Safety Risk Investigation of Horizontal Directional Drilling Projects

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SAFETY RISK INVESTIGATION OF HORIZONTAL DIRECTIONAL DRILLING PROJECTS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

by
Phalguni Yamuna Moganti
August 2016

Accepted by:
Dr. Kalyan R. Piratla, Committee Chair
Dr. Leidy Klotz, Co-Chair
Dr. Kapil Chalil Madathil
Traditional underground utility construction and rehabilitation methods entail cutting open the ground which not only disrupts traffic causing delays and inconvenience, but also damages surface-based vegetation in some areas. Additionally, underground infrastructure density has been growing thereby making it more challenging to employ the traditional open-cut construction method. A sustainable alternative is the use of trenchless construction methods where underground infrastructure is installed or repaired with minimal surface disruption.

Horizontal Directional Drilling (HDD) is one of the popular trenchless methods for installing buried utility pipelines. Risk dimensionality and severity is generally greater in the case of HDD projects because of the fact that only limited soil and other sub-surface sampling will be done to choose the right type equipment, labor, materials, and drilling plan. Some of these risks have led to accidents on HDD projects in the past that not only damaged the equipment and other infrastructures, but also injured workers which proved fatal in some cases. In order to minimize the safety risk in HDD projects, there is an outstanding need for the investigation of hazards, factors and project characteristics that propel the probability of occurrence of accidents.

This thesis report presents the development and demonstration of the hierarchical safety risk assessment framework for investigating the safety risk, especially the probabilities of occurrence of various hazards, of HDD projects. The developed “Hierarchical Risk Assessment” framework is demonstrated using two real-world HDD
projects. The safety risk analysis performed on the two case studies highlighted the factors and project characteristics that aggravate the hazards and their probabilities of occurrence. The proposed approach for investigating safety risk on HDD projects needs to be further investigated and extensively evaluated on more real-world case studies before it can be developed into an adoptable tool for practice.

**Key Words:** Horizontal Directional Drilling, Hierarchical Risk Assessment.
DEDICATION

I dedicate this work to my beloved mother, Mrs. Anantha Lakshmi.
ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere appreciation and gratitude to my advisor Dr. Kalyan R. Piratla for his encouragement, extensive help throughout the research process and assistance over my graduate career. His willingness to provide invaluable insight has greatly enhanced my learning experience. I also extend my thanks to Dr. Kapil Chalil Madathil and Dr. Leidy Klotz for accepting to be on my thesis committee. I would like to specially thank my family and friends, who are always there for me when I need them.
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CHAPTER 1: INTRODUCTION

Underground pipeline infrastructure is must for supporting the increasing needs of growing population. Trenchless methods offer significant benefits over the conventional open-cut construction in many cases for installing buried pipelines. The conventional open-cut method follows the cut-dig-bury-fill approach which is inconvenient to employ in high-traffic, dense urban areas mainly due to the surface-related disruption and the resulting economic, environmental and societal consequences. Open-cut method can be expensive in cases where deeper cover is specified for the pipe or where the cost of relocating conflicting utilities and other surface structures is high. The significant amount of excavation associated with open-cut method, especially in deeper installations, also produce significant greenhouse gas emissions. Needless to say, they result in several societal consequences that include but not limited to the disruption of traffic and surface vegetation. Trenchless techniques are a class of underground construction methods that eliminate substantial digging and its associated challenges. Trenchless techniques usually require insignificant amount of excavation and preserves the surface-based activities.

Horizontal Directional Drilling (HDD) is a popular trenchless construction method that is often employed to install buried utilities. Pipelines as long as 5,000 ft and sizes of up to 36 inches have been reported to be installed using HDD (Duyvestyn, 2014). HDD offers significant environmental and societal benefits in addition to cost benefits which makes this method stand out of other trenchless construction methods (Ariaratnam, 2008).
HDD technique entails three sequential steps following the pre-planning phase, namely pilot boring, reaming and product pipe pullback.

**Pre-planning phase:** One of the primary tasks in the pre-planning phase of any HDD project is conducting a thorough surface and subsurface investigation in the project location and its surroundings to identify the constraints for a better design and construction planning. The sub-surface exploration includes testing of rock and soil samples for geologic characteristics and engineering properties. Details on existing subsurface utilities and soil conditions will help plan a proper drill path and choose appropriate drilling equipment that suits the soil conditions. Boring locations need to be subsequently planned considering the horizontal and vertical axis of the existing utility lines. Boring depth also needs to be determined so as to avoid conflicts with existing buried utilities and other obstacles.

**Pilot boring:** A drilling equipment, called drill rig, is used in this step to drill through the ground and create a small diameter borehole which will be enlarged using a larger diameter reamer (step 2) and into which a product pipe will be pulled in (step 3) before final connections are made. A set of drill rods which are connected to one another to form a drill string is used in the pilot boring step to create the borehole. The drill string is pushed into the ground using the drill rig which comes in different capacities in terms of thrust force and torque. A drill head is attached to the beginning of the drill string to penetrate through the ground by cutting the soil and displacing it. The penetration of the drill string through the ground can be achieved either just by pushing or in some cases rotating the drill string. The drill head has a slant face that enables steering of the drill string in the desired direction.
based on the real-time location monitoring during the drilling. The drill head is also equipped with a monitoring device that transmits information to an above surface receiver and the information of interest includes its horizontal and vertical location, its clock position among other inputs. The drill head makes a slightly larger hole than the drill string to create annular space for the movement of soil cuttings back to the ground with the help of a pressurized drilling fluid. Bentonite mixed in water is commonly used as the drilling fluid which helps to reduce the friction between the drill string and the borehole, cools the cutting head, and also stabilizes the bore hole. An operator sitting on the drill rig machine controls the drilling operation based on real-time data inputs on the location of the drill head and also based on the desired drilling path. The “pilot boring” phase ends when the drill string reaches the exit pit which is the other end of the desired pipeline installation. The illustration of the pilot boring phase of HDD Operation is presented in the Figure 1.1.

**Figure 1.1.** A picture illustrating the pilot bore phase of HDD operation (J. D. Hair & Associates Inc., 2010)

**Reaming:** This stage, often called back reaming, involves enlarging the drilled pilot borehole. A reamer, show in the Figure 1.2, is attached to the drill string at the exit point
and the drill string is pulled back into the bore hole in order to enlarge it for the product pipe to fit through. The size and type of the reamer used depends on the size of the product pipe and geological conditions. Pressurized drilling fluid is continuously pumped even this phase to push the soil cuttings out of the borehole. The reaming phase of HDD construction method is illustrated in Figure 1.3. Reaming phase can be avoided in soft soils for the installation of smaller diameter pipelines (Hair, 1994).

**Figure 1.2.** Reamer (English, 2013)

**Figure 1.3.** A picture illustrating the reaming phase of HDD operation (J. D. Hair & Associates Inc., 2010).
**Pull Back:** In this final phase of HDD construction, the product pipe is pulled through the enlarged bore hole; in some cases, the pull back and reaming phases are combined. In order to minimize the torsion on the product pipe, a swivel is used to connect the pull section to the leading reaming assembly. The swivel prevents the product pipe from rotating even when the drill string is rotated. The pipeline installation is completed when the product pipe is successfully pulled back to the entry point. The illustration of the pullback phase of HDD Operation is presented in Figure 1.4.

![Diagram of pullback phase of HDD operation](image)

**Figure 1.4.** A picture illustrating the pullback phase of HDD operation (J. D. Hair & Associates Inc., 2010)

Risk dimensionality and severity is generally greater in the case of HDD because the equipment, labor and material that is used in the process are all selected to match the predicted soil condition, ground water table, and location of other utilities, which are all determined from limited sampling done during the pre-planning phase of the projects. Any deviation from the predicted project parameters will escalate the risk leading to possible accidents. Many accidents have occurred on HDD projects due to various factors that include but not limited to uncertain soil conditions, inappropriate drilling practices,
inaccurate locating of existing utilities, inappropriate worker apparel, and lack of effective communication among crew members on the jobsite. Some of these accidents have resulted in severe injuries and even deaths of workers (Marktgorman, 2010). These consequences present a need for evaluating the safety risk on HDD projects through investigating the current practices in the industry. Specifically, there is a need to identify and systematically study various possible hazards and identify factors and specific project characteristics that may aggravate the safety risk resulting from the identified hazards.

1.1 Objective of the Study:

The objective of this study is to develop and demonstrate a “Hierarchical Risk Assessment” framework for evaluating safety risk of HDD projects. By understanding the possible factors that aggravate the probability of occurrence of various hazards and the specific project characteristics that support such aggravation, it is hypothesized to alleviate the safety risk to some degree. The proposed framework and its demonstration is expected to enable HDD practitioners to mitigate the safety risk associated with the humans, equipment and infrastructure on the job site and carry out a productive HDD project.

1.2 Organization of the thesis:

This thesis is divided into five chapters. Chapter 1 presents an overview of the problem associated in terms of safety risk in HDD projects. Chapter 2 presents a brief review of the relevant literature. Chapter 3 describes the hierarchical risk assessment framework. Specifically, Chapter 3 presents the identification of specific hazards, factors responsible for the occurrence of the identified hazards, critical HDD characteristics that
influence the safety risk. Chapter 3 also describes the survey of the influence of project characteristics on the factors and the factors on the hazards. Chapter 4 describes the demonstration of HRA methodology on two real world HDD projects and discusses the findings. Chapter 5 concludes this study by summarizing the findings and their implications and making recommendation for future follow up studies.
CHAPTER 2: LITERATURE

This chapter presents a brief review of relevant literature on accident causation theories, followed by previous safety risk analysis frameworks for construction projects in general and specifically for underground construction projects.

