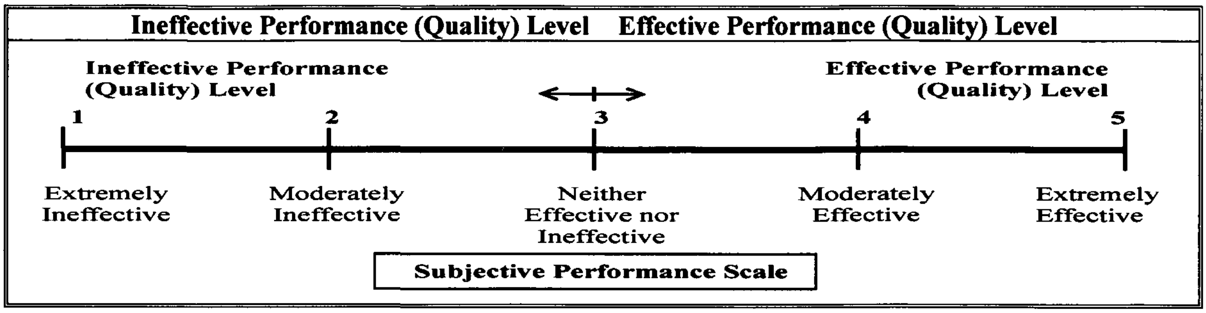
Please select ***one previously completed project for each questionnaire*** you will be completing and answering the following questions.

Project Start Date: 5/11		Project End Date: 9/11	
No. of Actual Working hours/day: 10		Pipe/Cable Length (m): 500	
Pipe/Cable Type: HDPE		Pipe/Cable Depth (m): 2.5	
Pipe/Cable Diameter (mm): 323		Soil Type: Silty Sand	
Drilling Rig Size:	□ Small	□ **Medium**	□ Large
Project Place: Laval III			

III. Activities Information:

A. Estimate most probable **duration** of each HDD **activity cycle time** for the selected project.

	Activities	Estimated Time (Minutes)
		Most Probable
Major	Site Preparation	360
Major	Pilot hole drilling	600
Major	Reaming	600
Major	Final pipe pulling	600
Minor	Angle adjusting at bit entrance	60
Minor	Drill pipe segments joining	120
Minor	Reamer with shackle attaching for pre-reaming	60
Minor	Pipe/Cable segments connection and layout	Parallel to major activities
Minor	Pipe swivel assembly for pipe pullback	60
Minor	All tracking activities	Parallel to pilot hole drill
Minor	All Assessment Activities	100



B. According to the above scale, please, rate the **effect** of the following factors **on HDD process productivity**.

	Questions	Scale 1	2	3	4	5
Management Conditions	Drilling rig operator and crew skills?				X	
	Rig size/drilling bit capabilities?				X	
	Safety regulations?				X	
Mechanical Conditions	Machine condition?			X		
	Slurry flow rate and slurry recycle equipment?				X	
	Steering problems? (Correction in direction)				X	
Environmental Conditions	Soil type?					X
	Unseen buried obstacles?			X		
	Site and weather conditions?			X		
Pipe Conditions	Pipe type?		X			
	Pipe length?				X	
	Pipe depth?		X			
	Pipe diameter?				X	

Thank you for your valuable time…