Domino theory of accident causation hypothesizes that identifying and finding ways to avoid the occurrence of one key event among a series of domino events that lead to an accident will diminish the risk of accidents and injuries (Heinrich 1931). Human Factor Theory proposed that many accidents are caused due to human errors and these errors were subsequently identified and categorized for risk evaluation (Ferrell 1997). Behavior-based Safety Theory of accident causation presented a psychological aspect of the worker behavior in the context of accidents (Gellar 2001). Another multi-level accident progression model is proposed by Bird in which ignorance of one basic state leads to severe injuries or accident in next levels (Bird, 1969). A few of these theories played a major role in the development of safety risk assessment frameworks that are currently employed in the construction industry.

2.1 Construction Safety Risk Assessment

Safety risk pertaining to general construction projects has been a research topic of interest for several decades now and there are numerous frameworks and standards that multiple construction companies currently follow. Some of these frameworks and standards are briefly reviewed.
There are many guidelines that were set internationally to enhance safety of construction projects.

Occupational Health and Safety Administration (OSHA), as part of the United States Department of Labor, published guidelines that provide information on rule-making process to improve the health and safety in the work place. OSHA also provides training, outreach, education and assistance activities on their standards to the work force so that they can be employed as required. Their standards are readily available online for anyone to adopt. Although the regulations are numerous, almost all of them reflect the general common sense, best practices, and includes examples on what experienced and prudent employees would do in their jobs to maintain a risk-free work place. Limitation of those regulations is that it does not provide quantitative assessment of risk aversion associated with each standard.

National institute of safety and health (NIOSH), established under Occupational health and Safety Act 1970, conducts research on workers wellbeing and spreads guidelines through manuals on work safety and measures to maintain good health of workers. NIOSH facilitates high-risk industrial sectors in proving innovative solutions for difficult-to-solve problems. This source helps in critical analysis of qualitative risk characterization and helps in management of occupational hazards.

Rand (1955) developed the Delphi method to calculate the impact of technology on modern world. The method involves a group of experts who reply to questionnaires related to their field of expertise and then receive feedback in the form of statistical notes of the
"group response." Which help in quantifying uncertainty and draw a conclusion on an opinion. Later Delphi based risk analysis was developed on the same basis to evaluate the safety risk of construction operations where no quantitative data is available. This method is a time consuming process and effectiveness of the work depends of the expert decision whose perceptions may change relative to the future research on that specific topic. Consequently, it is preferred to be used only where quantitative models are difficult to use.

Zadeh (1965) established the Fuzzy Set Theory to find a way of dealing with risk due to hazards where the source of information related to risk is absent. The risk factors are divided into sets. Fuzziness indicate the uncertainty in happening of a hazard which is often expressed in linguistic terms such as high, medium, and low. These terms are further converted into quantitative numbers by use of membership functions through which severity is calculated by various statistical procedures. This model proves its importance where typical mathematical models lack evidence for problem solving in complex phenomenon, and it consumes very less time for producing the results. The limitation is the lack of mathematical evidence for the obtained findings.

Analytical Hierarchy Process (AHP) (Wang 1977) is one popular method which helps in determining the relative importance of different attributes that causes risk by expert evaluation in three steps: (1) work breakdown structure on risks due to specific events, (2) compare and set priorities between structures by expert decisions, and (3) hierarchical arrangement of priorities. Based on the expert decisions, a weightage index system is established where the consistency between the factors causing risk is tested. This process is mainly used in cases where there is a presence of uncertainty in the available data, or
lack of necessary data required for risk assessment. The main advantage of AHP is its ability to check and decrease the inconsistency of expert findings. This research employs a methodology similar to AHP to evaluate the relative importance of factors that aggravate the occurrence of hazards and characteristics that affect factors leading to a hazard. Limitations of AHP method are that sometimes problems arise due to interdependence between criteria and alternatives which can lead to inconsistencies between judgment and ranking criteria.

Fault Tree Analysis (FTA) has been used for the evaluation of safety risk in construction projects (Suresh et al., 2003). In this approach, accidents are categorized into ground, machines, environment and management. FTA involves identifying the risk factors encountered by construction industry by collecting information on different construction risks and their consequences. Alternatives were developed to prevent or mitigate the risk effects. Experts with in-depth knowledge of construction projects can provide a valuable opinion on uncertainties. The advantage of this method is it takes less time to develop.

Construction Job Safety Analysis (CJSA) (Rozenfeld, 2006), a lean approach was developed to manage safety in the construction industry. Safety Analysis can be performed in three steps: (1) Identification of hazards and analysis of loss of control events that may aggravate, (2) Evaluation of probability of occurrence of the analyzed loss of control events, and (3) Finding the expected degree of severity caused due to possible loss-of-control events with possible accident scenarios. The advantage of this method is that relative quantitative measures for each event are obtained, but the risk reduction or the elimination measures are not provided.
Mitropoulos (2009) recently presented the Task Demand Methodology which relates productivity and safety of construction projects at the same time using basic construction operation parameters. This method is demonstrated in 4 steps: (1) Identifying the two key factors responsible for assessing the likelihood of accidents, (2) Determination of the exposure time on hazard, (Based on live observations and interviews), (3) Determining the factors affecting task demand during the exposure, which basically indicates that there will a probability of accident upon exposure to hazard, finally (4) Calculating the safety risk of the operation i.e. exposure times the task demand. The limitations of this method being it can only be used to compare the safety risk for same hazard under different operational parameters but cannot be used to compare different hazards. Other disadvantage is it does not correlate the task demand values with probability of incidents.

2.2 Safety Risk Assessment of Underground Utility Construction Projects

Several researchers conducted studies on deriving frameworks specifically for underground construction utility projects using general construction risk evaluation methods, depending on the extent of available data and job site conditions. A few previous studies are briefly reviewed in the following paragraphs.

Ariaratnam (2007) presented the Total Risk Index Model (TRI) which is used for calculating the risk value for underground urban utility projects. This model calculates the risk involved in the HDD and the Open Cut (OC) excavation for a specific project in two steps using four sub-indices namely contingency plans, determining bid price, eco-social factors, and consideration factors. Each of these indices contains a list of questions with
choices that pertains to a specific project. Users and the industry specialists are invited to participate in the questionnaire survey by choosing one option as their opinion. Risk Index is calculated using the answers obtained from the survey for each sub index using Eq. 1.

\[
\text{RI}_{\text{HDD or OC}} = f \{ \frac{\text{EI}}{\text{MI}} \}
\]  

(1)

Where RI = Risk Index; HDD = Horizontal Directional Drilling; OC = Open Cut; EI = Estimated Index (answers obtained from users); MI = Maximum Index (answers obtained from industry specialists);

In the next step, each sub-index is given equal weighted sub index value which is independent of the number of questions created for each sub index. After calculating all the sub index values, Total Risk Index (TRI) is calculated using Eq. 2.

\[
\text{TRI}_{\text{HDD or OC}} = f \left\{ \frac{\sum (\text{RI}_{\text{sub index}})}{4} \right\}
\]  

(2)

Where TRI = Total Risk Index; HDD = Horizontal Directional Drilling; OC = Open Cut; RI = Risk Index (obtained from equation 1.).

TRI value is calculated both for HDD and OC methods from the values obtained from the questionnaire. Smallest TRI value obtained method is chosen for the construction. Advantages of this model is it takes less time, compares two methods and gives feasible solution from four perspectives (addressed as sub-indices in the model). Disadvantage is that the choice of method is dependent all alone on the questionnaire results (which may vary in the future).
A framework using Fuzzy Comprehensive Evaluation Method (FCEM) and Analytical Hierarchy Process (AHP) was developed by Ma et al. (2010) for quantifying the risk of Maxi HDD projects. The methodology entails: (1) Identifying and classifying the risks in each level of HDD operation, (2) Finding weight value of each associated risk from structured matrices judgement matrices, membership matrices, and index systems using maximum membership functions and MATLAB software. The Total risk value for the entire project is obtained by combining all the values in each level risk classifications. Advantages are Risk management decisions can be made easily. FCEM is mainly used in the place of complicated projects as risk values can be easily derived using subjective judgements. Disadvantages are they provide only theoretical bases for risk evaluation but not mathematical evidence.

Gierczak (2014) proposed a model for evaluating the safety risk of Mini, Mid, Maxi HDD projects using Fuzzy Fault tree Analysis (FFTA). The research focuses on two main aspects namely: (1) Development of mathematical model and, (2) Development of risk management strategy. The first aspect is demonstrated in eight steps (1) Defining the analysis of scope of the work, (2) Gathering information, (3) Hazard identification, (4) Construction of Fault Tree (FT), qualitative analysis of fault tree, (6) Quantitative risk assessment applying using of trapezoidal membership functions fuzzy arithmetic followed by defuzzification using center of area method (Filev 1994) (7) Managing the assessed risk, (8) Decision making. The advantages of this method are it can be used on any type of construction practice. It gives a broad knowledge on failure mechanisms and reduces uncertainties. This proposed model especially carries out qualitative and quantitative risk
assessment for the trenchless pipe installation of various sizes; but the model includes complex calculations which take lot of time.

Choi (2015) developed a methodology named Risk Assessment Methodology for underground construction projects. This methodology consists of three main steps to arrive at obtaining the value of risk namely: (1) Identifying factors causing risk (2) Analyzing those factors (3) Evaluating the risk. The tools used in this study are survey sheets (to be filled by experts), detailed check sheets for risk identification, and a risk analysis software based on Fuzzy concept basically coded for subway projects. This software comprises of three modules: (1) Data input module (Data is input from the subjective judgements or probabilistic parameter estimates, (2) Probabilistic Analysis module, (3) Output Module (gives the risk value). The methodology is easy to use as data can be used either from subjective judgements, observations or historic data. But the disadvantage being the software is framed only for subway construction projects. So certain modifications are necessary to use the project for other underground construction practices.

2.3 Overview of Safety Risk Assessment Frameworks

Table 2.1 presents advantages and limitations of various commonly-used safety risk evaluation methods in the construction industry in general.
<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Domino Theory</td>
<td>1. Indicates that the accident is the result of a single root cause.</td>
<td>1. Does not account or consider effective analysis of environmental factors.</td>
</tr>
<tr>
<td></td>
<td>2. This is a Simple process, and considers only a single chain of factors (5 factors)</td>
<td>2. Do not provide any data on attributes leading to the considered factors.</td>
</tr>
<tr>
<td>The Delphi Method</td>
<td>1. Cost effective.</td>
<td>1. Drop outs in response rates of the experts may result in inconvenience of the survey.</td>
</tr>
<tr>
<td></td>
<td>2. Flexible, fast and versatile process.</td>
<td>2. Time delays may occur in the process in data collection process from the experts such as analysis and processing the data.</td>
</tr>
<tr>
<td></td>
<td>3. Prevents direct communication of experts with one another (avoids peer pressure and extrinsic pressure)</td>
<td></td>
</tr>
<tr>
<td>Total Risk Index</td>
<td>1. Consumes less quality time</td>
<td>1. Experts are the only source for the determination of TRI.</td>
</tr>
<tr>
<td></td>
<td>3. Although the method is proposed for underground projects, its simplicity makes it useful to other general construction projects.</td>
<td></td>
</tr>
<tr>
<td>Method</td>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td>-------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Fault Tree Analysis</td>
<td>1. Can be applied to analyze risk for which there is a lack of sufficient data and incomplete knowledge.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. It involves the cause-and-effect relationship between key factors and the exposure for each individual risk.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Key risks can be identified and managed quickly.</td>
<td>1. Difficulty in developing in the membership functions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Judgement is subjective.</td>
</tr>
<tr>
<td>Task Demand Methodology</td>
<td>1. This method measures safety and productivity of the operation at the same time.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. This method provides researchers and practitioners a tool for analyzing the accident potential under different operational parameters and identifies how changes in the operation affect the accident potential scenarios under one single hazard.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. This will allow to design more safer and productive operations.</td>
<td>1. This method focuses on emotionally disturbing injuries and does not capture the risks arising from overexertion injuries, physical fatigue.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Cannot be used to compare different hazards.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Does not correlate the task demand values with probability of incidents.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. The presence of multiple hazards may also increase the likelihood of incidents, as the workers may have to divide their attention.</td>
</tr>
</tbody>
</table>
2.4 **Chapter Summary**

In summary, although previous studies which were discussed in this chapter introduced many risk evaluation frameworks, only few presented easy-to-use, quick approaches for reliable risk assessment of underground construction projects, especially HDD projects. This thesis study proposed and demonstrated a hierarchical safety risk assessment approach which when further evaluated and improved could serve in diminishing the safety risk of HDD projects.
CHAPTER 3: HIERARCHIAL RISK ASSESSMENT METHODOLOGY

Safety risk in the context of this thesis is characterized as the probability of a person getting injured or equipment getting damaged during a Horizontal Directional Drilling (HDD) project. A Hierarchical Risk Assessment (HRA) approach is proposed for assessing the probability occurrence of hazards in HDD projects. Specific hazards, critical factors that aggravate or alleviate the hazards, and various project characteristics form the hierarchies of the HRA approach.

3.1 Hazard Identification:

Hazard in this study refers to the threat of injury or death to workers, damage to construction equipment or any infrastructure. HDD projects are typically completed in three sequential construction phases namely, pilot bore, reaming, and pull back. It has its share of hazards in all the three phases that must be controlled or eliminated in order to ensure worker and public safety (Kennedy, 2010). Several possible hazards are identified in Figure 3.1 for each of these three phases by gathering information from various previous HDD projects.
3.2 **Critical HDD hazard identification:**

Among the several hazards listed in Figure 3.1, four critical hazards have been chosen upon survey of literature and reviewing various case studies on accidents occurred on previous HDD projects. The four critical hazards are “Hitting other utilities,” “Stall/breakage of drill string / drill head,” “Injury to workers,” and “Workers falling into excavated pits.” These four hazards are briefly described along with accounts of accident histories that stand as examples of these hazards being realized.

H1 - Hitting other utilities:

“Hitting other utilities” is one of the possible hazards that could occur during the pilot bore phase of any HDD project. This hazard is realized when the drill head accidentally hits other utilities potentially resulting in several complications that include damages to infrastructures and resulting economic losses in addition to potential injuries.
to workers on the jobsite depending on what type of utility line is hit. For example, hitting a sewer line may not be as consequential as hitting a gas or electric line. This hazard may occur due to lack of details on depth and position of existing utility lines. The probability of occurrence of this hazard is determined to be dependent on various factors which in turn are dependent on various project characteristics.

The factors that influence the hazard “Hitting other utilities” are identified through survey of literature and synthesis of past accidents on HDD projects. The three major factors which are determined to influence “Hit other utilities” hazard in HDD projects are:

**F₁ - Experience of the worker on job site:**

In any boring operation, the project success is mainly dependent on the operator who is controlling the boring/drilling equipment. In such a case, the skill level the operator possesses would play an important role in successfully completing the drilling operation. In the presence of one or more utility lines, there is a good possibility for the contractor on lacking details on the vertical elevation in some cases, though the location of existing utilities is known through sub-surface utility investigation. During such conditions the contractor has to deal carefully to plan the drill above or below the utility line. This is more likely possible through experience in handling such situations. Lack of spontaneity, another experiential attribute, on such situations may result in hitting other utilities.

**F₂ - Accuracy of sub-surface utility Engineering (SUE):**

It is very important to have accurate SUE data which can be achieved, for example by following the guidelines presented in “ASCE 38-02” manual. From the accident case
studies, literature review and in person observation of the boring operation, it is understood that “Hitting other utilities” may occur due to the lack of accurate SUE data and therefore this factor is identified as one of the critical factors for this hazard.

F3 - Inappropriate/Lack of a communication mechanism among the crew:

Inappropriate communication or lack of a communication mechanism enabled through Walkie-talkies, Radios, or Walk-over systems influence the safety risk of a HDD operation. Any deviations in the drill path as noted by the walkover system or any other issues arising on the jobsite need to be notified to the drill rig operator in a timely manner for the safety of people, equipment and infrastructure.

The following real-world examples describe the circumstances and the consequences of accidents where other utility lines were hit during a HDD project due to lack of communication among the crew and thorough details on exiting utilities, and so these factors were identified as critical factors for the Hazard “Hitting other utilities.”

i. The gas explosion occurred in St. Paul, Minneapolis at Arden Avenue in Edina, which was due to a gas leak that eventually sparked the explosion when cable crews using directional drilling equipment ruptured a gas line. The consequences of this accident include the demolition of two houses near 5000 Arden Ave. in Edina (Nelson, 2010).

ii. In 1997, Datong No. 1 Coal Mine and Shihao Coal Mine in China used two units of LHD-75 Directional Drill System for gas drainage. The experiment was dropped because of the collapse of the borehole due to imported equipment that were
damaged during transportation and also the geology problems which were not detected in the sub surface investigation. The results are leaving sticking problems up to the bore depth of 45 m and 75 m in Datong No. 1 Coal Mine and Shihao Coal Mine, respectively. (Lu, 2011)

**H2 - Stall/breakage of drill string/drill head:**

This is considered one of the critical hazards that could possibly occur in any HDD project if safe design and drilling procedures are not given priority. Stall/breakage of the drilling tools might occur due to lack of proper geotechnical data or usage of aged tools which are no longer able to support the designed operation. There is a good possibility of this hazard occurring due to excess use of torque and drag by the operator than necessary. This hazard results in the breakage of the drill string thereby halting the drilling operation before the drilling tools are restored and operation reinitiated. Sometimes, the stalling of drill string may even topple the drill rig and injure the operator.

Three critical factors were identified to be influencing the probability of occurrence of this hazard. They are:

**F1 - Experience of the worker on job site:**

Any drilling operation is influenced by the person operating the primary equipment which is the HDD drill rig in this case. Maintenance of thrust and torque loads within the safe limits of the particular drill rig by keeping in mind the uncertainties with respect to the geological conditions of the ground is a responsibility of the drill rig operator that is expected to be more efficiently carried out by experienced operators. Inappropriate loads
on the drill rig in a given soil condition may lead to “Stall/breakage of drill string/drill head” and may even lead to the collapse of the drill rig (Boomana, et al., 2013).

**F4 - Age of the tool used for the HDD operation:**

Aged tools such as the drill string, drill head that are used in any HDD operation may no longer be able to handle the design loading when operating in tough sub-surface geology. In such cases, “Stall/ breakage of drill string/ drill head” is possible.

**F5 - Exceeding the force limits of the drill rig:**

Pipe movements such as drilling ahead or tripping create drag, while rotation produces torque (Ruiz, 2014); the normal contact force between pipe and the borehole wall is influenced by these force limits. Exceeding the limits of these forces may break the equipment and subsequently result in the stalling of the drill string. The consequence resulting in this factor occurrence were undesirable as observed in the past HDD projects, and so it is considered as one of the factors responsible for the hazard “Stall/breakage of drill string/drill head.” The force limits and the rotational capacity are equally important as other factors, for they may equally influence the safety risk. Lack of frequent monitoring of the values may lead to “Stall/breakage of drill string/drill head.” There are few scenarios where this hazard has been realized (Ugrich, 2007)

**H3 - Injury to worker:**

This is identified as one of the critical hazards in HDD projects as evidenced by its occurrences on past projects (Canada News, 2009). This hazard is mainly caused due to
machinery attacks or unforeseen conditions in addition to the workers being careless – e.g., moving in close proximity to working equipment, inattentive to the commination systems among the crew or due to the machinery attacks on the crew like the drill string hitting the workers while it exits the borehole. Even collapse of equipment due to unforeseen conditions may also happen due to natural hazards or human mistakes which lead to death or major injury to workers.

Three critical factors were determined to be influencing the probability of occurrence of this hazard and are briefly described in the following paragraphs:

**F₁ - Experience of the worker on job site:**

Construction workers constantly need to adapt to the changing work environments, and their attentiveness and general cognizance of the work environment influences their ability to be safe on the jobsite (Canadian Centre for Occupational Health & Safety, 2016). Although workers are trained to safely execute their specific tasks, their general response and attention to activities on the jobsite – a trait expected to grow on with experience – influence the safety risk.

**F₆ - Lack of PPE:**

Personal protective equipment (PPE) is of utmost importance in any construction activity no matter what the activity is. Many incidents in the past proved how useful PPE is for mitigating accidents when hazard-related uncertainties arise. Consequently, “Lack of PPE” is identified as a critical factor that affects the ability of a worker to be protected from potential injuries.
**F7 - Unsuitable apparel for the work conditions:**

Material, color and type of the apparel used for a HDD operation influence the safety risk of the operation. This has been found to be a crucial factor based on a few past accidents on HDD job sites.

The following is an example of a past project where this hazard occurred:

i. A worker got injured in Alberta, Canada on September 19th 2009, during a HDD operation. The worker got injured as a result of equipment failure in the middle of a culvert-drilling project under a highway. The injury turned out to be fatal leading to the death of the worker. The officials said that HDD operation is unusual practice for that kind of a project. (Canada News, 2009).

**H4 - Workers falling into excavated Pits:**

This could happen on a HDD job site due to the carelessness of workers in addition to several other factors such as lack of safe working conditions. The previous hazard related to worker injuries is only due to machinery and not workers carelessness. The consequence of the current hazard is that the workers could fall into entry or exit pits, or creeks and other large water bodies across which a pipeline is being installed using HDD due to inattentive behavior of the worker in reacting to the job site conditions.

Four critical factors were determined to be influencing the probability of occurrence of H4 hazard. The factors are briefly described in the following paragraphs:
**F1 - Experience of the worker on job site:**

Like any other hazard, the safety risk of “Workers falling into excavated pits” is also expected to be strongly influenced by the “Experience of the worker on job site”.

**F3 - Inappropriate/Lack of communication mechanism among the crew:**

Inappropriate real-time communication and lack of adequate training may also lead to Workers falling into excavated pits, and it is therefore identified as a critical factor.

**F8 - Lack of proper barricading around the pits and alarms:**

Safety on the job site is maintained by following a few minimum safety regulations. It is identified from the review of a few past projects that lack of proper barricading around the excavated pits and alarms influence the safety risk of a HDD operation.

**F9 - Behavior and postures of the workers during the drilling operation:**

The posture of workers on HDD projects, especially when they are pushed to be more productive, could become unsafe and may lead to them falling into pits or trenches. OSHA and the United States Department of Labor have set some guidelines to avoid accidents in such job site conditions.

The following is an example of a past HDD project where this hazard occurred:

i. During the mid-spring of 2008, a crew was using a Horizontal Directional Drilling (HDD) machine to install a water line along a rural Iowa roadway. After completion of the pilot bore phase, the worker who was 600ft away from the drill rig operator removed the drill bit from the exit pit to attach a back reamer to the end of the drill
rod. Before the worker set his position away from the rig, the drill rig operator started back-reaming operation. When the drill rig operator was asking the worker at the exit side for the reamers progress, he apparently discovered the victim’s body wrapped around the drill line in the area of the pre-cutter just ahead of the back reamer (University of IOWA, 2008).

3.3 HDD Project Characteristics that influence safety risk

While the hazards and factors identified hitherto are generic in nature, they are influenced by the specific characteristics of any HDD project. Characteristics are tied to the factors in the hierarchical risk assessment methodology. Several characteristics for each factor are identified in the following:

F₁ - Experience of the drilling contractor.

C₁ - Less than 3 years

C₂ - 3 to 7 years

C₃ - 7 to 10 years

C₄ - More than 15 years

F₂ - Accuracy of Sub surface Utility Engineering (SUE).

C₁ – Quality Level D (per ASCE 38-02): Information collected from existing records or oral recollection of existing utility holders
C2 – Quality Level C (per ASCE 38-02): Information gathered from surveying and by plotting utility features existing above ground/Use of professional judgement in correlating this information to quality level D

C3 – Quality level B (per ASCE 38-02): Information obtained by application of surface geophysical methods to determine the existence and approximate positioning of utilities in horizontal direction

C4 – Quality level A (per ASCE 38-02): Information regarding the horizontal and vertical location of utilities through actual exposure and measurement of subsurface utilities generally at a specific point

F3 - Inappropriate/Lack of communication mechanism among the crew.

C1 – Low Quality walk over system due to which obstacles where physical walk over is difficult

C2 – High Quality of the walk over system operated by skilled labor

C3 – Interference with the magnetic fields from the underground buried power lines due to quality of walk over system

C4 – A non-skilled locator operating a high quality walk over system/Improper Basics of reading and interpreting the signals.

F4 - Age of the tool used for the HDD operation.

C1 - More than 10 years

C2 - 7 to 10 years
C3 - 3 to 7 years

C4 - Less than 3 years

F5 - Exceeding the force limits of the drill rig.

C1 - Inexperienced operator performing the boring operation in maintaining the limits of buffer capacity of the drill rig

C2 - Experienced operator performing the boring operation in maintaining the limits of buffer capacity of the drill rig

C3 - Machinery problem.

F6 - Lack of PPE.

C1 - Lack of certain PPE availability on site to replace the damaged ones.

C2 - Unsuitability of the available PPE for that particular operation.

F7 - Unsuitable apparel for the work conditions.

C1 - Improper clothing of the worker whether it is material or type (wet/dry)

C2 - Attention to each other among the crew on the job site due to lack of high visibility clothing

F8 - Lack of proper barricading around the excavated pits and alarms.

C1 - Lack of Backfill/Adequate barrier around temporary wells, pits, shafts, etc.

C2 - Warning lines with high visibility material and low intensity sound of the alarm
F9 - Behavior and posture of the worker in the job conditions.

C1 - Mental Stability of the worker.

C2 - Physical Stability of the worker

C3 - Level of training of the worker received and experience of the worker.

3.4 Description of the Hierarchical Risk Assessment Methodology

In this pursuit, attributes influencing each hazard are known from a limited number of case studies, but there is dearth of quantitative data to develop relationship functions between the hazards and the influential factors.

A tree diagram presented in the Figure 3.2 represents the hierarchy of the hazards, influential factors and the project characteristics considered for the generation of “Hierarchical Risk Assessment” framework.
Figure 3.2. Hierarchical representation of the hazards, influential factors and the project characteristics.
A very minimum historic data is available on the factors and hazards used for this framework. In order to address this limitation a pair wise comparative questionnaire survey is prepared with five qualitative answer choices for each question. An example question in this survey is:

Q) Relative to the factor “wrongly marked utilities,” how significantly will the factor “experience of the operator performing the boring operation” contribute to the occurrence of “hit other utility” hazard?

(a) Very high
(b) Somewhat high
(c) Equal
(d) Somewhat Low
(e) Very Low

The complete questionnaire survey for understanding the influence of factors on the hazards is included in Appendix A. A similar questionnaire was used for the determining the relative influence of characteristics on the factors.

Experts having similar level of experience with HDD projects are invited to answer the questionnaire by choosing one option as their choice for each question. Their responses are later converted into quantitative numbers by use of the rating chart shown in Table 3.1.

Based on the experts’ responses and their subsequent conversion to quantitative ratings as per Table 3.1, relative influential measures (in percentages) of various factors on the hazards and similarly various characteristics on each factor (refer to the hierarchy in Figure 3.2) are estimated. The relative influential measures are estimated based on pairwise
comparison judgments and the resulting priority vector (Rangone, 1996; Saaty, 2003). Such pair-wise judgments are helpful where no quantitative data is available, which is the case in the risk assessment framework proposed in this study.

**Table 3.1. Rating Chart for Quantifying Questionnaire Responses**

<table>
<thead>
<tr>
<th>Qualitative Terms</th>
<th>Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high</td>
<td>3</td>
</tr>
<tr>
<td>Somewhat high</td>
<td>2</td>
</tr>
<tr>
<td>Equal</td>
<td>1</td>
</tr>
<tr>
<td>Somewhat Low</td>
<td>1/2</td>
</tr>
<tr>
<td>Very Low</td>
<td>1/3</td>
</tr>
</tbody>
</table>

For a given HDD Project, considering the job site details, crew details, durations, safety details, equipment details, the probability of occurrence of the hazard are estimated from the relative influence of factors on respective hazards and relative influence of characteristics on respective factors. The percentage influence values, i.e. the priority vector (Saaty, 2003), are derived from the questionnaire responses, as illustrated in Tables 3.2 and 3.3 for the influence of $F_1$, $F_2$ and $F_3$ on $H_1$. Table 3.4 presents the priority vector values which reflect the estimated relative influence of $F_1$, $F_2$ and $F_3$ on $H_1$. 
Table 3.2. Expert responses (quantitative) for the influence of factors F₁, F₂ and F₃ on H₁ hazard

<table>
<thead>
<tr>
<th></th>
<th>Hazard – 1 (H₁)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F₁₂</td>
</tr>
<tr>
<td>E₁</td>
<td>1</td>
</tr>
<tr>
<td>E₂</td>
<td>0.5</td>
</tr>
<tr>
<td>E₃</td>
<td>1</td>
</tr>
<tr>
<td>E₄</td>
<td>0.5</td>
</tr>
<tr>
<td>E₅</td>
<td>0.3</td>
</tr>
<tr>
<td>Avg. (E₁:E₅)</td>
<td>0.66</td>
</tr>
</tbody>
</table>

In Table 3.2,

E = Expert

F₁₂ = Influence of F₁ on H₁ compared to F₂; F₂₁ = 1/F₁₂

F₂₃ = Influence of F₂ on H₁ compared to F₃; F₃₂ = 1/F₂₃

F₁₃ = Influence of F₁ on H₁ compared to F₃; F₃₁ = 1/F₁₃

Avg. (E₁:E₅) = Average of all the responses

Table 3.3. Priority vector calculation (part 1)

<table>
<thead>
<tr>
<th>Factors</th>
<th>F₁</th>
<th>F₂</th>
<th>F₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₁</td>
<td>1</td>
<td>0.66</td>
<td>2.26</td>
</tr>
<tr>
<td>F₂</td>
<td>1.51</td>
<td>1</td>
<td>1.76</td>
</tr>
<tr>
<td>F₃</td>
<td>0.44</td>
<td>0.56</td>
<td>1</td>
</tr>
<tr>
<td>Sum</td>
<td>2.95</td>
<td>2.26</td>
<td>5.02</td>
</tr>
</tbody>
</table>

The priority vector is calculated by taking average of each row in Table 3.4.
### Table 3.4. Priority vector calculation (part 2)

<table>
<thead>
<tr>
<th>Factors</th>
<th>F₁</th>
<th>F₂</th>
<th>F₃</th>
<th>Priority Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₁</td>
<td>1/2.95</td>
<td>0.66/2.26</td>
<td>2.26/5.02</td>
<td>0.3616</td>
</tr>
<tr>
<td>F₂</td>
<td>1.51/2.95</td>
<td>1/2.26</td>
<td>1.76/5.02</td>
<td>0.4375</td>
</tr>
<tr>
<td>F₃</td>
<td>0.44/2.95</td>
<td>0.56/2.26</td>
<td>1/5.02</td>
<td>0.2007</td>
</tr>
</tbody>
</table>

Similarly, Priority Vectors are calculated to represent the influence of respective factors on other hazards, and the influence of project characteristics on the factors. Summarized survey responses that are used in performing the calculations of Priority Vectors are included in Appendix B. The hierarchical illustration presented in Figure 3.3 shows the estimated influence of various characteristics on the factors and similarly the influence of factors on the hazards.

The probability of occurrence (PO) of a hazard can be calculated using Eq. 3.

\[
\text{PO of any Hazard, } H_i = \sum_{a_i}(F_{a_i} \times C_{Fa})
\]  

(3)

Where 

\(H\) = Hazard;

\(i\) = Index of a given hazard;

\(a\) = Index of the specific factor that influences hazard \(i\);

\(F_{a_i}\) = Priority vector value of the respective factor \(F_a\) that influences hazard \(i\);

\(C_{Fa}\) = Priority vector value of the characteristic chosen for a given factor \(F_a\);
Figure 3.3. Hierarchical representation of the hazards, relative influential factors and the project characteristics.
CHAPTER 4: RESULTS AND ANALYSIS

This Chapter presents the description of two mini HDD projects and the findings from the demonstration of the HRA framework on them.

4.1 Case Study 1: Anderson, SC.

This construction project entails installing a 2” high density polyethylene (HDPE) water service line using horizontal directional drilling (HDD) method. The water service line connects the water main to a residential dwelling in Anderson, SC through a recently installed water meter. The dwelling is located at a significant higher elevation compared to the water meter and the average depth of installation is about 6ft. This case study analyzes only the pilot hole drilling part of this HDD project. All the data was recorded in person on the day of drilling which was 10th February of 2016.

Construction Operational Planning

The contractor chose to use a Mini HDD drill rig for this project to install the 2” HDPE pipeline through lean clay of low plasticity (i.e., CL type as per USCS classification). The contractor employed a two-person crew for this job with one operating the drill rig (hereafter referred as crew member A) and other locating the drill head and monitoring the drill path (hereafter referred as crew member B). It should be noted that the weather was not very supportive on the day of drilling with a recorded temperature of -4°C (or ≈ 25°F). The construction equipment and materials on the project site includes a D9x13 S3 Navigator Horizontal Directional Drill Rig, a fluid tank, drilling fluid, a manually-operated walk over system, 2” HDPE pipe spool, and a truck carrying various spare parts.
The drill rig used in this project, which is shown in Figure 4.1, has rated capacities of 13,000 ft-lb rotational torque and 9,000 lbs. of thrust and pull back forces. The fluid mixing tank, which is shown in Figure 4.2, has a capacity of 500 gallons. The 2” HDPE pipe spool, which is depicted in Figure 4.3, is of Schedule 40 type. The site layout is depicted in Figure 4.4.

Figure 4.1. D 9x13 S3 Navigator Horizontal Directional Drill
Figure 4.2. A 500-gallon fluid mixing tank
Figure 4.3. 2" HDPE Pipe Spool
Construction Challenges

The reason for including this case study in this thesis despite the fact that it covers only the pilot-hole drilling phase of the project is because of the unique challenges it presented in terms of existing subsurface utilities and jobsite landscape. There were four existing utility lines in the direction of the drill path which were marked by the respective utility departments prior to drilling; these include a gas line (marked in yellow, as shown in Figure 4.5), a drinking water line (marked in blue, as shown in Figure 4.5), a
communications line (marked in orange, as shown in Figure 4.5), and a power line (marked in red, as shown in Figure 4.6).

Figure 4.5. Water, gas and communications utility markings on the project site (White arrow indicates the drilling direction)
While the gas, communications and water lines did not prove to be conflicting with the proposed drill path, the power line which also crosses the creek from beneath posed a major conflict that resulted in re-initiating the drilling activity six times before it went smoothly. The challenge was to set the angle of entry for the pilot bore in such a way that the drill string maintains a safe distance from the power line (above or below) and at the same time stays at a safe depth beneath the creek and not hit the creek wall which is made up of rocks. As can be observed from the illustration presented in Figure 4.7, the drill path either had to be over the power line and under the rocks or much deeper than the power line and the rocks. Drilling at greater depths is not an option as the drilling radius is constrained by the equipment, and the dwelling to which a water line connection is being made is at a much higher elevation beyond the creek.
Figure 4.7. Illustration of the construction challenge associated with drilling under the creek wall and above the power line.

Another factor that exacerbated this challenge is the fact that there is no data available on the depth of the power line. Due to lack of data on the depth of the power line, the project crew had to employ a reasonably risky approach of trial and error with the objective of going over the power line and underneath the creek wall. To minimize the risk of hitting the power line, the crew had to constantly stop and evaluate the possibility of closer proximity to the power line by attempting to even expose the power line at times, as shown in Figure 4.8.
Figure 4.8. Crew members trying to expose the power line while the drilling is suspended

Due to the perceived risk, the crew decided to change the position and orientation (i.e., angle of entry) of the drill rig six times before they were able to overcome the hurdle of safely crossing the power line and the creek. In a few earlier attempts, the operator drilled through the soil up until the location of the power line and then the drilling had to be abandoned for the fear of close proximity in depth to the power line. In other earlier attempts, the operator drilled through the soil much deeper than the expected depth of the
power line but couldn’t get the drill string to a desired depth underneath the creek. The position and/or orientation of the drill rig had changed in each of the six attempts.

During the multiple failed attempts to safely navigate the subsurface and other constraints, some unsafe behavior, especially of crew member B, was observed. In an attempt to be efficient, the crew member B had leaned on to a tree dangerously closer to the creek, as shown in Figure 4.9, to estimate the depth of the drill head as it entered the creek.
Figure 4.9. A picture showing the crew member B hanging on to a tree closer to the creek

Although there were no accidents on this job, crew member B could have slipped or lost support from the tree branch he was hanging on to and may have fallen into the creek. This observation clearly relates to the Hazard 4 – Workers falling into pits as a result of their behaviors and postures – discussed in Chapter 3 as part of the Hierarchal Risk Assessment methodology. In such situations, the crew member could have used a more stable support or used some kind of protective equipment. The operational planning could
have also been better with safety risks such as this eliminated with better work organization and planning.

Contamination of creek water from the intrusion of drilling fluid was also observed in some of the failed attempts to drill underneath the creek. The drill head had pierced through the rocks at the surface level and as a result the drilling fluid mixed with the excavated soil is released into the creek water, as can be observed from Figure 4.10. The inadvertent release of drilling fluid into a water body is a major environmental concern (Ariaratnam et al., 2007) due to the effects of the drilling fluid additives and soil on the aquatic life in these water bodies. The operating crew could have easily avoided this by adopting the best practices for drilling under water bodies (Bennett and Ariaratnam, 2008).
Data Collection

The data necessary for performing the safety risk analysis of this HDD job was collected through personal observation and also through a brief interview of the drill rig operator who seemed to be the superintendent on the jobsite. The collected data is presented in Tables 4.1 to 4.5.
### Table 4.1. Job Site Details

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of the Job site</td>
<td>Anderson, SC</td>
</tr>
<tr>
<td>Date</td>
<td>2/10/2016</td>
</tr>
<tr>
<td>Season and weather conditions</td>
<td>Spring, -4°C (or ≈ 25°F).</td>
</tr>
<tr>
<td>Work timings</td>
<td>10:00 AM -</td>
</tr>
<tr>
<td>Length of the Bore hole</td>
<td>200 ft.</td>
</tr>
<tr>
<td>Depth of Installation</td>
<td>6 ft. (average)</td>
</tr>
<tr>
<td>Soil conditions</td>
<td>Low plasticity, Lean clay (CL)</td>
</tr>
<tr>
<td>Obstacles along the bore hole</td>
<td>One water body</td>
</tr>
<tr>
<td>Utility lines located in the surroundings</td>
<td>Gas, communications, power and water lines</td>
</tr>
<tr>
<td>Level of accuracy of SUE</td>
<td>Level 2</td>
</tr>
<tr>
<td>Number of excavated pits</td>
<td>2 (Entry pit, Exit pit)</td>
</tr>
<tr>
<td>Traffic around the work site</td>
<td>No traffic</td>
</tr>
</tbody>
</table>

### Table 4.2. Crew Details

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of workers at Entry pit</td>
<td>1</td>
</tr>
<tr>
<td>Number of workers at Exit pit</td>
<td>1</td>
</tr>
<tr>
<td>Position of the crew</td>
<td>Person A at the drill rig, person B monitoring the drill head</td>
</tr>
</tbody>
</table>

### Table 4.3. Durations

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot bore phase</td>
<td>10:00 To .......</td>
</tr>
<tr>
<td>Reaming phase</td>
<td>N/A</td>
</tr>
<tr>
<td>Pull back phase</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Table 4.4. Equipment Details

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type and Diameter of the pipe</td>
<td>2” HDPE Pipe</td>
</tr>
<tr>
<td>Amount of fluid used for operation</td>
<td>500 Gallons</td>
</tr>
<tr>
<td>Drill fluid return timings</td>
<td>No returns</td>
</tr>
<tr>
<td>Torque</td>
<td>13,000 ft-lb.</td>
</tr>
<tr>
<td>Pull back</td>
<td>9,000 lbs.</td>
</tr>
<tr>
<td>Type of Communication System</td>
<td>Walk over system</td>
</tr>
<tr>
<td>Angle of the drill rig at the entrance</td>
<td>20°</td>
</tr>
<tr>
<td>Age of the tools used in the operation</td>
<td>3 Years</td>
</tr>
</tbody>
</table>

Table 4.5. Safety Details

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPE of the Labor</td>
<td>Leather clothing, Shoes, Hat</td>
</tr>
<tr>
<td>Type of barricading around the job site</td>
<td>N/A</td>
</tr>
<tr>
<td>Unsafe behavior and posters of the workers</td>
<td>One (Hanging to the branches of the tree)</td>
</tr>
<tr>
<td>Safety Regulations followed by the crew</td>
<td>None</td>
</tr>
<tr>
<td>Color of clothing</td>
<td>N/A</td>
</tr>
<tr>
<td>Material of the Clothing</td>
<td>Leather as it is cold</td>
</tr>
<tr>
<td>Number of warning lines around the job site</td>
<td>1</td>
</tr>
</tbody>
</table>

Analysis:

Based on the data collected for the pilot-hole phase of this mini HDD project, safety risk is estimated using the Hierarchical Safety Risk Assessment approach described in Chapter 3. Characteristics are chosen for each factor based on the data from Tables 4.1 through 4.5 and presented in Table 4.6. The relative percentage preferences of the characteristics in terms of their safety attributes, which are derived from a survey of HDD contractors, are also presented in Table 6.
Table 4.6. Characteristics and Corresponding Percentage Scores for each Factor

<table>
<thead>
<tr>
<th>Factor</th>
<th>Characteristic</th>
<th>Weightage</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1 - Experience of the operator performing the boring operation</td>
<td>C4 - More than 10 years</td>
<td>16.36%</td>
</tr>
<tr>
<td>F2 - Accuracy of SUE</td>
<td>C4 - Quality level B (per ASCE 38-02): Information obtained by application of surface geophysical methods to determine the existence and approximate positioning of utilities in horizontal direction.</td>
<td>25.96%</td>
</tr>
<tr>
<td>F3 - Failure in Communication mechanism</td>
<td>C2 - Good quality walk over system operated by the skilled labor</td>
<td>21.52%</td>
</tr>
<tr>
<td>F4 - Age of the tools used for the operation</td>
<td>C2 – 3 to 7 years</td>
<td>24.05%</td>
</tr>
<tr>
<td>F5 - Increased Torque/drag/Rotational Speed of the drill rig</td>
<td>C1 - Experience of the operator performing the boring operation in maintaining the limits of buffer capacity of the drill rig</td>
<td>25.54%</td>
</tr>
<tr>
<td>F6 - Lack of PPE</td>
<td>C1 - Unsuitable material / Color of the clothing</td>
<td>43.30%</td>
</tr>
<tr>
<td>F7 - Unsuitable apparel for the work conditions</td>
<td>C2 - Attention towards the worker on the job site due to lack of High visibility Clothing</td>
<td>47.61%</td>
</tr>
<tr>
<td>F8 - Lack of Proper barricading around the excavated pits</td>
<td>C1 - Lack of Backfill / Adequate barrier around temporary wells, pits, shafts, etc.</td>
<td>50.78%</td>
</tr>
<tr>
<td>F9 - Behavior and Posture of the workers</td>
<td>C3 - Physical Stability of the worker</td>
<td>37.44%</td>
</tr>
</tbody>
</table>

The probability of occurrence of various hazards is calculated based on the characteristic scores along with the relative weightings of factors for each hazard. Figure 4.11 shows a hierarchical tree diagram with percentages values for each factor under each hazard and for each characteristic under each factor. The probability of occurrence of a hazard in case of an accident can be calculated using Eq. 3.
Figure 4.11. The probabilities of occurrence of various hazards derived from the data of case study #1
It can be observed from the results that the probabilities of occurrence of the four hazards are not high, which is a comforting fact. Hazards 3 and 4 have relatively high values of estimated probabilities of occurrences of 0.33 and 0.29 respectively, followed by Hazard 1 with 0.21 and finally Hazard 2 with 0.18. The following can be inferred from the findings of the HRA approach employed on the mini HDD project in case study #1:

1. The probability of occurrence of Hazard 1, Hit other utilities, is low mainly due to:
   (a) significant experience of the drill rig operator that made him cautious of this hazard, as evidenced by the adjustments made in this case study, and (b) the use of appropriate communication systems that reliably relay data on the drill head position. These considerations were very much in line with the expected safety standards. The significant issue in this case study, however, is the lack of adequate sub-surface utility engineering data, especially the depth of the conflicting power utility. If the power utility depth was known, the contractor would not have faced the issues that he did in drilling above the power line.

2. The probability of occurrence of Hazard 2 is also found to be very low, mainly due to the facts that the used HDD equipment is not very old, the operator is experienced and was careful enough to be within the limits of the thrust and torque loads. Furthermore, HDD is expected to do well with clayey soils that existed in this case study, thereby not making this it a challenging soil cutting job.

3. The probability of occurrence of Hazard 3, Injury to workers is found to be high although the workers are well experienced in HDD projects. This is mainly due to lack of appropriate apparel such as high visibility clothing and also lack of PPE
such as head protection, both of which are most influential factors as described in the chapter 3 for the hazard, Injury to workers.

4. The probability of occurrence Hazard 4, Workers falling into excavated pits is found to be slightly lower than that of Hazard 3. Hazard 4 was aggravated by: (a) Lack of barricaders around the creek, (b) unsafe posture of the worker noticed when he is tried to reach over and the creek to monitor the drill head position. However, knowing the depth of power line burial would have prevented the unsafe behavior of crew member B in this case study.

4.2 **Case Study 2: AnMed Health Women's & Children's Hospital, Anderson, SC.**

This construction project entails installing a 1” high density polyethylene (HDPE) electric service line using horizontal directional drilling (HDD) method. The electric service line connects the grid to a lake down the AnMed Health Women's & Children's Hospital, Anderson, SC. The average depth of installation is about 10ft. This case study analyzes pilot bore and Pull back phase of the HDD project. All the data was recorded in person on the day of drilling which was 5th May, 2016.

**Construction Operational Planning**

The contractor chose to use Mini HDD drill rig for this project to install the 1” HDPE pipeline through lean clay of low plasticity (i.e., CL type as per USCS classification). The contractor employed a two-person crew for this job with one operating the drill rig (hereafter referred as crew member A) and other locating the drill head and
monitoring the drill path (hereafter referred as crew member B). The weather was supportive on the day of drilling with a recorded temperature of 18°C (or ≈ 64.4°F). The construction equipment and materials on the project site includes a D 9x13 S3 Navigator Horizontal Directional Drill Rig, a fluid tank, drilling fluid, a manually-operated walk over system, 1” HDPE pipe spool, and a truck carrying various spare parts. Several of these tools are similar to those used in the first case study. The drill rig used in this project has rated capacities of 13,000 ft-lb rotational torque and 9,000 lbs. of thrust and pull back forces. The fluid mixing tank, which is shown in Figure 4.12, has a capacity of 500 gallons. The 1” HDPE pipe spool is depicted in Figure 4.13 and the truck carrying various accessories and tools is shown in Figure 4.14. The site layout is depicted in Figure 4.15.

![Figure 4.12. A 500-gallon fluid mixing tank](image)
Figure 4.13. 1" HDPE pipe spool
Figure 4.14. Truck with spare parts
Construction Challenges

There were no unique construction challenges faced on the day of drilling as a brief job site survey was conducted prior to start of drilling process and depth of the existing utility lines were clearly marked by the respective utility departments, as shown in the Figure 4.16. This case study covers pilot-hole drilling phase and pull back phase of the project. There were three existing utility lines in the direction of the drill path which were marked by the respective utility departments prior to drilling; these include a power line (marked in Red, as shown in Figure 4.16), a drinking water line (marked in blue, as shown in Figure 4.16), and a communications line (marked in orange, as shown in Figure 4.17).
Figure 4.16. Water and Power utility markings on the project site

Figure 4.17. Power and communication utility markings on the project site
The drilling operation went smoothly in both pilot bore and reaming phases without any disturbances. There were also no obstacles and disturbance along the drill path, and the risk of “hitting other utilities” was negligible, as there were no existing utilities in the planned drill path.

The position and the orientation of the drill rig were appropriate and didn’t need to be changed throughout the drilling process which helped the operation go smoothly. The safety on the job site is maintained well enough as per the traffic conditions by arranging safety cones as shown in the Figure 4.18.

![Safety cones arranged to shut the traffic for duration of the work](image)

**Figure 4.18.** Safety cones arranged to shut the traffic for duration of the work

Though the site was inspected by the contractor before the day of drilling, some unsafe behavior in terms of working posture of the crew member B was observed at the
exit pit as shown in the Figure 4.19. After the successful completion of the operation, the crew member B was working with a compact excavator in between the bushes to fill the excavated exit pit to even the ground surface. It seemed to be an unsafe act by crew B as the area where the compact excavator is placed is not clear enough to perform such work.

Figure 4.19. A picture showing the crew member B filling the excavated pit
The picture shown in the Figure 4.20 relates to the Hazard 3 – Injury to workers (as a result of lack of PPE) - which was discussed in Chapter 3 as part of the Hierarchal Risk Assessment methodology. In such situations, the crew member could have either used an appropriate helmet or simply could have done the job from other safe direction. The operational planning could have also been better with safety risks such as this eliminated with better work organization and planning.

**Data Collection**

The data necessary for performing the safety risk analysis of this HDD job was collected through personal observation and also through a brief interview of the drill rig operator who seemed to be superintendent on the jobsite. The collected data is presented in Tables 4.7 to 4.11.
### Table 4.7. Job Site Details

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of the Job site</td>
<td>Anderson, SC</td>
</tr>
<tr>
<td>Date</td>
<td>5/5/2016</td>
</tr>
<tr>
<td>Season and weather conditions</td>
<td>Spring, 18(^0) C (or (\approx) 64(^0)F).</td>
</tr>
<tr>
<td>Work timings</td>
<td>9:45 AM – 11:00 AM</td>
</tr>
<tr>
<td>Length of the Bore hole</td>
<td>455 ft.</td>
</tr>
<tr>
<td>Depth of Installation</td>
<td>10 ft. (average)</td>
</tr>
<tr>
<td>Soil conditions</td>
<td>Low plasticity, Lean clay (CL)</td>
</tr>
<tr>
<td>Obstacles along the bore hole</td>
<td>-</td>
</tr>
<tr>
<td>Utility lines located in the surroundings</td>
<td>Communications, power and water lines</td>
</tr>
<tr>
<td>Level of accuracy of SUE</td>
<td>Level 2</td>
</tr>
<tr>
<td>Number of excavated pits</td>
<td>2 (Entry pit, Exit pit)</td>
</tr>
<tr>
<td>Traffic around the work site</td>
<td>No traffic</td>
</tr>
</tbody>
</table>

### Table 4.8. Crew Details

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of workers at Entry pit</td>
<td>1</td>
</tr>
<tr>
<td>Number of workers at Exit pit</td>
<td>1</td>
</tr>
<tr>
<td>Position of the crew</td>
<td>Person A at the drill rig, person B monitoring the drill head</td>
</tr>
</tbody>
</table>

### Table 4.9. Durations

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot bore phase</td>
<td>09:45 AM to 10:15 AM</td>
</tr>
<tr>
<td>Reaming phase</td>
<td>N/A</td>
</tr>
<tr>
<td>Pull back phase</td>
<td>10:25 AM to 11:00 AM</td>
</tr>
</tbody>
</table>
Table 4.10. Equipment Details

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type and Diameter of the pipe</td>
<td>1” HDPE Pipe</td>
</tr>
<tr>
<td>Amount of fluid used for operation</td>
<td>500 Gallons</td>
</tr>
<tr>
<td>Drill fluid return timings</td>
<td>No returns</td>
</tr>
<tr>
<td>Torque</td>
<td>13,000 ft-lb.</td>
</tr>
<tr>
<td>Pull back</td>
<td>9,000 lbs.</td>
</tr>
<tr>
<td>Type of Communication System</td>
<td>Radio</td>
</tr>
<tr>
<td>Angle of the drill rig at the entrance</td>
<td>30°</td>
</tr>
<tr>
<td>Age of the tools used in the operation</td>
<td>1 Year</td>
</tr>
</tbody>
</table>

Table 4.11. Safety Details

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPE of the Labor</td>
<td>Leather clothing, Safety vest, Shoes, Hat</td>
</tr>
<tr>
<td>Type of barricading around the job site</td>
<td>Safety Cones</td>
</tr>
<tr>
<td>Unsafe behavior and posters of the workers</td>
<td>One ( working under the trees to clear the ground surface )</td>
</tr>
<tr>
<td>Safety Regulations followed by the crew</td>
<td>OSHA</td>
</tr>
<tr>
<td>Color of clothing</td>
<td>N/A</td>
</tr>
<tr>
<td>Material of the Clothing</td>
<td>Leather Jackets</td>
</tr>
<tr>
<td>Number of warning lines around the job site</td>
<td>1</td>
</tr>
</tbody>
</table>

Analysis

Based on the data collected for the pilot-hole and Pull-back phases of this mini HDD project, probabilities of occurrence of various hazards are estimated using the Hierarchical Safety Risk Assessment (HRA) approach that was described in Chapter 3. Characteristics are chosen for each factor based on the data from Tables 4.7 through 4.11 and presented in Table 4.12. The relative percentage preferences of the characteristics in terms of their safety attributes, which are derived from a survey of HDD contractors, are also presented in Table 4.12.
**Table 4.12. Characteristics and Corresponding Percentage Scores for each Factor**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Characteristic</th>
<th>Weightage</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1 - Experience of the operator performing the boring operation</td>
<td>C4 - More than 10 Years</td>
<td>16.36%</td>
</tr>
<tr>
<td>F2 - Accuracy of SUE</td>
<td>C3 - Quality level B (per ASCE 38-02): Information obtained by application of surface geophysical methods to determine the existence and approximate positioning of utilities in horizontal direction</td>
<td>21.52%</td>
</tr>
<tr>
<td>F3 - Failure in Communication mechanism</td>
<td>C2 - Good quality walk over system operated by the skilled labor</td>
<td>21.52%</td>
</tr>
<tr>
<td>F4 - Age of the tools used for the operation</td>
<td>C1 – Less than 3 years</td>
<td>13.70%</td>
</tr>
<tr>
<td>F5 - Increased Torque/drag/Rotational Speed of the drill rig</td>
<td>C1 - Experience of the operator performing the boring operation in maintaining the limits of buffer capacity of the drill rig</td>
<td>25.54%</td>
</tr>
<tr>
<td>F6 - Lack of PPE</td>
<td>C1 – Unsuitable material / Color of the clothing</td>
<td>43.30%</td>
</tr>
<tr>
<td>F7 - Unsuitable apparel for the work conditions</td>
<td>C1 – Improper clothing/PPE of the worker</td>
<td>52.38%</td>
</tr>
<tr>
<td>F8 - Lack of Proper barricading around the excavated pits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F9 – Behavior and Posture of the workers</td>
<td>C3 – Level of Training received by the worker</td>
<td>37.44%</td>
</tr>
</tbody>
</table>

The probability of occurrence of various hazards is estimated based on the characteristic scores along with the relative weightings of factors for each hazard. Figure 4.21 shows a hierarchy tree diagram with percentages values for each factor under each hazard and for each characteristic under each factor. Probability of occurrence any hazard can be calculated using Eq. 3.
Figure 4.21. The probabilities of occurrence of various hazards derived from the data of case study #2
As can be observed from Figure 4.21, the probabilities of occurrence of various hazards are not significantly high with the maximum value being 0.33. Some inferences based on these findings:

1. The probability of occurrence of Hazard 1, Hit other utilities, is 0.20 in this case study. This low value is mainly due to: (a) Accuracy of the SUE marking, (b) the use of appropriate communication systems that reliably relay data on the drill head position. These considerations were very much in line with the expected safety standards. There were no significant construction challenges as the drill path was carefully planned before the start of actual drilling.

2. The probability of occurrence of Hazard 2, Stall/ Breakage of the drill string/drill head is significantly low with a value of 0.18. The reason behind this is: (a) use of drill tools with good age criteria, (b) significant experience of the drill rig operator that made the operation go successfully in estimated time. However, proper planning of the drilling activity in each phase has also helped the crew to perform the job without facing surprising challenges.

3. The probability of occurrence of Hazard 3, Injury to workers is relatively high at 0.33 and it is mainly aggravated by: (a) the unsafe behavior exhibited by the worker B at the end of the operation while leveling the ground surface using a back-hoe, and (b) due to lack of suitable PPE for performing such an activity.

4. The probability of occurrence of Hazard 4, Workers falling into excavated pits has a low value of 0.16 because appropriate safety procedures such as placing of safety
cones along the length of the obstacles and excavated pits to avoid general public or workers moving in closer proximities of the pits were followed.
CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

Safety is of primary importance in any construction operation. Safe working environment promotes the wellbeing of the crew, decreases equipment and infrastructure damage and its associated costs. Although HDD construction method has helped with urban infrastructure development, there is still a need to evaluate the practices in the context of safety risk to workers, infrastructure and HDD equipment. To address this limitation this study proposed and demonstrated the Hierarchical Risk Assessment methodology using two HDD projects happened in the State of South Carolina. This research has made a good attempt to evaluate the risk of HDD projects. Extended research in this area in the near future will help in mitigating the safety risk further more.

The hierarchical risk assessment methodology entails the identification of specific hazards, factors that influence the hazards and the project characteristics that aggravate the safety risk characterized through the hazards and the influential factors. Four hazards, nine factors and several project characteristics have been identified in this study to investigate the safety risk of HDD projects; a review of case studies of accidents on past HDD projects informed the selection of the hazards and factors in this study. Experts are surveyed to quantify the influence of factors on the hazards and the characteristics on the factors using the basic principles of analytical hierarchy process.

The hierarchical risk assessment methodology has been demonstrated on two mini HDD projects which entailed installing small diameter pipelines in residential communities. Findings demonstrated the utility of the proposed “Hierarchical Risk
Assessment” (HRA) Methodology in assessing the probabilities of occurrence of various hazards on HDD projects. Furthermore, the evaluation process is easy and less time consuming after required data inputs are obtained. Knowing the safety risk value, necessary care can be taken to mitigate the hazards.

5.1 **Limitations of the study:**

1. A major limitation of this study is that the HRA methodology uses expert opinions alone for determining the percentage influence values for factors influencing hazards and characteristics influencing factors. And these opinions are subjective and lack evidence.

2. Another limitation is that responses from only five experts have been used to tabulate the priority vectors that were later used in assessing the probabilities of occurrence of HDD hazards. Basing the methodology on only five experts’ opinion may have not produced a very reliable priority vectors.

3. The lack of consideration of other hazards that may be significant is another limitation. The four hazards considered in this study are based on a brief review of the past HDD accident histories and not many accidents are well reported with all the factors leading to them clearly identified. Similarly, the factors used in this study may very well not be a exhaustive list.

4. The demonstration of the methodology is also limited in terms of the size of the HDD projects. The two case studies presented in this study are very small diameter (≤2 inches diameter) service line installations, and more informative findings would have been obtained if the methodology would have been demonstrated on HDD projects that installed
large diameter pipelines. The methodology would also be more useful for large diameter pipeline installation projects which are more intense.
REFERENCES


APPENDIX - A
**Questionnaire:** Comparative Questionnaire Survey for factors influencing hazards.

1) Relative to the factor “Accuracy of Sub surface utility Engineering (SUE),” how significantly will the factor “Experience of the worker on job site” contribute to the occurrence of “Hitting other utilities” hazard.

a) Very high  
(b) Somewhat high  
(c) Equal  
(d) Somewhat Low  
(e) Very Low

2) Relative to the factor “Inappropriate/Lack of communication mechanism among the crew,” how significantly will the factor “Accuracy of Sub surface utility Engineering (SUE)” contribute to the occurrence of “Hitting other utilities” hazard.

a) Very high  
(b) Somewhat high  
(c) Equal  
(d) Somewhat Low  
(e) Very Low

3) Relative to the factor “Inappropriate/Lack of communication mechanism among the crew,” how significantly will the factor “Experience of the worker on job site” contribute to the occurrence of “Hitting other utilities” hazard.

a) Very high  
(b) Somewhat high  
(c) Equal  
(d) Somewhat Low  
(e) Very Low
4) Relative to the factor “Age of the tools used for the HDD operation,” how significantly will the factor “Experience of the worker on job site” contribute to the occurrence of “Stall/breakage of drill string/drill head” hazard.

a) Very high
(b) Somewhat high
(c) Equal
(d) Somewhat Low
(e) Very Low

5) Relative to the factor “Exceeding the force limits of the drill rig,” how significantly will the factor “Age of the tools used for the HDD operation” contribute to the occurrence of “Stall/breakage of drill string/drill head” hazard.

a) Very high
(b) Somewhat high
(c) Equal
(d) Somewhat Low
(e) Very Low

6) Relative to the factor “Exceeding the force limits of the drill rig,” how significantly will the factor “Experience of the worker on job site” contribute to the occurrence of “Stall/breakage of drill string/drill head” hazard.

a) Very high
(b) Somewhat high
(c) Equal
(d) Somewhat Low
(e) Very Low
7) Relative to the factor “Lack of PPE,” how significantly will the factor “Experience of the worker on job site” contribute to the occurrence of “Injury to worker” hazard.

a) Very high

(b) Somewhat high

(c) Equal

(d) Somewhat Low

(e) Very Low

8) Relative to the factor “Experience of the worker on job site,” how significantly will the factor “Lack of PPE” contribute to the occurrence of “Injury to worker” hazard.

a) Very high

(b) Somewhat high

(c) Equal

(d) Somewhat Low

(e) Very Low

9) Relative to the factor “Unsuitable apparel for the work conditions,” how significantly will the factor “Experience of the worker on job site” contribute to the occurrence of “Injury to worker” hazard.

a) Very high

(b) Somewhat high

(c) Equal

(d) Somewhat Low

(e) Very Low
10) Relative to the factor “Inappropriate/Lack of communication mechanism among the crew,” how significantly likely will the factor “Experience of the worker on job site” contribute to the occurrence of “Workers falling into excavated Pits” hazard.

a) Very high

(b) Somewhat high

(c) Equal

(d) Somewhat Low

(e) Very Low

11) Relative to the factor “Lack of proper barricading around the pits and alarms,” how significantly will the factor “Inappropriate/Lack of communication mechanism among the crew” contribute to the occurrence of “Workers falling into excavated Pits” hazard.

a) Very high

(b) Somewhat high

(c) Equal

(d) Somewhat Low

(e) Very Low

12) Relative to the factor “Behavior and postures of the workers during the drilling operation,” how significantly will the factor “Lack of proper barricading around the pits and alarms” contribute to the occurrence of “Workers falling into excavated Pits” hazard.

a) Very high

(b) Somewhat high

(c) Equal

(d) Somewhat Low

(e) Very Low
13) Relative to the factor “Behavior and postures of the workers during the drilling operation,” how significantly likely will the factor “Experience of the worker on job site” contribute to the occurrence of “Workers falling into excavated Pits” hazard.

a) Very high
(b) Somewhat high
(c) Equal
(d) Somewhat Low
(e) Very Low

14) Relative to the factor “Behavior and postures of the workers during the drilling operation,” how significantly will the factor “Inappropriate/Lack of communication mechanism among the crew” contribute to the occurrence of “Workers falling into excavated pits” hazard.

a) Very high
(b) Somewhat high
(c) Equal
(d) Somewhat Low
(e) Very Low
15) Relative to the factor “Experience of the worker on the job site,” how significantly will the factor “Lack of proper barricading around the pits and alarms” contribute to the occurrence of “Workers falling into excavated pits” hazard.

a) Very high

(b) Somewhat high

(c) Equal

(d) Somewhat Low

(e) Very Low
Comparative Questionnaire Survey results for factors influencing hazards and characteristics influencing factors.

Table B.1. Comparative questionnaire survey results converted to quantitative numbers for factors influencing hazards $H_1$, $H_2$, $H_3$ and $H_4$.

<table>
<thead>
<tr>
<th></th>
<th>Hazard One ($H_1$)</th>
<th>Hazard Two ($H_2$)</th>
<th>Hazard Three ($H_3$)</th>
<th>Hazard Four ($H_4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_{12}$</td>
<td>$F_{23}$</td>
<td>$F_{13}$</td>
<td>$F_{14}$</td>
</tr>
<tr>
<td></td>
<td>$Q_1$</td>
<td>$Q_2$</td>
<td>$Q_3$</td>
<td>$Q_4$</td>
</tr>
<tr>
<td>E1</td>
<td>1</td>
<td>0.5</td>
<td>3</td>
<td>0.33</td>
</tr>
<tr>
<td>E2</td>
<td>0.5</td>
<td>0.33</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>E3</td>
<td>1</td>
<td>3</td>
<td>0.33</td>
<td>2</td>
</tr>
<tr>
<td>E4</td>
<td>0.5</td>
<td>3</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>E5</td>
<td>0.3</td>
<td>2</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Sigma(E1:E5)$</td>
<td>3.3</td>
<td>8.83</td>
<td>11.3</td>
<td>3.83</td>
</tr>
<tr>
<td>Avg.$(E1:E5)$</td>
<td>0.66</td>
<td>1.76</td>
<td>2.26</td>
<td>0.76</td>
</tr>
</tbody>
</table>
**Table B.2.** Comparative questionnaire survey results converted to quantitative numbers for characteristics influencing factors F₁, F₂ and F₃.

<table>
<thead>
<tr>
<th>E1</th>
<th>Q₁</th>
<th>Q₂</th>
<th>Q₃</th>
<th>Q₄</th>
<th>Q₅</th>
<th>Q₆</th>
<th>Q₇</th>
<th>Q₈</th>
<th>Q₉</th>
<th>Q₁₀</th>
<th>Q₁₁</th>
<th>Q₁₂</th>
<th>Q₁₃</th>
<th>Q₁₄</th>
<th>Q₁₅</th>
<th>Q₁₆</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.5</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
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<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>E2</td>
<td>2</td>
<td>0.5</td>
<td>0.33</td>
<td>2</td>
<td>0.5</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E3</td>
<td>2</td>
<td>0.5</td>
<td>0.33</td>
<td>2</td>
<td>0.5</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E4</td>
<td>2</td>
<td>0.5</td>
<td>0.33</td>
<td>2</td>
<td>0.5</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E5</td>
<td>2</td>
<td>0.5</td>
<td>0.33</td>
<td>2</td>
<td>0.5</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>∑(E1:E5)</td>
<td>8.5</td>
<td>6.83</td>
<td>7.66</td>
<td>6.66</td>
<td>7.83</td>
<td>6.66</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Avg.(E1:E5)</td>
<td>1.7</td>
<td>1.36</td>
<td>1.53</td>
<td>0.33</td>
<td>1.56</td>
<td>1.33</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
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<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Table B.3. Comparative questionnaire survey results for characteristics influencing factors F3, F4, F5, F6, F7, F8 and F9.

|       | F3  |       | F4  |       | F5  |       | F6  |       | F7  |       | F8  |       | F9  |
|-------|-----|-------|-----|-------|-----|-------|-----|-------|-----|-------|-----|-------|-----|-------|
|       | C13 | C24   | C12 | C23   | C34 | C14   | C13 | C24   | C12 | C23   | C13 | C12   | C12 | C23   | C13 |
| E1    | 0.33| 0.5   | 2   | 2     | 3   | 0.33  | 3   | 0.33  | 2   | 3     | 0.5 | 3     | 2   | 0.33  | 1   | 1     | 0.33|
| E2    | 2   | 2     | 0.33| 0.33  | 0.33| 0.33  | 0.33| 0.33  | 3   | 2     | 2   | 0.33  | 0   | 0.33  | 1   | 0.33  | 0.5 |
| E3    | 0.33| 0.33  | 0.33| 0.33  | 0.33| 0.33  | 0.33| 0.5   | 0.5 | 2     | 0.5 | 0     | 1   | 2     | 1   | 0.5   | 0.5 |
| E4    | 0.33| 0.33  | 0.33| 0.5   | 2   | 0.33  | 0.33| 1     | 0.5 | 2     | 2   | 0     | 2   | 2     | 0.5 | 2     | 0.5 |
| E5    | 0.33| 0.33  | 0.33| 0.33  | 0.33| 0.33  | 0.33| 0.33  | 0.5 | 0.33  | 0.5 | 0     | 0.5 | 0     | 2   | 0.33  | 2   |
| Σ(E1:E5) | 3.32| 3.49  | 3.32| 3.49  | 5.99| 1.65  | 4.32| 2.49  | 6.5 | 9.33  | 5.5 | 3.83  | 5.5 | 5.16  | 5.5 | 4.16  | 3.83|
| Avg.(E1:E5) | 0.66| 0.69  | 0.66| 0.69  | 1.98| 0.33  | 0.86| 0.49  | 1.3 | 0.86  | 1.1 | 0.76  | 1.1 | 1.03  | 1.1 | 0.83  | 0.76|

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